Aotearoa New Zealand's renewable energy transition: critical mineral & metals demand

Final Report

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Glossary

Terms

- **Acid rock drainage** – A natural process produced when mining activities expose sulphur-bearing minerals to oxygen and moisture, resulting in production of sulfuric acid.
- **Amorphous silicon** – The non-crystalline form of silicon with disordered silicon atoms, used in some solar cells and thin films. Lower quality silicon is used in glass.
- **Anode** – One of the electrodes through which current enters a device (in conventional current).
- **Beneficiation** – A process that improves the economic value of an ore by removing unwanted gangue materials.
- **Bioaccumulation** – The process of accumulation of chemicals in an organism where the intake rate exceeds that of excretion.
- **Biogenic methane** – Methane gas emitted from biogenic sources including farming livestock.
- **Coking coal** – A grade of coal that can be used to produce good quality coke, which is used as a fuel and reactant in a blast furnace to produce steel.
- **Critical materials** – Key materials required for a certain use-case. In this research it refers to materials in CSIRO's Critical Minerals Roadmap and the Draft NZ Minerals Strategy, which are core to manufacturing renewable energy technologies as part of an energy transition.
- **Demand-side management** – A strategy used by electricity providers to control demand by incentivising customers to modify their usage patterns, for example shifting loads to off-peak times.
- **Dispatchable energy** – Power sources that can be adjusted on demand by grid operators to match supply with electricity demand.
- **Distributed generation** – Electricity generated from sources near the point of use, instead of the typical centralised generation system.
- **Drag-head** – Steel structure connected to a dredger used in undersea mining.
- **Electric arc furnace** – Furnace heating materials by means of an electric arc, commonly used for manufacturing steel.
- **Electrolyser** – The process of using electricity to split water into hydrogen and oxygen.
- **Electrolyte** – Substances that have a natural positive or negative electrical charge when dissolved in water. When an electric potential is applied, a charge separation occurs, and the electrolyte conducts electricity.
- **Electrowinning** – Electro-deposition of metals from an applied voltage over a concentrated solution of the metal.
- **Emissions reduction pathway** – Potential models of carbon emissions reductions over time.
- **Energy transition** scenario – The combinations of technological developments and technology growth used across renewable energy technologies for this research.
- **Eutrophication** – Accumulation of nutrients in a system, resulting in increased growth of microorganisms that may delete the water of oxygen.
- **Hard carbon** – A solid form of carbon that cannot be converted to graphite.
- **Heavy fleet** – Larger vehicles used for commercial and industrial purposes including medium and heavy trucks.
- **Hydrometallurgical** – Use of aqueous solutions for the recovery of metals from ores, concentrates, and recycle or residual materials.
- **Intermittent generation** – A source of energy that is not continuously available for conversion into electricity, and outside the direct control of a grid operator.
- **Leaching** – Loss of extraction of certain materials from a carrier into a liquid (typically a solvent).
- **Light fleet** – Smaller vehicles used for light commercial means, and personal passenger transport.
- **Market share** – Percentage of total sales in an industry from a company. In this research, this is the share of the total sales accounted for by different technological developments.

- **Material flows** – In this research, this is the annual input or output from the cumulative stock of materials in the system of renewable energy technologies.
- **Material stocks** – The cumulative stock of materials in the system of renewable energy technologies.
- **Materials requirements** – The number and range of materials required to manufacture a functional unit of a renewable energy technology.
- **Materials tiers** – Sets of materials used for grouping based on shared properties.
- **Monocrystalline silicon** – A consistent unbroken silicon crystal lattice. This is the most common and efficient form of silicon for use in solar PV panels.
- **Non-wire alternatives** – Alternative methods for distributing energy to loads without large requirements for cabling, and other transmission and distribution infrastructure.
- **Orebody** – A connected mass of ore in a mine, suitable for mining.
- **Overburden** – Rock or soil overlying a mineral deposit.
- **Peakers** – Energy generation that generally only runs when there is high demand.
- **Platinum group elements** – Six noble, precious metallic elements, grouped together in the table of elements – typically used as catalysts.
- **Polycrystalline silicon** – A material consisting of many small silicon crystals instead of a single consistent lattice.
- **Post-lithium-ion batteries** – Future batteries that will replace the current set of common lithium-ion battery developments.
- **Pyrometallurgical** – Extraction and purification of metals by processes involved the application of heat.
- **Rare earth elements** – Seventeen lustrous silvery-white soft heavy metals with diverse applications in electronics, photonics, and industrial processes.
- **Renewable energy technologies** – In this research, these are considered to include renewable energy generation, energy storage, and electric vehicles.
- **Reverse osmosis filtration** – Processed used to remove contaminants from water.
- **Salar brines** – Highly concentrated brine, typically consisting of lithium, potassium and sodium.
- **Slag waste** – A byproduct of smelting ores and recycled metals.
- **Spodumene** – A silicate material of lithium and aluminium.
- **Sulphides** – A family of inorganic and organic compounds containing sulphur anions.
- **Tandem solar panels** – Solar panels with stacks of semiconductor materials with different electron bandgaps, allowing for the capture of a wider range of the wavelengths of incident light – improving the efficiency of the solar panel.
- **Technological developments** – In this research, these are considered different versions of a technology e.g., LFP lithium-ion batteries, and $NaPF_6$ sodium-ion batteries.
- **Technology growth** – The overall growth of the use of a certain technology.
- **Technology Readiness Level** – A method for estimating the maturity of technologies.
- **Thermochemical** – Chemical reactions or phase changes resulting from the application of heat.
- **Thin films** – A type of solar cell made by depositing thin layers of photovoltaic materials onto a substrate. These are typically thinner and lighter than standard PV panels.
- **Titanomagnetite** – Mineral containing oxides of titanium and iron.
- **Transitionary development** – A development of a technology which serves as a temporary option while more long-term developments are further commercialised.
- **Transmittance** – The portion of incident light that is transmitted through a material.
- **Waste tailings** – The materials left over after the process of separating the valuable fraction from the unwanted gangue.

Acronyms

- **ASSLIB** – “All Solid-State Lithium-Ion Battery”. Uses a solid electrolyte as a separator for lithium ions to pass through, instead of the typical aqueous electrolyte.
- **CAPEX** – “Capital Expenditure”. Funds used to undertake new projects or investments, rather than support ongoing operations.
- **CCGT** – “Combined-Cycle Gas Turbine”. Captures waste heat from initial combustion cycle as steam, driving further energy generation.
- **CdTe** – “Cadmium-Telluride”. A semiconductor material used in thin film solar PV developments.
- **CIGS** – “Copper-Indium-Gallium-Selenide”. A semiconductor material used in thin film solar PV developments.
- **c-Si** – “Crystalline-Silicon”. The most common semiconductor material used in solar PV panels.
- **DFPP** – “Double-Flash Power Plant”. A geothermal power plant design employing two stages of steam generation to generate more energy compared to a single-flash design.
- **GTI** – “Gas Turbine Unit”. Includes a gas turbine engine, sub-engine frame, and foundation.
- **HFCV** – “Hydrogen Fuel-Cell Vehicle”. A vehicle propelled by hydrogen, producing only water as a by-product.
- **ISE** – “Inorganic Solid Electrolyte”. A type of all-solid-state electrolyte constituted by an inorganic material in the crystalline state, conducting ions through diffusion through the lattice structure.
- **LATP** – “Lithium-Aluminium-Titanium-Phosphate”. Chemical mixture used in solid-state electrolytes or separators in some lithium batteries.
- **LCA** – “Life-Cycle Assessment”. An environmental footprint assessment used to estimate impacts throughout a product or system’s life cycle.
- **LEC** – “Low-Emissions Combustion”. Techniques used to reduce carbon dioxide and nitrogen oxides emissions produced through combustion in gas turbines.
- **LFP** – “Lithium-Iron-Phosphate”. The most common development of the lithium-ion battery, used in electric vehicles, residential PV system storage, and grid-scale energy storage.
- **LIB** – “Lithium-Ion Battery”. A category of rechargeable batteries that use Lithium in the electrolyte.
- **NaBOB** – “Sodium bis(oxalate)borate”. An electrolyte used in some Sodium-ion batteries.
- **$NaPF_6$** – “Sodium hexafluorophosphate”. An electrolyte used in some Sodium-ion batteries.
- **NCA** – “Nickel-Cobalt-Aluminium”. A type of lithium-ion battery development.
- **NiMH** – “Nickel-Metal-Hydride”. A category of rechargeable batteries with a lower energy density compared to lithium-ion batteries but are less prone to leakage.
- **NMC** – “Nickel-Manganese-Cobalt”. A type of lithium-ion battery development.
- **Non-PM** – “Non-Permanent-Magnet” – A wind turbine generator development that doesn’t use permanent magnets.
- **OCGT** – “Open-Cycle Gas Turbine”. A single-stage gas turbine with no additional heat capture technologies.
- **OPEX** – “Operating Expenditure”. Funds used to support ongoing, existing operations, rather than new acquisitions or projects.
- **PMDD** – “Permanent Magnet, Direct-Drive”. A category of wind turbine generator technology that uses a permanent magnet in the production of electricity, with rotation transmitted directly from the rotor to the generator.
- **PMGEAR** – “Permanent Magnet, Geared”. A category of wind turbine generator that uses a permanent magnet in the production of electricity, with rotation translated through a reduction gearbox to match its speed to the frequency of the grid.
- **PSC** – “Perovskite Solar Cell”. An upcoming solar cell development using a perovskite-structured compound. The perovskite crystal structure is one of the most abundant structural families and is found in many compounds.

- **PV** – “Photo-voltaic”. Production of an electrical charge through the photoelectric effect. Typically used in “PV panel”, which is also referred to as a solar panel.
- **RFB** – “Redox-Flow Battery”. A type of electrochemical cell, where energy is provided by an aqueous solution of chemical compounds pumped through different sides of a membrane.
- **SIB** – “Sodium-Ion Battery”. A category of rechargeable batteries that use Sodium in the electrolyte.
- **T&D** – “Transmission & Distribution”. Infrastructure that enables the reticulation of energy from the site of generation to where the loads exist.
- **VRFB** – “Vanadium Redox-Flow Battery”. A common development of the redox-flow battery, which uses vanadium pentoxide as the pumped solution.

1 Executive Summary

This research report details the results and insights from an investigation into the quantity of ‘critical materials’ (key metals and non-metallic minerals) required to manufacture renewable energy technologies. New Zealand requires these technologies to achieve an energy transition towards the 2050 carbon emissions reduction targets under the Zero Carbon Act. Renewable energy technologies covered in this research report include renewable electricity generation technologies, battery energy storage, and electric vehicles.

1.1 Overview

Sections 2 and 3 of this report introduces the research, and background on critical materials and their role in an energy transition. The report then details the methods used to estimate the growth, technological developments, and materials requirements of various renewable energy technologies throughout Sections 4, 5 and 6. Following this, Sections 7 and 8 provide analysis and discussion around a set of indicative scenarios for NZ’s energy transition. The discussion considers related factors including mineral extraction and waste. This analysis also includes a deep dive on key materials of interest, outlining how each material is relevant to an energy transition, and the specific environmental risks associated with them. Final conclusions from the research are provided in Section 9.

Three indicative energy transition scenarios are used in this report including a default Net-Zero scenario which meets Zero Carbon Act targets, a Business as Usual (BAU) base case, and a Rapid Decarbonisation scenario where NZ exceeds targets (these are explained in more detail in Section 7). The material requirements in each scenario are reported across three tiers of materials based on their importance to the energy transition, and an additional set of materials identified in the Draft NZ Minerals Strategy (included in Appendix 10.1 on Page 69). Materials not included in any of these lists are excluded from analysis.

Estimates produced through this research are based on existing research and datasets. Sources used throughout the development of this research are included in Appendix 10.3. Where gaps have been identified, Aurecon have provided indicative numbers in place of existing research (this is stated clearly where applicable). These indicative numbers are based on related research and professional judgement.

1.2 Key Findings (Net-Zero Scenario)

- Tier 1 materials, which includes graphite and lithium used in batteries, are estimated to increase in annual demand by approximately **53** times by 2050 compared to the 2020 baseline year. In contrast, these materials account for only **4.1%** of the total annual critical materials requirements in 2050 across all tiers.
- Estimated material requirements across the renewable energy technologies in scope are dominated by contributions from electric vehicles. Over **80%** of the materials in each tier are attributed to these vehicles by mass.
- Reductions in fleet sizes modelled in the underlying Climate Change Commission data result in smaller overall materials requirements in the Net-Zero and Rapid Decarbonisation scenarios – compared to the BAU base case. This reduction offsets the increase in materials requirements from increased renewable electricity generation buildout.
- Uptake of technological developments can offset a proportion of the increase in materials requirements over time, through the replacement of these with less critical alternatives. The resulting increase in demand for less critical materials (those not included in Appendix 10.1) are not modelled in this exercise.
- Materials included in the Draft NZ Minerals Strategy may play a relatively minor role in an energy transition by mass. In the Net-Zero scenario, these materials would account for an estimated **1.4%** of the total requirements by mass, and **12.6%**, if structural metals (aluminium and iron) are excluded from analysis.
- Waste streams of materials embodied in assets that are reaching their end of life begin to increase in the mid-2030s. This poses an opportunity for re-use and recycling of materials, to reduce the requirement for virgin materials in following years.
- Supply chains for different materials share common environmental risks, including direct environmental effects, water usage, pollution from mining and beneficiation, and both indirect and direct carbon emissions from refining and smelting.
- The materials included in the Draft NZ Minerals Strategy vary significantly in terms of their environmental risk profiles – associated with their extraction techniques.

2 Introduction

2.1 Purpose

This report has presents findings from research to estimate the mass of 'critical materials' (key metals and non-metallic minerals) embodied in renewable energy technologies (RETs). These technologies, including renewable electricity generation, battery energy storage, and electric vehicles, are required by NZ to meet the country's net-zero 2050 greenhouse gas emissions (GHG) reduction targets under the Zero Carbon Act.

2.2 Context

New Zealand has a National Determined Contribution (**NDC**[1]) under the UN Paris Agreement to reduce net GHG emissions to 50% below 2005 gross GHG emissions levels by 2030. [2]Under NZ's Climate Change Response (**Zero Carbon**) Amendment Act, the country has also set targets to reduce net GHG emissions (excluding biogenic methane emissions) to zero by 2050. These targets are in line with limiting the global average increase in temperature resulting from climate change, compared to pre-industrial levels, to well-below 2 degrees.

Central to achieving these targets is the decarbonisation of energy use, and industrial processes and product use (IPPU), which accounted for **42.3%**[3] of NZ's gross GHG emissions in 2022. While NZ's electricity system is already largely renewable, many industrial processes, and most of the country's vehicle fleet is currently fossil fuel powered. Decarbonisation of energy use in industrial settings requires a large investment in renewable energy, as the current total generation cannot support the demand for electricity that would result from mass fuel-switching. Equally, the vehicle fleet consists overwhelmingly of internal combustion engine (ICE) vehicles. Decarbonisation of the vehicle fleet aims to replace the ICE fleet with electric alternatives – which itself requires a substantial buildout of renewable energy to support the electricity demand of electric vehicle (EV) charging.

While there are many potential pathways to achieving the required emissions reductions to meet these targets, models from the Climate Change Commission (CCC) have been used as the basis for the analysis in this report.

2.3 Scope

This research estimates the total mass of materials (key metals and non-metallic minerals) embodied in the technologies that will enable NZ to meet its 2050 net-zero carbon target. The technologies assessed were:

- Solar photovoltaic (PV) electricity generation
- Wind turbine electricity generation
- Battery energy storage systems (BESS)
- Plug-in hybrid and battery electric road vehicles
- Transmissions & distribution infrastructure
- Geothermal electricity generation

Materials included in the scope of this exercise are outlined in **Appendix 10.1**. It's important to note that modelled technologies may include materials outside these tiers, and the model therefore may not be a representation of total mass breakdowns, only of the minerals and materials deemed 'critical.' An example of this is sodium-ion batteries, where the lithium and graphite from lithium-ion batteries are replaced by sodium and hard carbon, which are outside the modelling scope.

Limitations of the estimates are provided in the methodology in **Section 4.5**, and exclusions from this analysis are outlined in **Section 4.6**. The estimates were developed through compiling existing research and datasets and integrating results into a single interactive Microsoft Excel workbook. This report details the methodology adopted, provides analysis of the resulting estimates and discusses the related consequences.

The final deliverables of this work are the dataset, this report, and a final presentation of the findings.

2.4 Dataset

The dataset is an interactive Excel workbook which allows users to select a combination of future scenarios across each technology and develop visualisations of the outcomes for both cumulative stocks and annual flows of materials. While the research scope looked to develop a standalone dataset for analysis, Aurecon has taken steps to ensure the modelling is reusable and serves as a revisable tool rather than solely a point-in-time estimate.

3 Background

3.1 Overview

The energy transition is fundamentally changing the types of resources that society demands. Critical minerals are often talked of as ‘the new oil’ but this is too simplistic – there are dynamics at play that influence the growing demand for these resources. This section aims to provide an overview of these dynamics, and outline how this report has taken them into account in the estimates of Aotearoa NZ’s future demands for metals and minerals used in the energy transition.

At the most fundamental level, the dynamics reflect how critical resources are used, where they come from, risks associated with their supply chains, and how the dynamics themselves are likely to change in the future:

- **Supply chains (current paradigm):** Current-state fossil resources need to be continually extracted and consumed to maintain annual energy requirements, but the energy transition changes this dynamic. Instead, minerals are extracted to meet the needs of growth and change on a one-off basis, e.g. for a solar panel that will continually generate energy for 20 years. The supply chains associated with these resources are different to the current state; they involve different countries, manufacturers, processes, and environmental risks.
- **Technological change (ever-present):** The technologies that use these resources are changing rapidly, and increased production can have its own impact on overall demand. Manufacturers get better at producing components, designing out expensive or risky materials and making their products cheaper. This in turn drives further demand growth, and further improvements to efficiency.
- **The circular economy (emerging driver):** Technological change isn’t the only way to reduce resource demand. Critical mineral and metal resources are often used as stocks within technological systems rather than flows, as they can be recaptured and processed at the end of life. Asset lifetimes can be expanded, and materials can be repurposed, reducing or even removing the need for continual extraction of these minerals and metals.

3.2 Supply Chains: Geography and Risks

This driver is already significant for both the energy transition and the energy system. This marks a key focus of many reports already published in the literature. Critical minerals themselves aren’t new – the US created its **first list of minerals**[4] deemed nationally-significant during WWI, and the concept has been expanded significantly since. Australia, China, the EU, the US, India, and Japan all have similar lists that account for resources critical to their respective economies or strategic objectives. Some include the energy transition as a specific driver.

Just like when the US identified resources it couldn’t supply domestically 100 years ago, many of the minerals on current critical mineral lists are primarily extracted or refined in countries offshore. On a surface level, this isn’t too dissimilar from the fossil resource economy – some countries have the resources, and others don’t. There are a few core differences between these supply chains, however: different metal and mineral commodities can require significant ore processing before they become economically viable to ship, there is an incredible variety in the resources themselves (as well as the processes required to refine them), and some resources are much more geographically constrained than others, even more so than oil and gas today.

Geographical Drivers

The geopolitical drivers to secure resources are becoming increasingly important for critical materials for the energy transition, with China having a dominant position for domestic resource refining, clean energy manufacturing, and (to a lesser extent) resource extraction. This has led to trends for Western-aligned countries to encourage onshoring, near-shoring (moving production closer to end-demand countries) or “friend-shoring” (moving production to allied countries). Although this may help de-risk political disruptions, it also introduces new risks; where supply chain fragmentation may end up slowing the overall energy transition, reducing economies of scale and slowing the innovation possible through open and global partnership. This report will not comment on the relative merits of each strategy but will highlight these dynamics where they occur in supply chains.

An additional driver for these geographic constraints relates to how to fund the future expansion of these supply chains where long-term projections indicate that supplies of these critical materials will need to increase drastically. For example, the IEA project that more than 1.2 Mt of lithium production will be needed by 2040, with current announced supply growth expected to cope with demand increases until

2030. However, recent supply expansions have led to a glut of lithium on the market, pushing prices down, and disincentivising investment in either exploration or developing new mines. There may be long-term demand growth forecast, but there is a risk that financial drivers alone may not be enough to encourage investment.

This is somewhat complicated by the distribution of financial value along the value chain. The International Renewable Energy Agency (IRENA) illustrate this point (shown in **Figure 1**) using EVs and batteries as an example; where most of the value is made during cell assembly and the production of the vehicle itself, with mining, refining, and chemical production all capturing a much smaller proportion of the economic benefits. For countries with mineral wealth, this pattern represents a continuation of the 'resource curse' where profits are exported, and extractive countries are stuck at the front end of the value chain. When mining only reflects 0.6% of the total value, climbing this value chain seems to be a much more attractive goal.

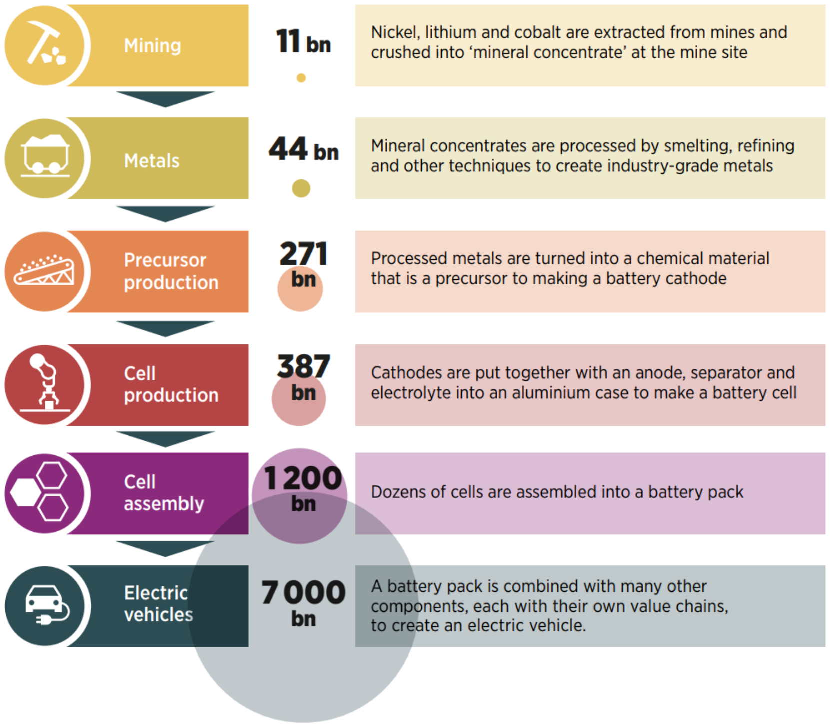


Figure 1: IRENA estimates of the global battery and EV value chain, as adapted from UNECA data

Environmental Risks

A final supply-chain constraint relates to the environmental risks associated with resource extraction. As an example, the concentration of a valuable metal within its ore can be tiny, meaning large volumes of waste rock, or *gangue*, are produced during processing. This needs to be stored in actively managed disposal facilities such as tailings dams, especially where chemical methods are used to help recover the metals from the ore. Similarly, the methods used to smelt metals from ores can also have severe local environmental impacts.

As the global society extracts more material using the current supply chains, the risks associated with this extraction also increase. However, we cannot use these risks alone as a reason to prevent this transition. The current fossil extraction industry also has its own environmental risks from drilling, mining, transport, and refining. As we transition away from fossil fuels, we reduce their risks too. An increasing level of environmental impact from one part of the industry should be considered alongside a decrease from other areas.

3.3 Technological Disruption

The nature of a disruptive technology, by definition, is that it's hard to predict change until it happens. There's always a limiting factor that causes the incumbent to write it off, to say it's not good enough to replace the current paradigm. Digital cameras were initially less capable of capturing detail than film, and more expensive to boot. But development continued, digital took over, and Kodak was almost wiped out as a company. EVs were never going to be able to work for road trips. Their batteries would need replacing every few years, and they cost twice as much as an equivalent petrol car. But development continues to address these concerns.

The rollout of new technological developments over the last 100 years has almost always occurred on S-curves (see **Figure 2Figure 2**, taken from the Rocky Mountain Institute's (RMI) **X-Change Electricity**[5] report). Growth and market penetration is small at first, slow, even. But once a tipping point is reached, the rate of change becomes more visible. The volumes increase exponentially until a saturation point is reached, and the upstart becomes the dominant player. This change is a constant, and it is expected to be the same for the energy transition as it was for the digital revolution.

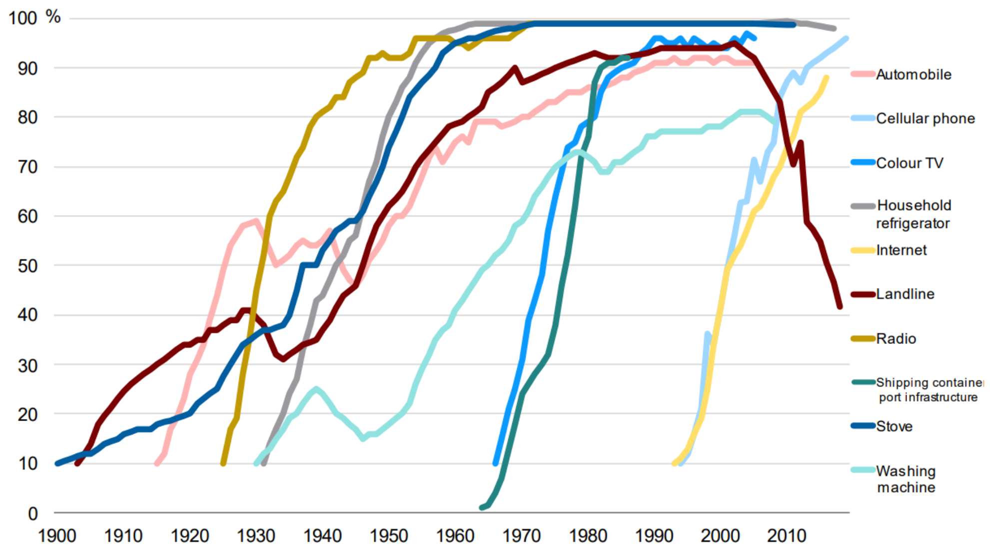


Figure 2: S-curves from historic technology rollouts, the share of US households using technologies - from RMI's X-Change Electricity report

The challenge with modelling changes such as technological disruption is that it's very easy to assume that this saturation point will happen early, and that the shift will happen slower. Models from both the IEA and from BloombergNEF have constantly underestimated the growth in EVs, solar PV, wind deployment, and battery storage, as shown in **Figure 3** taken from the RMI's 2024 **Cleantech Revolution**[6] report.

In the New Zealand context, this has an additional challenge. We're a relatively small, isolated market, especially for electricity. We don't have the flexibility to export or import energy in the same way as, say, a European country can, and overall demand can be changed significantly by a small number of internal drivers. The recent announcement that aluminium will continue to be produced at Tiwai Point for another 20 years at least, was enough for significant **new investments**[7] in generation to be confirmed. A single large industrial user had a measurable impact on the national system, independent of these international trends.

When modelling the future energy system and its demand for materials, we must be cognisant of how these macro trends and technological developments are implemented within the local NZ context.

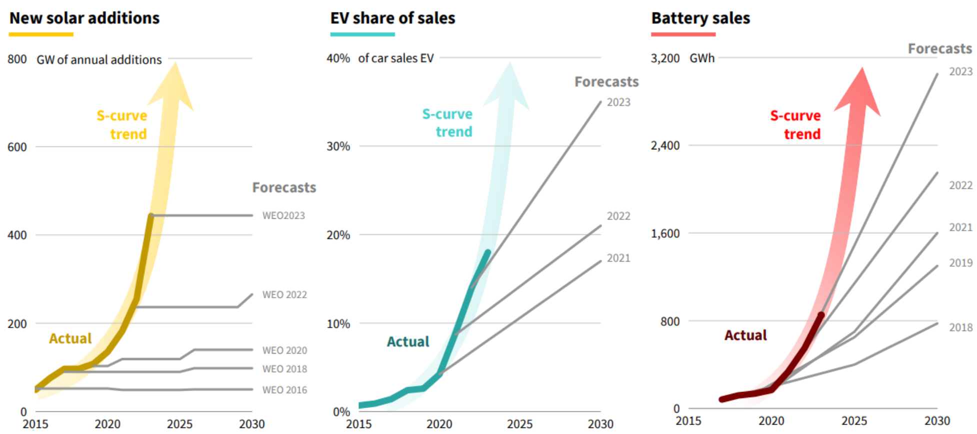


Figure 3: Underestimating the speed of change in solar PV, EV, and battery storage rollout, taken from RMI's Cleantech Revolution report

Further to this challenge, these technological developments have implications on the types of materials that will be demanded; in fact, technological developments that remove costly materials for PV or batteries are in themselves drivers for a further and faster energy transition.

The more production that occurs, the better manufacturers get at producing technologies. This 'learning curve' is called Wright's Law, which demonstrates a general pattern of a 20% reduction in costs with each doubling of production. These price declines come from increased efficiencies, and a gradual change of technology even within the wider PV or battery sectors. For example, expensive components such as silver conductors in PV panels have had their usage minimised in the last 20 years, and materials with risky supply chains such as cobalt can be designed out of batteries entirely, such as for LFP chemistries.

When taken as an aggregate, these changes have significant impacts on the forward estimates of material usage demand – when both total volumes and the more detailed makeup of deployments are changing rapidly, final estimates are highly uncertain. To develop this model, our chosen pathway forward has prioritised local NZ demand models in a globally changing context, adopting scenarios for analysis that can account for some of these changes and challenges.

3.4 The Circular Economy

One of the key differences between the future energy system and the current fossil-dominated system is what the resources extracted by these systems are fundamentally used for. We dig up coal, drill for oil and gas, and then burn them. That energy is used up in a single hit, and we need to continually extract more to meet the constant demand for energy. But resource extraction in the emerging energy system is different – we use these minerals to produce assets that generate, store, or use energy for years, even decades at a time, and these resources don't get 'used up' in the same way as fossil resources. From this starting point, the circular economy will increase in importance over time as a thematic driver for change within the energy transition.

The circular economy is based around three core design **principles**[8], each of which influence the material requirements for the energy transition:

Removing waste and pollution from the mining and refining process creates a positive feedback loop. For example, when the electricity grid decarbonises by building out renewable generation, or when mining & refining processes electrify or become more efficient, these changes act to reduce the environmental impacts of manufacturing key materials for the energy transition itself.

Retaining value in assets and materials can occur through many individual strategies, including designing products for reuse or repair, extending the lifespans of generation technologies, repurposing old vehicle batteries as grid storage, as well as recycling the materials themselves at the end of life. As the asset lives of many of these products will be 10-20 years, there will likely need to be massive scaling of virgin material supply before secondary materials will become available in significant volumes, however.

This highlights the need to encourage the development of infrastructure to support the circular economy over the coming 10-20 years, so that by the time secondary materials and assets make up a significant proportion of the potential supply, we have the capacity to take advantage of them and reduce the need for virgin material extraction.

Finally, the regeneration of natural systems goes together with minimising the direct physical impacts of resource extraction. Nature-based solutions go beyond carbon offsets, and can include natural wetlands for wastewater management, habitat restoration for mine sites themselves, and changing where resources come from (such as technologies to extract minerals from tailings waste or geothermal fluids and brines) to reduce the need for resource extraction as it happens today.

4 Methodology

The development of the dataset revolves around three lenses: the **Technology Growth**, the **Technology Developments** (and their corresponding "**Market Share**"), and the **Materials Requirements** of each development within a technology. Here, the market share relates to the proportion of the annual demand serviced by different technological developments. These three lenses are built as "modules" within the dataset, as shown in Figure 4. This allows the dataset to consider how the gross demand for a technology is changing over time, how different developments account for portions of the market over time, and what materials are required to assemble a functional unit of each technology. The functional unit refers to the mass per unit of technology, for example kilogram per megawatt (kg/MW) for electricity generation technologies.

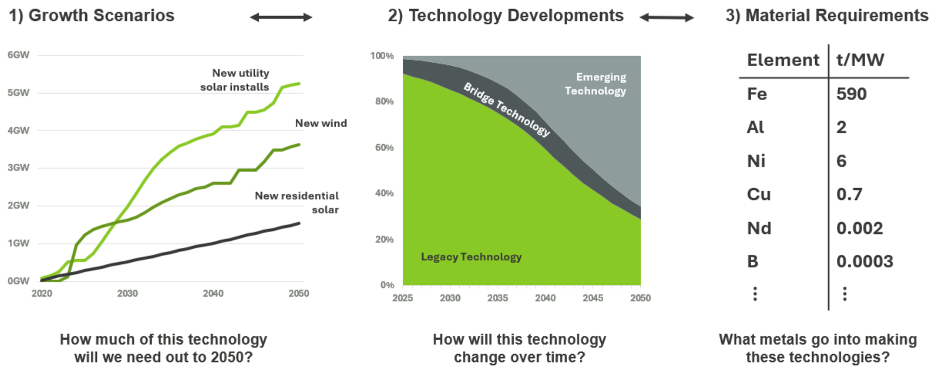


Figure 4: Three interconnected lenses used to develop the dataset scenarios

The first lens, **Technology Growth**, accounts for the cumulative stock of that technology installed in NZ at a given time, or in some cases, the annual additions to stock. In the case of renewable electricity generation this is measured in MW, for battery storage, MWh, and for vehicles and some transmission & distribution infrastructure, simply the number of units. This is covered in more detail in Section 4.1.

The second lens, **Technology Developments**, relates to how individual technologies (e.g. solar and wind generation and EVs) are expected to change over time, and is scaled by the first lens. The market share of technology developments represents the proportion (between 0 and 100%) of the market that each development accounts for in any given year. This enables the model to capture changing materials requirements as different developments enter the market (examples of technology development modelled include new battery chemistries, perovskite solar cells and direct drive wind turbines). Through this lens, the model can consider how new technological developments can displace older versions of the same technology over time. Section 4.2 provides more detail on this lens.

The third and final lens, **Material Requirements**, is the breakdown of what key metals and non-metallic minerals are required to manufacture a functional unit of that technology development. While the first two lenses change over time, the materials requirements for each development are static throughout the modelling period. Changing efficiencies and material intensities are not considered in this exercise. Setting up the values this way enables consistent, and simple calculations of estimates for visualisation. Section 4.3 includes more background on this.

With these calculations in the background of the dataset, the reader/user may simply select a combination of scenarios to model from a list in drop-down boxes for each technology. The workbook then sums individual requirements from the technologies, sorts them into common materials for each model year, and will present the results visually across three accounting methods, and four materials tiers.

The three accounting methods, "**stocks**", "**flow-in**", and "**flow-out**" enable the user to visualise how these materials accumulate over time, and at what point in time they are entering and leaving the system according to their expected useable lifespan. Additional explanations of how this achieved is given in Section 4.4. Finally, tier-sorting enables users to view these results separately for materials with different levels of importance and covers three tiers of importance from Australia's Commercial Scientific and Industrial Research Organisation (CSIRO) Critical Minerals Roadmap[9], and the set of materials covered in NZ's Draft Minerals Strategy[10].

Aurecon has taken a modular approach to modelling which enables values to be replaced easily. For example, if a new technology growth scenario was available, this could be easily integrated without affecting other aspects of the model. The release of the updated Electricity Demand and Generation Scenarios (EDGS[11]) from the Ministry of Business, Innovation, and Employment (MBIE) – is an example of an alternative set of scenarios that was released late into the delivery of this research. Here, users simply need to format these scenarios to fit the CCC framing and replace them in the dataset. Appendix 10.2 shows this methodology in more detail.

4.1 Technology Growth Scenarios

The additional electricity generation capacity, or equivalent unit of RET required by NZ to reach its net-zero-2050 targets, is taken directly from the emissions reduction pathways modelled by the CCC in their draft advice on the second Emissions Reduction Plan (ERP) and accompanying Fourth Emissions Budget (EB4[12]). The default pathway used for this research is the **Demonstration** pathway, aligned with NZ's obligations under the Zero Carbon Act. To provide comparisons, their **Reference** and the High Technology, High Systems-Change (**HTHS**) pathway are also included in analysis (shown in Figure 5). The net annual emissions values in Figure 5 account for sequestration of carbon from the atmosphere from land-use, land-use change, and forestry (LULUCF). They do not account for carbon offsets. The Demonstration Pathway corresponds with NZ meeting its net-zero long-lived gas targets, with remaining net emissions corresponding to biogenic methane emissions.

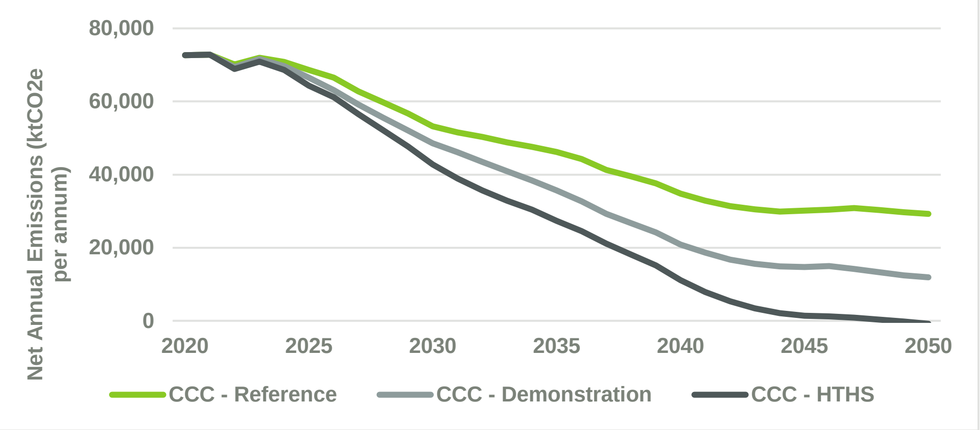


Figure 5: Net GHG emissions reduction pathways from the CCC's EB4 technical annex

Each of these pathways from CCC consider the Tiwai Point aluminium smelter staying in the market. Tiwai Point has a power purchase agreement (PPA) with Meridian, Contact and Mercury to supply up to 572MW of electricity. If Tiwai Point were to be decommissioned, this load would be available to support decarbonisation of other loads. In this case, the spare generation capacity would reduce the requirement for new generation to be built, and therefore may reduce the materials requirements of the RETs modelled in this exercise.

4.1.1 Electricity System

The GHG emissions reduction pathways in Figure 5 correspond to varying degrees of electricity generation buildout. In the Reference pathway, Figure 6 shows a steady buildout of RETs including solar PV and wind generation.

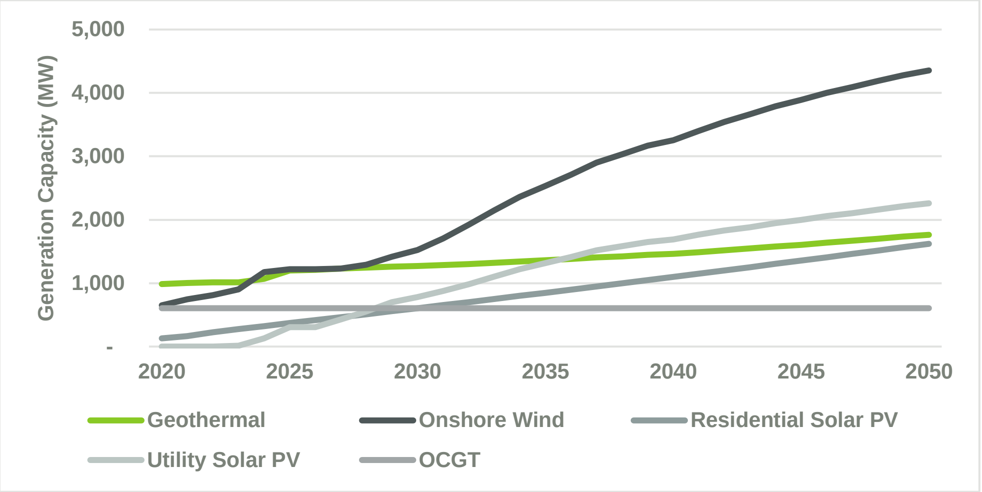


Figure 6: Electricity generation buildouts under the CCC Reference pathway

Onshore wind sees the largest increase, reaching levels in 2050, that in 2024, would account for approximately half[13] of NZ's total electricity generation capacity. It's important to note that some of these technologies are intermittent, only producing electricity when sufficient light, or wind, are present. In lieu of supporting this buildout of RETs with a buildout of other baseload generation (like hydroelectric power), other supporting infrastructure including battery energy storage systems (BESS) would be required to best utilise the increased intermittent generation.

The HTHS pathway in Figure 7 goes beyond the net-zero 2050 targets. This scenario not only includes the rapid buildout of technologies that are already deployed in NZ (e.g., solar, onshore wind, geothermal), but allows for a small buildout of offshore wind towards the end of the modelling period.

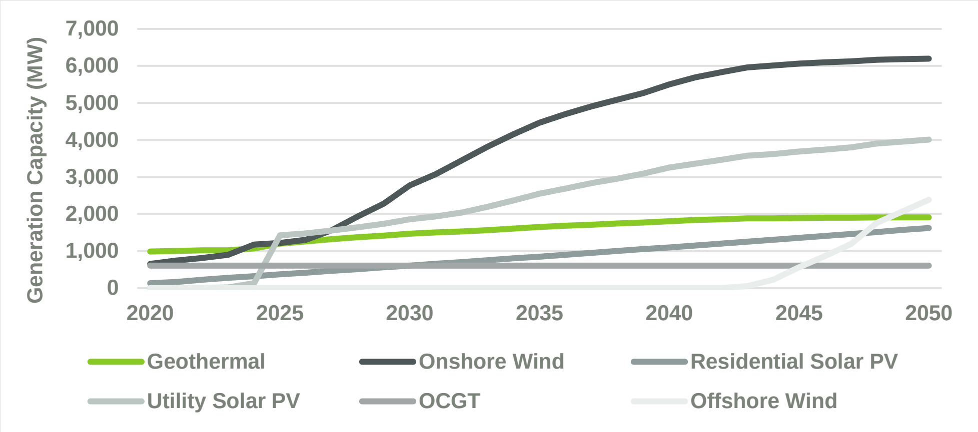


Figure 7: Electricity generation buildouts under the CCC HTHS pathway

The Demonstration pathway sits in between the Reference and HTHS pathways as indicated in **Figure 5**. As mentioned, intermittent generation requires a storage mechanism for use where generation times don't align with demand. An example of this is solar PV generation peaking during the middle of the day in the summer, where the country's electrical load peaks in winter mornings and evenings.

As the CCC electricity modelling doesn't include storage mechanisms directly, equivalent models from Boston Consulting Group (BCG)'s **The Future is Electric**[14] report were used to fill the gaps as shown in **Figure 8**.

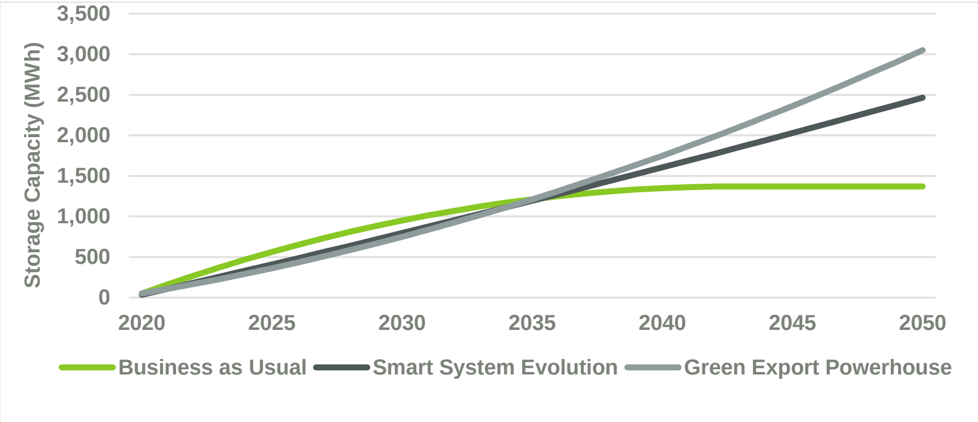


Figure 8: Estimated battery storage buildouts under the BCG "The Future is Electric" pathways

The trends for energy storage capacity shown in **Figure 8** are polynomial interpolations of summary data for 2030, 2040 and 2050, provided in the figures from the "Future is Electric" report. With no underlying data available, these trends are used in the dataset. The three selected battery energy storage system (BESS) pathways from BCG were selected by Aurecon as being the closest equivalents to the Reference, Demonstration, and HTHS pathways from the CCC EB4 models.

For the BCG BAU pathway the later values are manually capped, as the polynomial trend passed the point of inflection and started to decrease – which is unlikely to happen in practice. With the general uncertainty involved in these projections, Aurecon suggests that this approximation will not appreciably impact the results and analysis.

BCG's business as usual pathway for BESS growth is based on the existing pipeline of projects at the time of preparing their "Future is Electric" report. Assumptions used to estimate buildout for the other two scenarios are not explicitly documented in that report.

4.1.2 Transport System

The CCC EB4 technical annex includes projections for the NZ vehicle fleet over time. These projections are derived from the Ministry of Transport's (MOT) Vehicle Fleet Emissions Model (**VFEM**[15]). Aligned with the three EB4 emissions reduction pathways, these scenarios alter both the electrification rate of light and heavy fleet, and the number of vehicles entering the fleet in each year. shows the overall percentage of EV's entering the market across all vehicle types, and the total number of vehicles entering the fleet, for each included scenario.

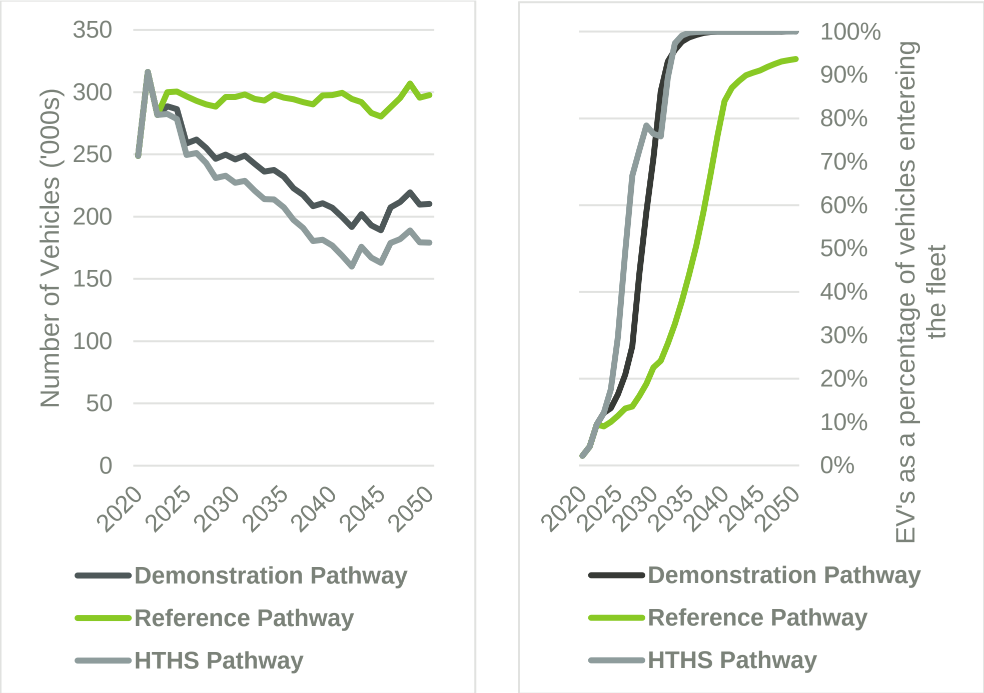


Figure 9: Annual vehicle fleet additions and electrification rates under the CCC's GHG emissions reduction pathways

The models show the percentage of vehicles entering the market becoming entirely EV's (including a combination of plug-in hybrids, and battery EVs), by the mid-late 2030's for the Demonstration and HTHS pathways. The more aggressive scenarios assume greater uptake of public transport and active modes and therefore show lower amounts of vehicles entering the market overall.

While it is assumed that by the mid-late 2030's, 100% of vehicles entering the fleet will be electric (under the Demonstration and HTHS pathways), it will take time for this to impact fleet composition. NZ's vehicle fleet is typically aged, with 41.5%[16] of light vehicles being at least 15 years old. With a large proportion of cars entering the country second-hand, predominantly from Japan, there is a lag effect where EVs need to be produced and used overseas before being imported into NZ, and a further lag while the EV fleet itself grows. Given the current reliance on these second-hand supply chains, fleet electrification depends not only on international production, but the churn of these vehicles within their initial markets.

The indicative scenarios used in this report exclude ICE and hybrid electric vehicles (HEVs) from analysis, but a sensitivity analysis showing the effect of this addition is included in **Section 6**.

4.1.3 Transmission & Distribution Infrastructure

Power transformers and cabling are included in the modelling of T&D infrastructure. Both transformers and cabling are funded by electricity distribution providers (EDB's) and by Transpower who owns and maintains the national transmission network. Growth in the investment across T&D infrastructure is not directly linked to the same projections of future capacity from CCC or BCG. EDB's will often have their own investment and growth plans, and Transpower develops their own projections for future grid demand, as in the Transmission Planning Report (TPR[17]).

Overall growth of T&D infrastructure was estimated using trends of planned operating expenditure (OPEX) and capital expenditure (CAPEX) from Vector, Orion, and Transpower's asset management plans (AMPs).

For distribution, Vector provides proportions of OPEX spent on different assets, while Orion provided total capital expenditure CAPEX numbers in their AMPs. The proportion of investment into transformers and cabling was applied to Orion's totals, before being scaled by population to account for all EDB's in NZ. Transpower's investment in the transmission system differs in that funding cycles are periodic and spend peaks in the middle of 5-year funding periods. Here, the cycle was modelled as a sinusoid and projected out over the modelling period of 2020-2050.

A significant source of spend that wasn't modelled in this exercise was AC substations. Substations, or switchyards, are nodes in the electricity system that convert electricity to different voltages, for example going from high voltage transmission down to medium voltage distribution, and low-voltage residential levels. Substations, and related equipment like power factor correction (PFC) and residual current devices (RCDs) were not included in the model due to the large range of assets involved, and the time required to model each of them compared to their materiality with respect to the overall energy transition.

4.2 Technology Developments and Market Share

The developments of renewable energy technologies represent new ways to achieve the same outcome. This could take the form of increased output efficiency, a new manufacturing process, a completely different chemistry, or other technological developments.

This dataset accounts for a range of technological developments in renewable energy technologies – shown in **Table 1**. Some developments are already deployed, and some are at a stage, indicated by their "Technology Readiness Level", that they could be commercialised very soon. Inclusion of alternative developments allows different scenarios to be developed, indicating where trends simply continue, and where new developments come through and take over the market – and consequently how this effects the materials embodied in our technologies.

Table 1 details the market share scenarios considered in this exercise.

Technology	Market Share Scenario	Developments Considered
Solar PV Module (Utility and Residential-Scale)	c-Si Dominates	Crystalline-Silicon (c-Si) Copper-Indium-Gallium-Selenide (CIGS) Cadmium-Telluride (CdTe)
	Thin-Films Take Lead	cSi, CIGS, CdTe
	Perovskite Sensitivity Analysis	c-Si, Pérovskite Solar Cell (PSC)
Wind Gearbox & Generator	Onshore – Non-Permanent Magnet (PM) Rapid Decline	Doubly-Fed Induction Generator (Non-Permanent-Magnet "Non-PM") Permanent-Magnet Synchronous Generator – Direct Drive (PMDD) Permanent-Magnet Synchronous Generator – Medium Speed/High Speed (PM-GEAR)
	Offshore Sensitivity Analysis – PM Steady Increase	Non-PM, PMDD, PM-GEAR
Batteries (EVs, Grid Storage)	Grid Storage (Indicative Market Share)	Lithium-iron-phosphate (LFP) Nickel-manganese-cobalt (NMC) Nickel-cobalt-aluminium (NCA) Sodium hexafluorophosphate ($NaPF_6$) Sodium bis(oxalato)borate (NaBOB) Vanadium Redox Flow Battery (VRFB)
	EV Batteries – Lithium-Iron-Phosphate (LFP) Market Share	LFP, NMC, NCA, nickel-metal-hydride (NiMH), lead acid
	EV Batteries Sensitivity Analysis – Post-Lithium-Ion-Batteries (PLIB) Market Share	All-Solid-State lithium-Ion-Battery (ASSLIB), LFP, NMC, NCA, NiMH, lead acid
Geothermal Plant	N/A	Double-Flash Power Plant (DFPP)
Open-Cycle Gas Turbine	N/A	Gas Turbine Unit GTU-16P Low-Emissions Combustor (LEC)

Table 1: Technology developments and market shares included in analysis

No additional developments, and therefore market share scenarios, were included for geothermal and OCGT generation, as these were not focus areas for this study.

4.2.1 Electricity System

- **Solar PV** developments are based on a 2020 paper in the Elsevier Journal of Applied Energy by K. Ren, et al., titled "**Evaluating metal constraints for photovoltaics: Perspectives from China's PV development**". This paper models two potential future market shares covering c-Si and thin-film technologies. The future market shares were based off values from the China Renewable Energy Outlook 2018, using the "below 2-degrees" modelling scenario. Both market shares assume an initial 90% of the market being c-Si in 2020. The first projection shows c-Si decreasing linearly by 1% every 10 years, and the second shows CdTe and CIGS thin films growing 0.5% each year to 20% of the overall market in 2050. Considering China's large contribution to solar PV manufacturing, and NZ's import-dependence on Chinese RETs, it's likely these market shares are applicable domestically.
- **Wind generation** developments are based off a paper from the same author as the solar PV market shares, a 2021 paper in the Elsevier Journal of Energy titled "**Bridging energy and metal sustainability: Insights from China's wind power development up to 2050**". Traditional non-PM generators, and PM generators across direct drive and gearbox-driven developments are included in this market share. The selected market share reflects the current trends in the NZ market. Manufacturers tend to produce only a single technology, and with many manufacturers involved in the NZ market, it's likely the breadth of developments will continue, with no single development taking over. In this market share, geared PM generators account for 50% of the market, with the remaining non-PM generators decreasing over time to 10% and making way for direct-drive PM generators (40%).
- **Battery** developments follow the "LFP scenario" from Xu, et al., in their 2020 paper in Nature Communications Materials titled "**Future material demand for automotive lithium-based batteries**". This market share follows current trends of lithium-ion batteries dominating the battery market and shows a consistent growth of LFP cells over the modelling period to 2040, up to 60% of the total market. LFP cells are relatively cheap and reduce requirements for cobalt and nickel used in alternative lithium-ion cells – making them a popular development not only for EVs but for grid storage. Limited information or projections around grid storage development market shares meant no "off the shelf" projection was used here. The indicative scenario presented is influenced by the LFP scenario (with LFP dominating other lithium-ion developments), and models growth in newer developments including VRFB's and sodium-ion cells.

4.2.2 Transport System

Plug-in hybrid, and battery electric vehicles (PHEVs, and BEVs) are included in this analysis. These vehicle powertrain developments are included across passenger, and commercial light vehicles, and both medium and heavy trucks. Electrification rates, and the types of vehicles entering the fleet annually (as a proportion of the total) were sourced through CCC's modelling – based on MoT's VFEM.

Models are based on the masses of common examples of these vehicles used in NZ, namely the Toyota Corolla (**light passenger**), Toyota Hiace (**light commercial**), Mitsubishi Fuso Fighter (**medium truck**), and Kenworth C509 (**heavy truck**) respectively. Similarly, when considering the battery requirements of electric vehicles across this range, these were based on the Skoda Superb (light passenger PHEV), Tesla Model 3 (light passenger BEV), Ford Transit Custom (light commercial PHEV), LDV eDeliver9 (light commercial BEV), and Volvo FL Electric series (medium, heavy truck BEV). As detailed in **Table 1**, the dataset also allows users to analyse how the materials requirements change for EVs with the PLIB scenario considering solid-state batteries.

A sensitivity analysis, showing how materials requirements change when ICE vehicles are included in analysis, is provided in **Section 6**.

4.3 Material Requirements

Materials requirements for each technology and development were aggregated through existing research. This was primarily academic research and LCAs, supplemented with existing datasets including the Renewable Energy Materials Properties Database (**REMPD**[18]) and Greenhouse gases, Regulated Emissions, and Energy use in Technology (**GREET**[19]) databases from the US Department of Energy. With several metals and non-metallic minerals included in analysis, these were sorted into tiers to simplify visualisation.

Unlike the overall growth scenarios and development market shares, this lens required significant adjustment to the base data before use in the dataset. This is largely due to reference data using a range of different functional units and measurements, and some sources selectively choosing what numbers to include in summary statistics.

4.3.1 Material Tiers

Tiers of materials were used for this research to enable the visualisation of results on few plots. Early draft results included individual line-plots for all materials, which required a log-plot to capture the vast range of values across the materials requirements of technologies, which was found unhelpful for analysis. Grouping materials into tiers of relevance allows these differences to be captured, while allowing better understanding of the results.

CSIRO's Critical Minerals Roadmap sorts relevant materials into tiers of significance. This incorporates their demand for important use-cases, and criticality to trading partners. Aurecon have used these tiers, outlined in **Table 2**, for this exercise. Ahead of NZ releasing its own Critical Minerals Plan, the dataset has also been sorted to focus on minerals and metals mentioned in the Draft Minerals Strategy: titanium, vanadium, REEs, antimony, lithium, and phosphorus. Note, not all minerals in the Draft Minerals Strategy are present in the materials breakdowns of technologies for this research (heavy mineral sands garnet and zircon, potash, and hydrogen) – these are simply excluded from data and visualisations.

CSIRO Material Tier	Material	In Draft NZ Strategy
1 – High demand from energy technologies *AND* listed as critical by all key trading partners	Graphite (C)	N
	Cobalt (Co)	N
	Lithium (Li)	Y
	Platinum Group Elements (PGEs)	N
	Rare Earth Elements (REEs)	Y
2 – High demand from energy technologies, listed as critical by some key trading partners *OR* lower demand from energy technologies, listed as critical by all key trading partners	Aluminium (Al)	N
	Chromium (Cr)	N
	Copper (Cu)	N
	Magnesium (Mg)	N
	Manganese (Mn)	N
	Titanium (Ti)	Y
	Nickel (Ni)	N
	Phosphorus (P)	Y
	Silicon (Si)	N
	Vanadium (V)	Y
3 – Low demand from energy technologies *AND* listed as critical by some key trading partners *OR* not listed as critical	Boron (B)	N
	Iridium (Ir)	N
	Iron (Fe)	N
	Molybdenum (Mo)	N
	Silver (Ag)	N
	Zinc (Zn)	N

Table 2: Tiers of critical materials from CSIRO's Critical Minerals Roadmap

Not included in the CSIRO lists but relevant to the NZ strategy is antimony (Sb). platinum group elements (PGEs) and rare earth elements (REEs) account for some of the rarest and most valuable materials – especially in the context of the energy transition. They are broken down in **Table 3**.

Element Group	Element
Platinum Group – PGEs have applications in energy including catalytic converters in vehicles with ICE's and hydrogen electrolysis.	Platinum (Pt)
	Palladium (Pd)
	Rhodium (Rh)
	Ruthenium (Ru)
	Iridium (Ir)
	Osmium (Os)
Rare Earth – REEs play a critical role in energy including the manufacturing of permanent magnets and batteries.	Lanthanum (La)
	Cerium (Ce)
	Neodymium (Nd)

	Praseodymium (Pr)
	Yttrium (Y)
	Scandium (Sc)
	Dysprosium (Dy)
	Terbium (Tb)
	Samarium (Sm)
	Lutetium (Lu)
	Ytterbium (Yb)
	Gadolinium (Gd)
	Holmium (Ho)
	Thulium (Tm)
	Europium (Eu)
	Erbium (Er)
	Promethium (Pm)

Table 3: Platinum group and rare earth elements

4.4 Waste Streams

Using the annual additions to stocks of RETs and an expected useful lifespan of each asset, the waste streams associated with these RETs have been estimated in this exercise. This enables forecasting of the magnitude of these materials exiting the system, which in ideal circumstances, can be circulated back into the system through re-use in new assets.

Waste stream estimates modelled in this research exercise include only wastes from assets and materials that enter the system within the modelling period of 2020 to 2050. This is a limitation of the input data, related to the where we can estimate the end of life of assets built within the modelling period, but don't have the appropriate information to know when current assets will reach their end of life. Using the cumulative stocks of generation/storage/vehicles in the system at any one time, we use the marginal differences between years to model the flow into the system. Then applying assumed useable lifespans to each asset, we can model the flow of materials out of the system at the end of life of the asset.

Integrating waste streams of assets already in place would require sourcing exhaustive asset lists, and ages of plant and was outside the scope of this research. Maintenance schedules, and planned decommissioning would also need to be understood to model the overall waste from renewable technologies, which was not the focus of this study.

It should also be noted the waste stream model assumes waste materials can be split into its constituent materials with complete efficiency and no losses, where in practice many of these elements will be in compounds and alloys such as steel.

The projected useable lifespans of different assets that have been used for this research are provided in **Table 4**. The sources for these assumed lifespans are included in **Appendix 10.3** and throughout the dataset itself.

Technology	Development	Assumed Useful Life (Years)
Solar PV	c-Si	25
	CIGS	15
	CdTe	15
	PSC	20
Wind	Onshore (All Developments)	20
	Offshore (All Developments)	20
BESS	Lithium-Ion Batteries (LIBs)	10
	Sodium-Ion Batteries (SIBs)	10
	Redox-Flow Batteries (RFBs)	20
Vehicles	Vehicle w/o Battery	15
	Battery	10
T&D Infrastructure	N/A	Assumed doesn't fail within modelling period.

Geothermal	DFPP	30 (Doesn't fail within modelling period).
OCGT	GTU-16	25 (Excluded as no units are flowing in).

Table 4: Assumed useful lifespans of technological developments

An exercise was completed to test the effect of the proposed waste stream estimation method. This was compared against using the actual build numbers and calculating the waste stream as the difference between the sum of the build numbers, and the stocks summary data (with implicit flows).

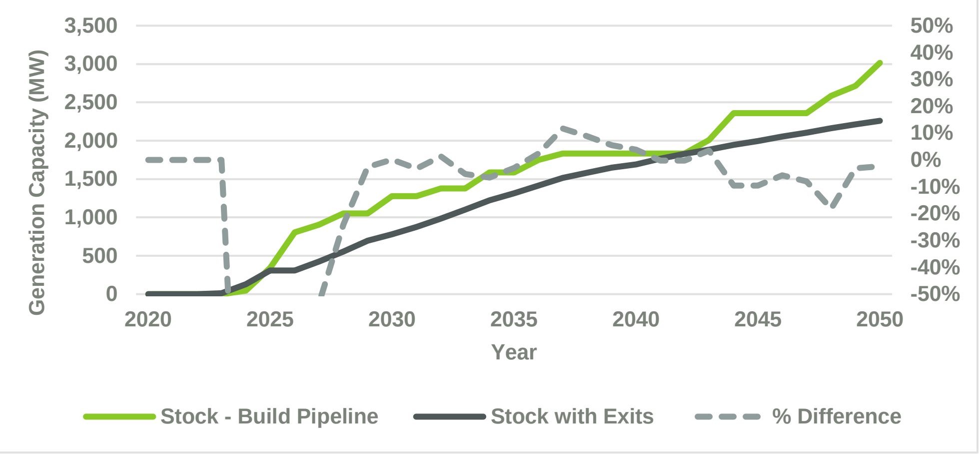


Figure 10: Quantifying the error in waste stream modelling - utility-scale solar PV (Reference pathway)

For the base case, Figure 10 shows that early in the modelling period, the proposed methodology varies largely from using the actual buildout numbers, this settles over time, reaching close to 20% in places. Note again that even the CCC model is a projection, so values differing from this projection doesn't necessarily indicate a lack of accuracy in real terms. When we look at the same comparison for the Demonstration Pathway in Figure 11, we see the difference is smaller, and that both methods overlap closely in places. These differences should be noted by the readers and users of this data when considering the waste stream estimates.

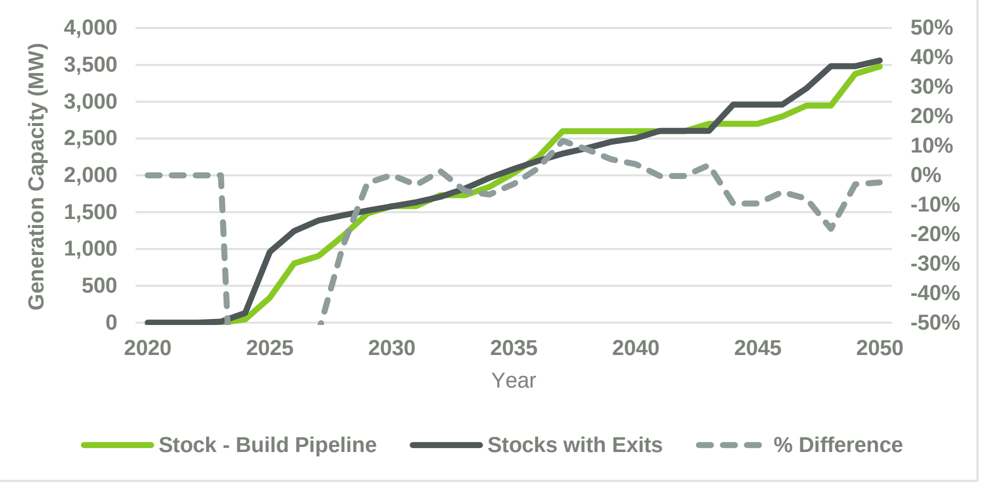


Figure 11: Quantifying the error in waste stream modelling - utility-scale solar PV (Demonstration pathway)

4.5 Uncertainty and Limitations

The following uncertainties and limitations are provided in relation to the methodology and dataset. Aurecon notes the dataset is simply an estimate based on models and external resources, and that any decisions made resulting from the use of this research should also be informed by other sources and exercising professional judgement. Aurecon provides no guarantee of the accuracy of the estimates and takes no responsibility for the effects of decisions made using the estimates.

- The technology growth scenarios assume the Tiwai Point aluminium smelter stays open for the foreseeable future, in alignment with the latest data from the Climate Change Commission (CCC).
- Overall technology growth scenarios are limited to "off the shelf" models from the CCC's "Emissions Budget 4" technical annex and Boston Consulting Group's (BCG's) "The Future is Electric" report. These models are both based on the Emissions in NZ (ENZ) model developed by Concept Consulting. Aurecon has identified that other forecasts exist, for example in Transpower's Transmission Planning Report, and have designed the dataset workbook to be reusable to enable updating these scenarios.

Cumulative stocks of generation capacity, storage, and vehicles that implicitly include the exits of assets from the stock are used instead of the actual asset buildout figures for this exercise. This choice was made primarily for consistency, where some technologies simply don't have easily accessible buildout figures (e.g., residential solar PV), and where some overall growth scenarios are projections not based on exact buildout scenarios (e.g., CCC's "high technology, high systems-change – HTHS" scenario). Without exact buildout figures, and scheduled (de)commissioning dates, waste flows are estimated using cumulative stocks and assumed useable asset lifespans.

The quantification of the impact of this methodology is included in **Section 4.4**. The main consequence is that flows out of the system account only for assets entering the system within the modelling timeframe of 2020-2050 (not assets already installed), and show up as waste flows mostly starting in the mid-late 2030's.

- While most factors involved in the modelling are automated and easily adjustable, the assumed lifespans of assets (used to model the outflow of materials from the system) is hard-coded. This is still adjustable but requires manual user input.
- Technology development market share scenarios are primarily developed based on research that focus on the Chinese market. Considering China is a **leading supplier**[20] of these technologies, Aurecon believes this is an acceptable assumption. Where no "off the shelf" market share scenarios were identified, indicative scenarios have been developed in-house. These scenarios typically include developments with a Technology Readiness Level (TRL) of 6 or above. Any exceptions to these methods are detailed in the sections of this report relevant to each technology.
- The nature of the technologies in the dataset is that development follows a logistic curve, or "s-curve". This suggests the shift from a proof of concept to a fully commercial product can happen rapidly and can often be difficult to predict, and that these changes can reinforce further change. Because of this, some developments not considered in the model may well be relevant in the future – it's simply too difficult to predict this. The reader and users of this research should acknowledge the uncertainty in these predictions and understand the level of variability in the actual outcomes.
- Materials requirements for different technologies and their developments are based primarily on Life Cycle Assessments (LCAs) from academic research. The result of this is that trace materials that fall under the 99% cutoff rule (<1% of total mass) are typically not included in the analysis.
- The model assumes a static material efficiency over time for each technology and development. In the case that, for example, crystalline silicon PV panels became more efficient in the future, a scaling factor of the ratio of the historic, and new efficiencies, should be applied to the values to account for this. This is easily achieved due to the reusable nature of the dataset and is already implemented for wind generation.
- The assessment scope focusses only on the resource 'costs' of the renewable energy transition, not the wider benefits of shifting resource demand away from fossil resources.
- NZ generally exports raw materials and imports finished products associated with energy transition related technologies. Onshore processing capability and capacity may change over time and change the value chains and risks associated with them as a result.
- Waste modelling does not include end-of-life pathways for assets, just masses of materials exiting the modelled system. Detailed end-of-life pathway modelling can include specific waste recovery processes - depending on the specific pathway, some materials do not make it to recycling, or are lost in the recycling process.
- Other assumptions, uncertainties, and limitations exist throughout the model. These are described for the individual technologies and developments they apply to throughout **Sections 4** and **5**.

4.6 Exclusions

Excluded from the model are the following:

- Hydroelectric generation is excluded as there are no planned additions to this generation capacity in the short-medium term.
- Combined-cycle gas turbines (CCGTs) are not included as the last existing plants are scheduled for decommissioning in the coming decade, and there are no plans to renew or replace these assets.
- Coal generation is not included, as we do not expect any additional coal-fired capacity to be built in NZ. There is potential for the Huntly Power Station to be converted to burn alternative fuels, but we do not include this in our assessment.
- Petrol and diesel grid generation is excluded from the model – existing diesel peakers are projected to be decommissioned without direct replacement. Aurecon notes smaller generators serve as backup generation across a range of sectors, and this is expected to continue in the medium term until viable low-carbon alternatives replace them.
- Distributed solar PV generation (the sum of both residential PV and commercial/industrial systems) is excluded due to a lack of models that incorporate the effect on the rest of the electricity system. Residential solar PV by itself is included, as these numbers are provided in CCC's modelling. It is expected an uptake in commercial/industrial systems would simply offset the requirement for utility-scale solar PV generation and, apart from differences in mounting/structural requirements (steel, aluminium), would largely deliver a similar materials breakdown.
- Nuclear fission, and the prospect of fusion, are both trivially excluded.
- The effect of demand-side management (DSM) on the requirement for electricity generation and storage has not been considered in the model.
- Hydrogen fuel-cell vehicles (HFCVs) are excluded from analysis, as it is assumed the supply of this fuel is not at, or close to, the level required to support the uptake of these vehicles. A future piece of work could look at how investment in hydrogen production, and fleet transition towards HFCVs could affect materials requirements for NZ's net-zero transition, or the electricity supply required to support decarbonisation of the transport system in NZ.

5 Analysis

This section will look at each technology and provide commentary on the three lenses used in this research exercise – technology growth scenarios, technology developments and material requirements. References for the data used to create data visualisations are included in the Appendix 10.3.

5.1 Solar Photovoltaic Electricity Generation

Solar PV panels generate renewable electricity through conversion of incident light from the sun into electrical energy through the photoelectric effect. A stack of semiconductors forms the core of the panel, which generates electricity based on the energy of the wavelengths of incident light, and the energy required to move electrons between atomic structures of the semiconductors.

5.1.1 Technology Growth Scenario

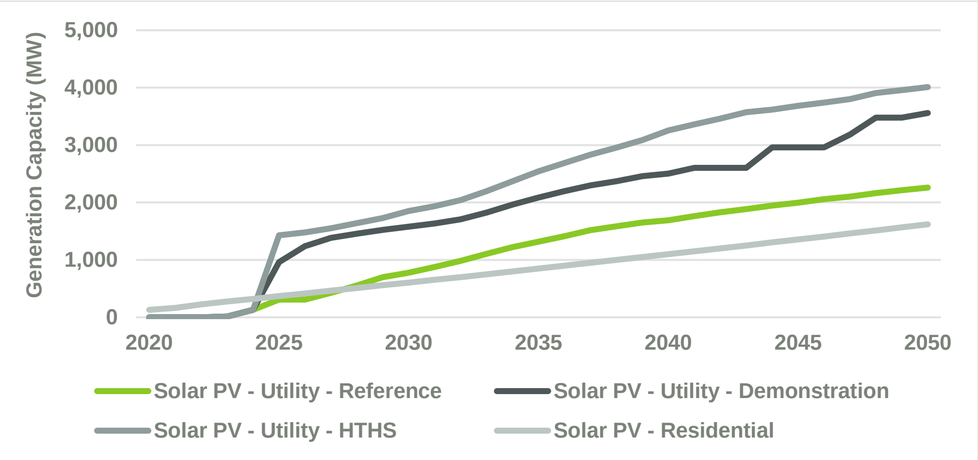


Figure 12: Solar PV generation growth (utility and residential) across CCC GHG emissions reduction pathways

Figure 12 shows the stock of utility-scale solar PV installations increases across the more aggressive decarbonisation scenarios from CCC, while residential growth follows only a single trend across all scenarios. In all scenarios we see a consistent, almost linear growth in the projected solar PV generation capacity. Distributed solar is not covered entirely in this exercise (residential solar is), but it is expected that if commercial and industrial loads installed on-site solar generation, then the requirement for utility-scale solar generation would reduce as a result – making the totals similar. While there may be some differences in the T&D investment needed between utility-scale installations, and a distributed-centric approach to solar generation, these components are typically common materials including aluminium, copper, and iron for steel.

5.1.2 Technology Developments

The two scenarios used to represent the developments within solar PV generation are (1) where c-Si panels continue to dominate the market, and (2) where thin-films (CdTe and CIGS) rapidly increase and start to make up a significant portion of the market. These are based off models from Ren, et al. – as described in Section 4.2.1. Thin-films are currently a small development, with between 5-10% of the overall market while c-Si is the most common – as shown in Figure 13.

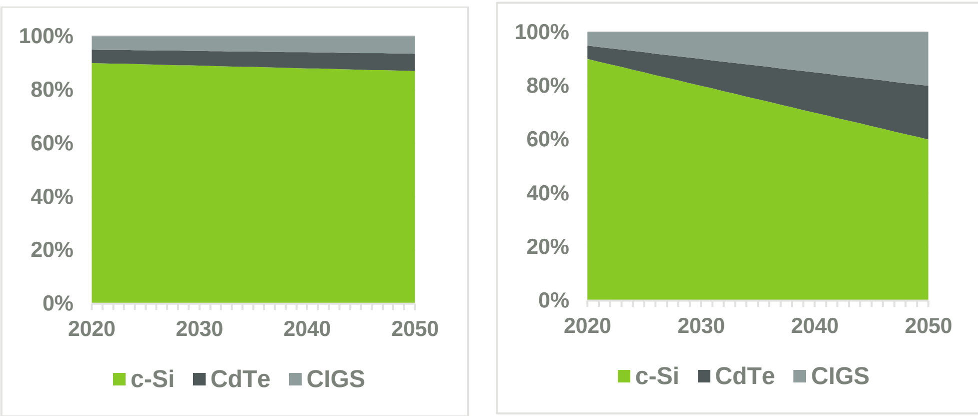


Figure 13: Solar PV development market shares from Ren, et al. (1) c-Si dominates, (2) thin films expand market share

There are minor variations in the models of c-Si panels available on the market, including Passive-Emitter Rear-Contact (PERC), Passive-Emitter Rear-Totally-Diffused (PERT), Passive-Emitter, Rear-Locally-Diffused (PERL), Silicon Heterojunction (SJH), silicon-tandem (Si-tandem), Tunnel Oxide Passivated Contact (TOPCon), and Interdigited Back Contact (IBC). Between these models there are small variations in the design that can lead to different efficiencies, costs and manufacturing processes. The most common model is PERC, so this is used to inform the materials breakdowns used in this exercise. Availability of the materials requirements for the newer and less-common types (e.g., IBC, TOPCon) limited the ability to produce an average breakdown representing all potential models.

Thin films are an alternative to c-Si panels, and sacrifice efficiency for lower cost, ease of manufacture, and reduced mass. Their lightweight and thin nature enables the films to be flexible and more affordable, so are useful for applications where rigid and heavier c-Si panels can't be used – including some consumer electronic appliances, and curved surfaces like buildings and vehicles.

For residential solar PV installations, the model includes a portion of attached residential battery storage. While there is limited information, or projections around the uptake of residential PV-attached storage, assumptions have been made for this research. We use a base size of 10kWh (approximately the capacity of a Tesla Powerwall battery), and assume a growth of 2.5% each year, while the number of residential solar PV installations with a battery increase by 2% a year, starting at 10%. These assumptions are relatively conservative when compared to other markets such as Australia or Germany, but we have chosen these assumptions as these other markets have significant government subsidies to drive these higher rates of adoption and growth.

For the battery technology developments, the Lithium-Iron-Phosphate (LFP) market share (Figure 14) for EV's has been used, as included in Table 1, and described in Section 4.2.1. This market share assumes LIBs continue to dominate the battery market, and within this LFPs are the most common type. With residential solar installations largely bound by the same safety and density requirements as that of an EV, this is likely a reasonable assumption. Considering the LFP development dominates market shares across EV batteries and grid-scale BESS, it's likely this development will dominate this market in any case. Section 5.4 on vehicles explores this battery market share in more detail.

The same technology developments and market shares are used across utility and residential-scale solar PV generation.

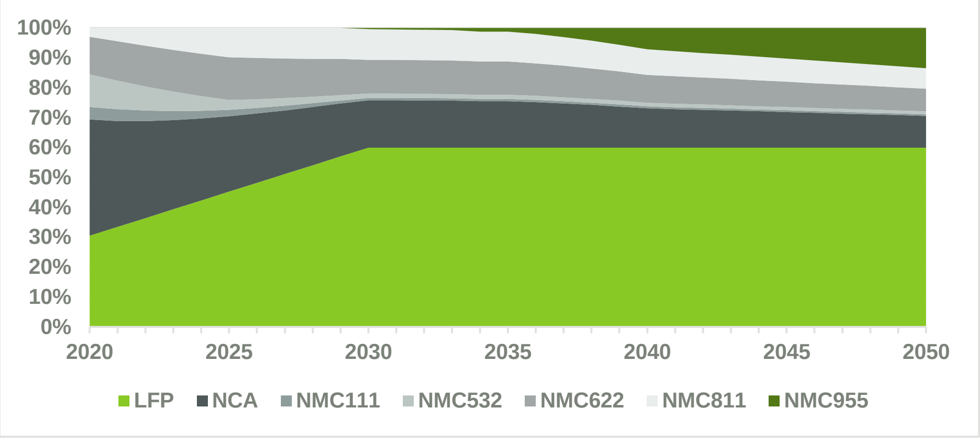


Figure 14: LFP-dominated battery development market share for residential solar PV-tied storage (Xu, et al.)

5.1.3 Material Requirements

The materials requirements of solar PV panel are dominated by structural requirements from the panel frame – as shown in Figure 15 (c-Si), and Figure 16 (CdTe).

Figure 15: Proportions of material requirements of a c-Si solar panel

Figure 16: Proportions of material requirements of a CdTe thin film

The relative structural requirements are greater for thin films than c-Si cells due to their lightweight nature. It's important to note that only key metals and non-metallic minerals included in the CSIRO tiers have been included here. The glass in a solar PV panel also accounts for a substantial component of the total mass but is not relevant to the key materials. An exception to this is the antimony used in solar PV panels to increase the transmittance of light to the semiconductor stack – which has been accounted for.

The numbers in Figure 15 and Figure 16 show the proportions of mass across the PV cells alone are dominated by the mass of the frame. This is due to the large source of mass in the cell itself not being relevant to our list of key metals or non-metallic minerals (e.g., we are accounting for the highly ordered crystalline silicon used in the semiconductor, but not the amorphous lower-quality silicon used in the panel's glass).

	Monocrystalline c-Si	Polycrystalline c-Si	CdTe	CIGS
Silicon	5.20%	5.58%	0.00%	0.00%
Indium	0.00%	0.00%	0.00%	0.02%
Cadmium Telluride	0.00%	0.00%	0.14%	0.00%
Cadmium Sulphide	0.00%	0.00%	0.00%	0.00%
Gallium	0.00%	0.00%	0.00%	0.01%
Selenium	0.00%	0.00%	0.00%	0.04%

Table 5: Percentages of material mass across solar PV technology developments

The proportions of mass across the entire utility PV system (like in Figure 17) follow a similar trend, with the racking dominating the overall mass. This is especially true for the thin-film technologies whose materials of interest make up an even smaller proportion of the cell. To analyse purely the materials of interest, Table 5 shows the percentage of mass of the key semiconductor materials used in the cells across these developments.

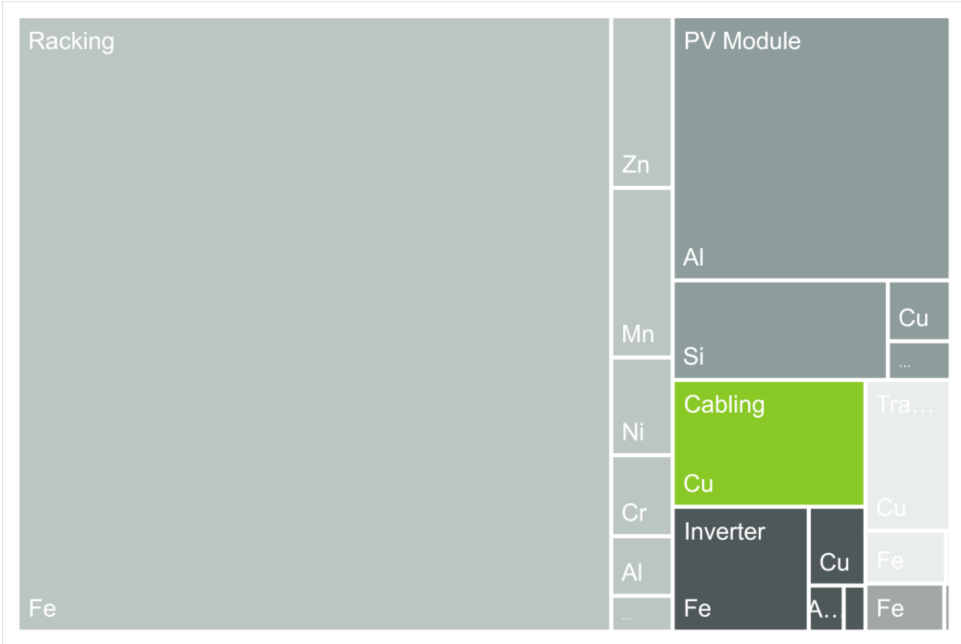


Figure 17: Proportions of material requirements of a c-Si solar PV system

Figure 17 shows that silicon makes up a significant proportion of the crucial materials in the PV module itself, being the fifth-largest contributor to the system. By mass, more silicon is required for a c-Si panel than an equivalent material used in a thin-film technology such as CdTe or CIGS. This is significant, given the supply chain constraints for solar-grade silicon production. Although the quartz used as a raw material is not rare, China alone dominates the refining and production of the material, as well as the production of the panels themselves. Prices have come down significantly over time, as these processes have become more efficient, however.

Solar PV panels are the only technology for which antimony is present as a core material. While typically only used as a fire-retardant, antimony is also used in the glass for utility-scale solar PV panels to increase the transmission of light through it. While antimony doesn't appear on the CSIRO critical minerals tiers, it is present in NZ's Draft Minerals Strategy as a potential area of investigation and has therefore been included in the analysis.

5.2 Wind Electricity Generation

Wind turbines generate renewable electricity through the movement of turbine blades with incident wind. The blades in turn rotate an assembly of coils and magnets within the nacelle, via a gearbox or direct drive system, and induces an electrical current according to Faraday's Law.

5.2.1 Technology Growth Scenario

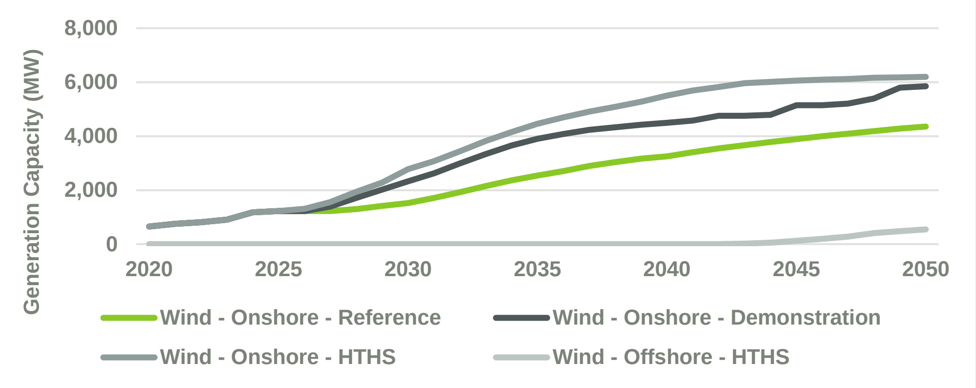


Figure 18: Wind generation growth (onshore and offshore) across the CCC's GHG emissions reduction pathways

The future rollout of wind generation has been modelled by the CCC as being more significant in scale than solar PV generation. Located in the 'roaring '40s' (a reference to NZ's latitude and associated belt of strong wind), NZ has among the highest quality wind resource in the world, with higher average capacity factors than many other countries. Offshore wind generation is only included in a single growth scenario – the HTHS pathway – which is used to model the sensitivity analysis in Section 6.2. The Reference and Demonstration pathways show steady growth in onshore developments throughout the transition, while the HTHS scenario is initially more aggressive, before slowing towards the end of the 2030s (Figure 18). We suggest other technologies modelled in the HTHS pathway may provide cheaper generation in these later stages, hence the reduction in growth.

5.2.2 Technology Developments

A single market share scenario is considered for three developments of wind turbines, which indicates the rapid decline of non-permanent magnet "non-PM" gearbox and generator systems which are less efficient (Figure 19).

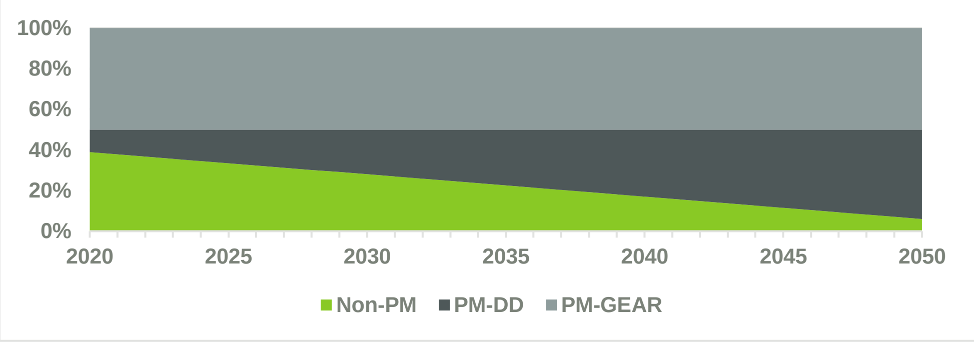


Figure 19: Wind development market share from Ren, et al.

The generator types, and their acronyms are provided in Table 1. As turbine manufacturers tend to produce only a single development type, and the range of manufacturers used in NZ is varied – it is expected the split of these systems will remain competitive, with no single dominant technology. Due to this variability in the single provided market share scenario, no alternatives have been presented.

5.2.3 Material Requirements

The indicative split of materials across the system components is shown in Figure 20 This differs slightly from solar PV in that the generation component of the wind turbine accounts for a substantial proportion of the total mass. These proportions are largely the same across all development types.

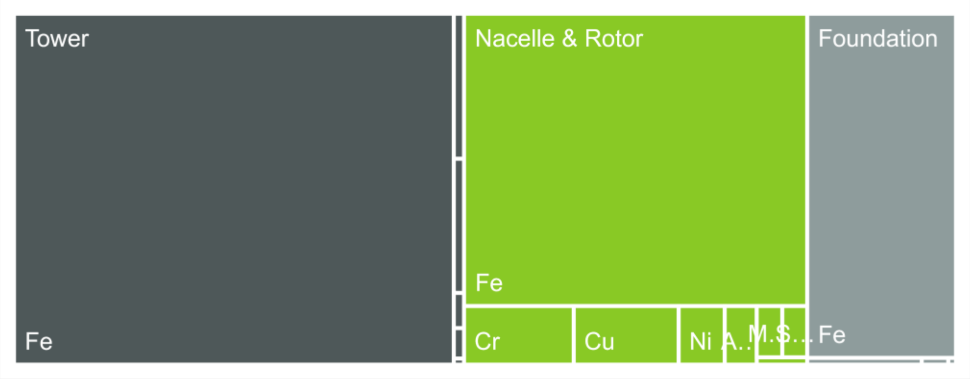


Figure 20: Proportions of material requirements in a non-PM wind turbine

Permanent magnet generation systems are much higher efficiency than non-PM systems due to the larger magnetic fields generated through relative motion of the magnet and the rotor and require fewer base materials like steel and aluminium as a result. The trade-off is the requirement for NdFeB (neodymium-iron-boron) permanent magnets. These magnets contain rare-earth elements (neodymium, praseodymium and dysprosium) and other Tier-1 CSIRO materials like cobalt – as shown in **Table 6**. The direct-drive PM generators have even larger magnets than the gearbox-driven systems, with over 150kg of rare earth elements estimated to be required per MW of generation. Considering the HTHS target of over 6,000MW of generation in 2050, this would equate to around 900 tonnes of rare earth metals for onshore wind generation alone.

Materials	Non-PM	PM-DD	PM-GEAR
Iron	5.9	334.1	52.8
Neodymium	2.3	127.5	20.1
Praseodymium	0.6	31.9	5.0
Dysprosium	0.1	5.1	0.8
Cobalt	0.2	10.3	1.6
Boron	0.1	5.1	0.8

Table 6: Material requirements of neodymium permanent magnets across wind turbine generator technologies (kg/MW)

5.3 Battery Energy Storage Systems

Battery energy storage systems provide redundancy to the electricity system – storing energy during times of excess generation and dispatching it when necessary. BESS installations can support the development of intermittent generation like solar PV and wind, where generation doesn't always align with demand. While there are other mechanisms for storing energy (e.g., pumped hydro, compressed air, thermal systems), only chemical batteries are investigated in this research.

5.3.1 Technology Growth Scenario

The overall growth scenarios for BESS are taken from BCG (**Figure 8**). Each of the BCG pathways show a steady increase in storage capacity towards the mid-2030's, after which the pathways split. The BAU pathway slows growth, while the "Smart System Evolution" pathway, the equivalent of CCC's "Demonstration" pathway, continues at a similar rate. The aggressive change pathway "Green Export Powerhouse", selected by Aurecon as the closest equivalent to CCC's "HTHS" pathway, shows the rate increasing up to 2050, reaching a total of around 3,000MW. This capacity is still smaller than the projected high growth scenarios for solar PV and wind generation (approximately 4,000 and 6,000MW respectively). It's important to note however, that these intermittent generation technologies will rarely generate at their maximum capacity, so the generation capacity and battery storage capacity may be well aligned under these projected growth scenarios.

5.3.2 Technology Developments

As mentioned in **Section 4.2.1** the development market share used for this utility-scale grid storage is not based in research or existing models due to a lack of publicly available references. The indicative market share provided has been prepared by Aurecon based on the dominance of LFP cells in the LFP scenario (Xu, et al.), and technologies that are beginning to be utilised in grid-scale BESS – shown in **Figure 21**. This includes both sodium-ion batteries, and vanadium redox-flow batteries (VRFB).

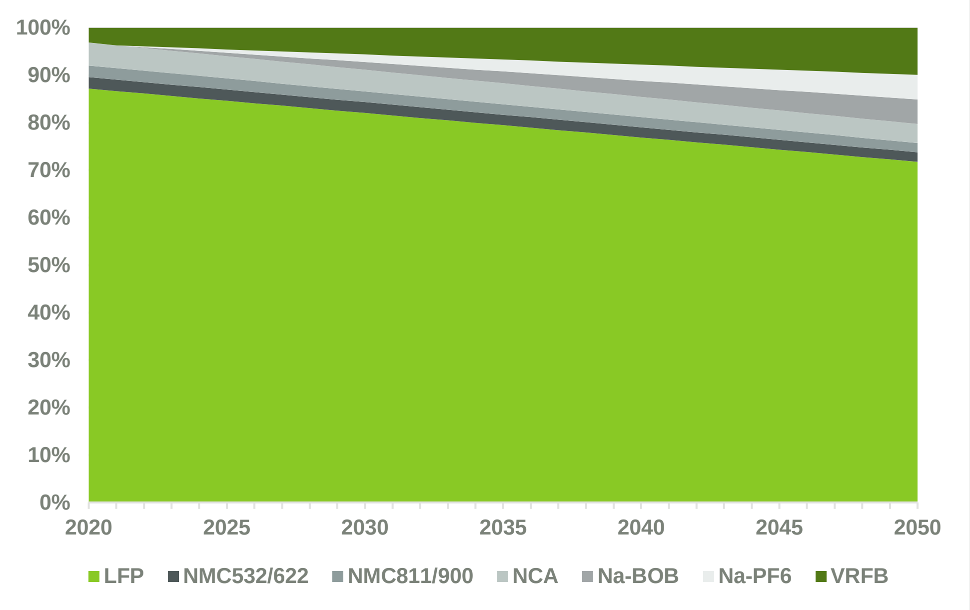


Figure 21: Indicative estimated development market share for BESS

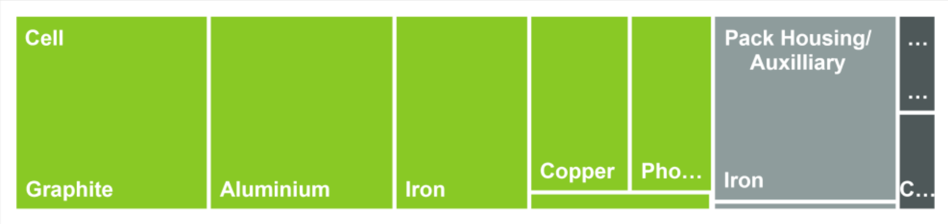
The LFP scenario used for residential solar PV storage (Section 5.1.2) and used later for vehicles (Section 5.4.2), was not used for BESS because of the difference in use-cases. Both residential solar and EV battery storage require energy density due to the limitations on the size and weight of the system. BESS, storing energy at a much larger scale, does not have this same density requirement, allowing technologies like VRFB's to be used. VFRB's are also a longer-term storage, designed to output lower power over 24 hours or more, where other technologies have higher power outputs over a shorter period. Sodium-ion batteries, while removing much of the critical materials requirements compared to lithium-ion batteries, also has a lower energy density which has limited its use in vehicles so far.

There were no "off-the-shelf" market share projections for BESS identified during the literature review phase of this research. In most cases the technologies used are like those used in EVs (lithium-ion batteries like LFPs). The modular and reusable nature of the dataset enables users to replace this indicative scenario with another easily. There is a general difficulty in projections of battery markets as they are not only driven by technological developments, but by price and supply volatility. An example of this is the rise of NMC cells from manufacturers like Tesla in the West, as an alternative to LFPs where the supply of lithium is primarily held by competitors in the East like China. This is one of the core drivers of technological developments in this space – replacing old chemistries of cells that rely on materials that are volatile in price and supply or rely on geopolitical stability and international trade, with chemistries that use readily available materials.

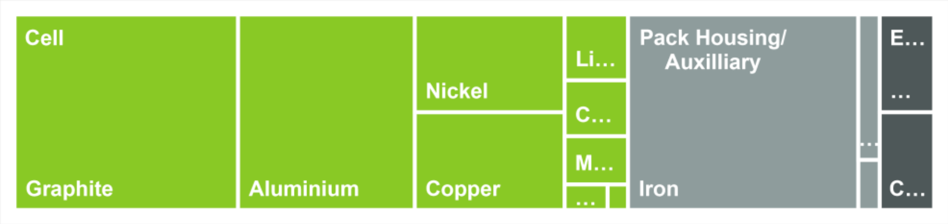
5.3.3 Material Requirements

The developments included in Figure 22 show the differences in the relative masses of assessed materials between LIB, SIB, and VRFB battery technologies.

LFP



NMC955



NCA

NaPF$_6$

VRFB

Figure 22: Proportions of material requirements for battery developments in the indicative BESS market share

Graphite is the most significant tier 1 material for the LFP, high-nickel NMC, and NCA lithium-based chemistries, with aluminium also making up a significant proportion of the cell itself, shown in green. The differences between them relate to the relative proportions of other materials such as nickel and cobalt, and the proportions of housing/auxiliary materials (light grey) as compared to the cell itself. We note that these are proportional impacts and not scaled for energy density, and that there are materials included in these cells that are not part of the assessment scope.

Sodium-ion cells have much lower dependencies on these critical materials than lithium-ion cells. Instead of lithium as the charge carrier, sodium is used – this is available in much greater quantities and in deposits more globally distributed than lithium. The assessed sodium-ion cell chemistries also remove the need to use graphite anodes, and instead use 'hard carbon' which can be produced from lower-grade carbon feedstock. As this is a separate material from graphite, it has not been included in the data or visualisations (as described in Section 4.3.1) but should still be noted here. Figure 22 also shows that these cells do not require materials like nickel or cobalt – instead relying mostly on common materials like aluminium and iron. These differences make SIB cells an alternative to LIBs with lower risks associated with material production, and this could help them grow in market share over the coming years.

VRFBs are a vastly different technology to both LIBs and SIBs. RFBs are structured fundamentally the same as other batteries, with a cathode, anode, and electrolytic material – but their use case of large-scale grid storage means that energy density is a less important factor. As a result, VRFBs separate these elements into separate components. RFBs pump a liquid electrolyte (in this case an aqueous vanadium solution) between large storage tanks via an electrolytic cell, where the direction of flow controls whether the battery is charging or discharging. While VRFBs can offer much longer useable lifespans than alternative chemistries and reach large storage capacities, they do require critical materials including vanadium, graphite, titanium, and platinum.

5.4 Road Vehicles

NZ has a substantial fleet of vehicles for its population. With the design of towns and cities, and urban sprawl of new developments further away from city centres, vehicles have emerged as a necessity for many Kiwis. Where this travel cannot be simply abated (VKT reduction is another goal in the emissions reduction plan), decarbonising this travel is the next most important mechanism.

5.4.1 Technology Growth Scenario

Figure 9 shows the number of vehicles entering the fleet annually, and the overall percentage of EVs across these vehicles, across each of the CCC overall growth scenarios. It shows that the more aggressive decarbonisation pathways model not only more rapid electrification of the fleet, but a general reduction in the fleet size. Across the Demonstration and HTHS emissions reduction pathways, most vehicles entering NZ will be electric (HEV, PHEV, or BEV) by the mid-late 2030's.

This reduction in overall fleet size, implicit in the CCC models used, is an important note and is later shown to be critical in the key findings from this exercise. It presents a trade-off where one driver (electrification rate) increases more in Demonstration and HTHS pathways (increasing critical material requirements over ICE equivalents), while the overall number of the cars required is reducing (reducing all material requirements). Vehicles have a considerable impact on the overall materials requirements of an energy transition given the sheer number of units required compared to electricity generation for example.

5.4.2 Technology Developments

The research provides results across battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs). These transitionary developments provide time for additional electricity generation and public EV charging infrastructure to be developed, and for the cost of BEVs to reduce. Optionally, the dataset has data for ICE vehicles which can be selected by the user to observe the impact of their inclusion (this is also presented in Section 6.4).

Hydrogen fuel-cell vehicles (HFCVs) are not included due to both the lack of vehicles manufactured and available on the market, and the lack of infrastructure to support charging these fuel cells. Common thinking suggests HFCVs could play a role in the decarbonisation of heavy fleet, where fuel-cell charging stations could be built into existing depots along the routes of distribution trucks. The widespread use of hydrogen for light passenger vehicles is different in that it would require a large buildout of electrolysers to produce the fuel – which itself is an inefficient process requiring large amounts of electricity. It may make sense simply to use the electricity directly to drive these passenger vehicles, rather than go through intermediate processes.

What isn't considered in this exercise but is a potential integration with the future electrical grid, is vehicle-to-grid (V2G) technology. BEVs are fundamentally a battery with a motor and wheels. When not in use, these batteries can be discharging electricity for use elsewhere including powering homes, or with substantial amounts – exporting back into the grid.

As alluded to in Section 4.2.1 and Section 5.1.2, the LFP lithium-ion scenario from Xu, et al., is used as the default battery market share for electric vehicles. These batteries are allocated to PHEV and BEV vehicles, while pure hybrids are given nickel-metal-hydride (NiMH) cells. The dominance of the LFP development reflects the large supply push from China who is quickly becoming the world's largest EV manufacturer. Companies like BYD have vertical integration across the battery and car manufacturing sectors, reducing prices overall and driving a high demand for Chinese EVs. China in general has a large endowment of lithium, making lithium-ion cells (specifically LFP's which require less nickel and cobalt), the leading battery development.

Section 6.3 includes a sensitivity analysis for replacing these developments with a "post-lithium-ion" market share. This market share is similar but includes a gradual shift towards newer battery technologies.

5.4.3 Material Requirements

The base materials breakdown of a battery electric vehicle (not including the different battery developments) is like that of many renewable generation technologies, in that the largest contributors by mass are simply structural elements like iron and aluminium – as shown in Figure 23.

Figure 23: Proportions of material requirements for a light passenger BEV - excluding batteries

The mass of copper, largely for wiring within vehicles is also substantial, with the next largest contributors largely elements used for alloying. What can't be easily seen in Figure 23 is the requirement for REEs in the motor of the BEV. This requirement is increased when the battery materials breakdown is added, which introduces materials like lithium, cobalt, and nickel (as shown in Figure 22) depending on the battery type.

It's interesting to consider that ICE vehicles contain a very small number of critical materials in comparison but are the highest-emitting development for vehicles. The most sustainable alternatives like BEVs, use a range of rare-earth metals and other critical non-metallic minerals to achieve its purpose. This is a trade-off between upfront investment in extraction, refining, and manufacturing of critical materials into batteries for the purpose of decarbonisation.

5.5 Transmission & Distribution Infrastructure

The renewable energy transition will require extensive investment in T&D infrastructure. This to support increased electricity demand due to the electrification of transport and industry and new grid-connected electricity generation and storage. The impact of increased T&D capacity on metal demand has been modelled, specifically the cabling and the power transformers required to support the energy transition.

5.5.1 Technology Growth Scenario

The growth of T&D infrastructure is modelled using the OPEX and CAPEX plans from Transpower, Vector, and Orion's AMPs. We have assumed that expected planned spend from Transpower and the EDBs is implicitly aligned with planned growth, so there are no scaling factors applied to align it to the CCC or BCG growth scenarios.

Spend on the transmission system is outlined in Transpower's AMP and shows the funding allocated to cabling and transformers in future funding periods. This planned spend is highly periodic, with spend peaking in the middle of five-year funding windows – shown in **Figure 24**. To estimate the spend, and therefore the km of cabling, and number of transformers installed over our modelling period, we have modelled this investment as a sinusoid (with negatives zeroed) and extrapolated the data out to 2050. This extrapolation resulting in an underestimate for transformer numbers, and an overestimate for cabling length as shown in **Figure 24**. The nature of the underlying CAPEX plans made it difficult to develop an estimate that followed the values accurately – this is a limitation of the model.

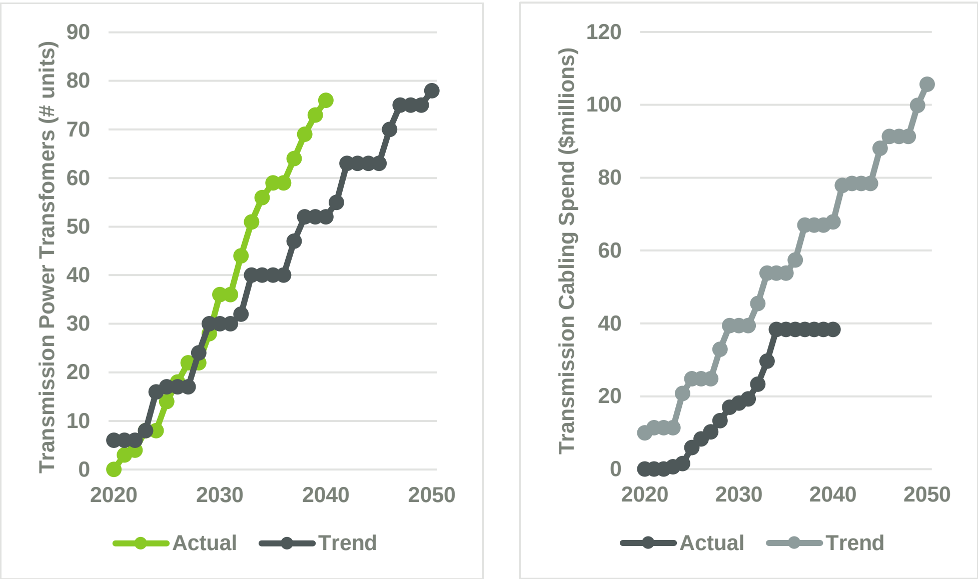


Figure 24: Extrapolating and estimating Transpower's CAPEX spend over the modelling period

Modelling distribution systems was different. Vector's AMP provides projections for spend as a total for the distribution system, but without splits of where the spend is allocated. Orion's AMP offers percentage splits of where their spend is allocated, so the two sources were combined, and scaled up via population to account for distribution systems across the country. Linear trends are then applied to fill out data over the modelling period as these weren't periodic like Transpower, resulting in the estimates in **Figure 25**. The graph shows a variance in investment across developments depending on their size, for example 0.4kV (400V residential distribution) cabling is the largest investment. Similarly, we see larger 300 and 500kVA transformers, and 110kV cable with lower investment over time, according to the spend allocations from Orion.

Spend from these entities' AMPs was converted to kilometres of cabling, and units of transformers using a study from the Australian Energy Market Operator (AEMO[21]), and transformer design and costing guide from PEGuru[22]. Considering the multiple estimation and inter/extrapolation steps required here, accuracy is likely to be low – though no alternative exercise estimating these material requirements has been found for comparison.

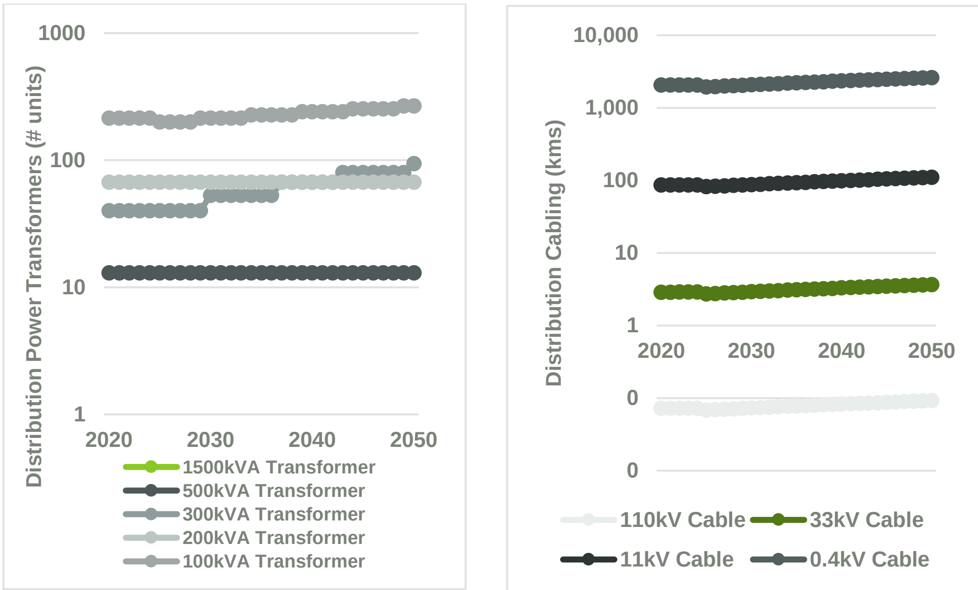


Figure 25: Extrapolating and estimating distribution infrastructure buildout based on Orion and Vector's AMPs

5.5.2 Technology Developments

Only standard oil-cooled, three-phase power transformers, and common cabling types were included in this exercise. Cabling is typically copper for residential and low-voltage distribution cabling, and generally moves to all-aluminium, or steel-reinforced-aluminium cabling towards the higher voltage ratings (transmission-level). There is still discussion in the T&D space regarding the best way to upgrade T&D infrastructure to cope with the requirements for increased generation and storage.

At the time of writing this report, Transpower is investigating "non-wire alternatives" to T&D, including using battery storage as a solution for required capacity. This hasn't been factored into the analysis, but this type of investment would increase materials requirements across metals common to battery developments, whereas typical T&D infrastructure would focus primarily on copper, aluminium, and steel. No future developments of technologies (such as superconducting transformers or cabling) have been factored into this analysis.

5.5.3 Material Requirements

As previously discussed, the materials requirements of T&D infrastructure are simplistic, mostly consisting of copper, steel and aluminium. Other materials like zinc, manganese, silicon, and magnesium appear here purely as agents for alloying. If other aspects of T&D infrastructure (e.g., substations) were to be modelled in this exercise, we would expect the same materials to be present, and that it wouldn't make a marked difference to the total across the energy transition.

5.6 Geothermal Electricity Generation

Geothermal power plants generate around 10% of NZ electricity. This generation is consistent, making it a suitable option for installation alongside solar PV and wind generation, which even with BESS, may not service the baseload requirement for NZ in the future.

5.6.1 Technology Growth Scenario

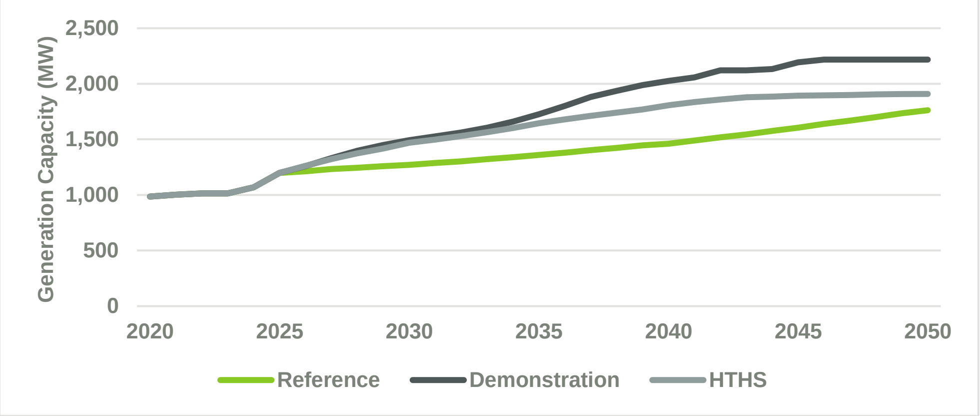


Figure 26: Geothermal energy generation growth across the CCCs GHG emissions reduction pathways

In all scenarios, there is a gradual increase in capacity, but this is less significant than for other technologies including solar PV and wind. Contrary to other assessed technologies, the HTHS pathway from the CCC provides an overall growth that is lower than for the demonstration pathway – shown in **Figure 26**.

5.6.2 Technology Developments

No developments to the standard double-flash generation method are included in analysis for this generation technology. Although it is modelled as growing over time, it does not benefit from the same learning curves that drive growth for solar PV or wind generation. While there are new technologies being developed in this space, the probability NZ will invest in these is unknown. This includes the use of laser-mechanical drilling[23] to develop deep geothermal wells rapidly and cheaper than is currently possible.

5.6.3 Material Requirements

The materials required for geothermal generation are less critical, with most of the construction consisting of iron for steel, and some alloying elements – as shown in **Figure 27**.

Figure 27: Proportions of material requirements used in GFPP geothermal developments

This contrasts with almost all other generation technologies that require key non-metallic minerals like silicon, or rare-earth elements for use in neodymium magnets. Where sourcing these materials is not possible, geothermal generation could still be built and installed in NZ.

6 Sensitivity Analysis

Sensitivity analyses undertaken in this research show potential changes to the status quo, and assumptions modelled and described in Sections 4 and 5, that could change the way technologies are utilised in the future. Some of these developments are used in the indicative scenarios in Section 7 for the HTHS scenario, including perovskite solar cells, offshore wind generation, and post-lithium-ion batteries.

Sensitivity analyses are included for developments of technologies that aren't yet present in the market share but are projected to soon. The nature of these RETs is that within a small time frame a new development could enter the market and take significant market share. These burgeoning developments are typically at a level of demonstration in a laboratory, or small-scale tests, but are not ready for mass manufacture and sales. Developments that are on the cusp of this, as indicated by a TRL[24] of at least 6 (full prototype at scale) according to the IEA[25], have been included as sensitivity analyses. This enables the model to present estimates of materials requirements outcomes in the case of these technologies reaching commercialisation and entering the market share. The developments included as sensitivity analyses and selectable in the dataset, are described below.

Included in the sensitivity analyses are internal combustion engine (ICE) vehicles, and traditional gas turbine electricity generation, and how they compare to their RET equivalents. This comparison shows the difference in materials requirements that support transitioning to cleaner alternatives.

6.1 Perovskite Solar PV Electricity Generation

Perovskite solar cells (PSC) have emerged as high-functioning semiconductors for both PSC-c-Si-tandem (PST) or PSC-PSC-tandem (all-PSC-tandem "APT") devices. The combination of high efficiency and ease of manufacture using existing coating techniques makes PSC a frontrunner[26] for a future PV technology. The tuneable bandgap of these panels makes it suitable for tandem installations with c-Si panels, enabling the system to capture a higher proportion of the wavelengths of incident light. An APT system would offer equally great coverage of the light spectrum, and offer increased ease of manufacture, and reduced usage of critical minerals like silicon.

A sensitivity analysis of APT PV systems is included as a "best case" future solar PV development. It is expected that other combinations including PST, or thin-film-PSC-tandems may appear as transitionary developments – but these are not included in this sensitivity analysis.

Perovskite solar PV generation uses a doped semiconductor consisting of indium, lead, tin, and caesium, which differs from the materials used in c-Si and thin films, as shown in Table 5. Only indium appears on CSIRO's critical minerals lists, and alongside the ease of manufacture for these panels, and their increased efficiency, PSC panels are on track to displace other technologies in the market when commercialised. While there are issues with the longevity of the panel yet to be worked through, samples have been produced and tested – showing efficiencies already comparable with the best c-Si models.

An indicative market share scenario for the introduction of PSC PV panels was produced (Figure 28) to estimate how this would replace some amount of c-Si panels (in place of thin films). It is noted PSC-PSC-tandems will not immediately enter the market, and some transitionary tandem combinations may exist in the short-term. This market share is based on the projected availability of commercial PSC panels, starting around 2030.

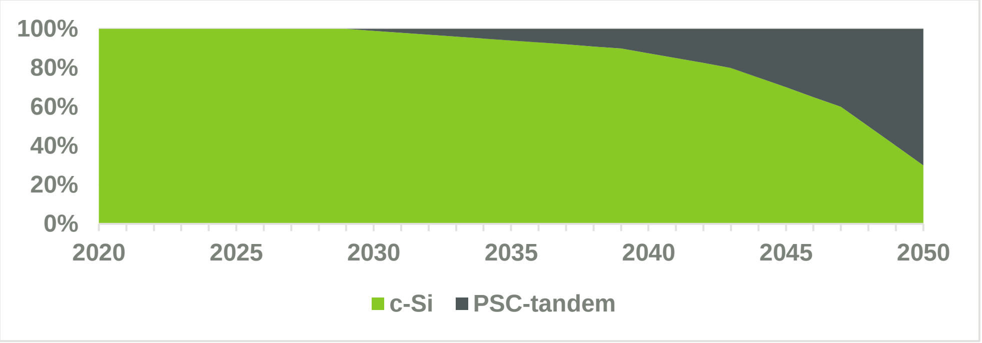


Figure 28: Indicative estimated development market share for perovskite solar cells

This development and market share is used in the indicative HTHS pathway analysed in Section 7, replacing the use of thin films.

6.2 Offshore Wind Electricity Generation

There are currently no offshore wind installations in NZ. With windspeeds typically higher and more constant at sea[27], and NZ having some of the world's best wind resources due to its geographic location, this is a technology that is being actively investigated. Offshore wind generators can generate large amount of electricity – which, via an offshore substation, is transmitted onshore using an underwater cable.

The CCC include an overall growth scenario for this technology in their HTHS pathway. Applying similar technological developments as onshore wind generation, and scaling values to cover the differences between on and offshore installations, we can estimate the materials requirements of this technology. We have considered fixed monopile installations only, given the relatively shallow water where offshore wind is being investigated for NZ – floating turbines are a potential solution for deeper waters, but are a less mature and more expensive technology. The differences in base materials between onshore and offshore wind are included in Table 7, based off scaling factors from Schreiber, et al. (Appendix 10.3).

Material	Onshore	Offshore
Copper	2.6	9.4
Steel	138.1	355.7
Aluminium	1.7	1.2

Table 7: Base materials intensities for onshore and offshore wind generation (t/MW)

With stronger winds at sea and addressing common concerns with disruption from onshore wind generation, this technology could form part of NZ's future energy makeup as indicated in the HTHS scenario in Section 7.

6.3 Post-Lithium-Ion Batteries

A secondary set of battery developments is used as a sensitivity analysis of the materials requirements of electric vehicles – the post-lithium-ion battery (PLIB) scenario. This scenario uses much of the same developments but considers newer cell technologies that could replace traditional LIBs. For this analysis, Aurecon has used solid-state lithium-ion batteries to serve as our PLIB development. These cells share many of the same materials as the traditional LIBs but use a lithium-aluminium-titanium-phosphorus (LATP) inorganic solid-state-electrolyte (ISE). Table 8 shows that this new development introduces significant materials demand compared to traditional LIBs. This development differs from other batteries, that are typically designed to reduce requirements for certain materials – and instead adds further demand but offers other benefits including increased safety.

Material	NCA	NMC532/622	NMC811/900	LFP	ASSLIB
Aluminium	0.70	0.67	0.65	0.88	0.24
Chromium	0.00	0.00	0.00	0.00	3.45
Cobalt	0.10	0.16	0.07	0.00	0.01
Copper	0.26	0.29	0.27	0.43	0.00
Graphite	0.78	0.77	0.82	0.92	0.00
Iron	0.02	0.02	0.02	0.64	13.63
Lithium	0.09	0.10	0.08	0.08	0.53
Manganese	0.00	0.16	0.06	0.00	0.39
Nickel	0.55	0.49	0.27	0.00	1.54
Phosphorus	0.01	0.01	0.01	0.36	0.82
Silicon	0.00	0.00	0.00	0.00	0.19
Titanium	0.00	0.00	0.00	0.00	2.14

Table 8: Material requirements of technology developments in the PLIB market share (kg/kWh)

Solid-state batteries aim to provide increased safety and energy density[28] above current LIBs. Prototypes of solid-state LIBs, considered PLIBs for this exercise, have been shown to store nearly twice as much energy as a standard LIB per kg. Additionally, the fire-risk posed by LIBs when punctured or overheated, has been almost entirely reduced though the removal of the flammable organic liquid electrolytes. While the materials requirements for critical materials is higher compared to standard LIBs, the overall mass for the same energy storage potential is lower. One material these solid-state LIBs have removed from the requirements is graphite which is typically the largest material requirement in LIBs – reducing the materials demand for tier 1 materials. More background on graphite, its importance, and related environmental risks are provided in Section 7.2.

These solid-state batteries are considered likely contenders in the EV battery market considering their reduced weight for the same energy storage capacity, and increased safety. Note that this is simply an assumption, and alternative technologies like Sodium-ion batteries (SIBs) could also end up displacing LIBs in the EV battery market share. With some input, this can be adjusted in the dataset. The development market share used is from Degen, et al., in their 2023 paper in Nature Energy titled "**Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells**" and is shown in Figure 29.

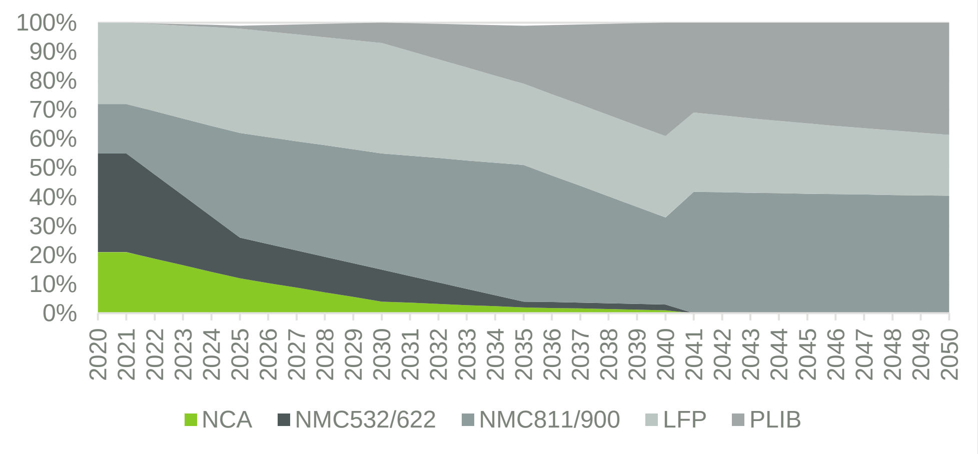


Figure 29: PLIB battery development market share from Degen, et al.

Note the sudden spike in some developments in this market share in 2040 is due to the linear trends used to extrapolate this data through to 2050, where the paper only provided projections until 2040. This development market share is used for PHEVs and EVs in the HTHS indicative scenario in Section 7.

6.4 Internal Combustion Engine Vehicles

CCC's vehicle fleet models, based off MoT's VFEM, show ICE vehicles will continue to enter the fleet until the mid-2030's under all emissions reduction pathways. ICE vehicles have lower materials requirements than their electric counterparts due to the lower requirement for batteries. While ICE vehicles typically only using a single lead-acid battery, and an iron or aluminium engine block, EV's will often have a lithium-ion battery and permanent-magnet electric motors. Table 9 shows the difference materials requirements between ICE and EV developments, based on data from the U.S EPA's GREET database.

Material	ICE	HEV	PHEV	BEV
Steel	778.7	773.5	769.6	776.1
Stainless Steel	0	0	0	1.3
Cast Iron	24.7	70.2	70.2	0
Aluminium Sheet	37.7	22.1	20.8	24.7
Aluminium Extrusion	23.4	13	13	14.3
Cast Aluminium	106.6	127.4	133.9	139.1
Copper	31.2	50.7	57.2	75.4
NdFeB Magnet	0	1.3	1.3	3.9

Table 9: Material requirements of light passenger vehicles across vehicle types, excluding batteries (kg/unit)

Considering the ICE vehicles still have a substantial structural metal requirement, when including this development in the model, they contribute to a significant amount of the total materials requirements of vehicles. In the Demonstration pathway, ICE vehicles are no longer entering the fleet from 2032, and peaked in 2021 as shown in Figure 30. These projections fail to capture the removal of the EV rebate however, where the level of EV purchases has fallen back to pre-rebate levels.

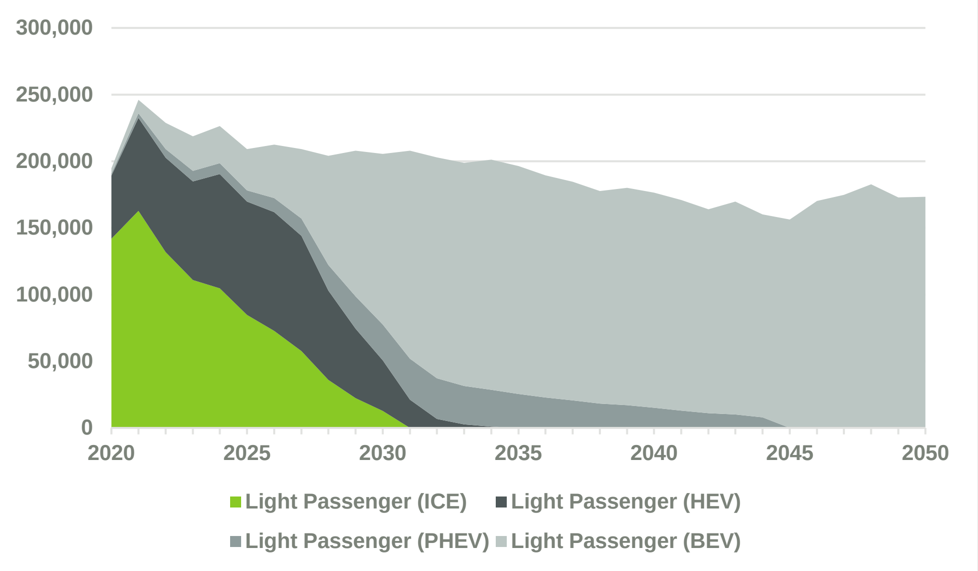


Figure 30: Annual additions to the light passenger vehicle fleet under the CCCs Demonstration pathway, across all vehicle types

In the Demonstration pathway, with ICE vehicles, we see vehicles requiring 50-70kt of tier 2, and almost 150-300kt of tier 3 materials annually, across all development types and including both light and heavy fleet as shown in **Figure 31**. The tier 3 materials drop significantly over the modelling period in line with the drop in annual entries of vehicles into the fleet. Tier 2 materials decrease by a smaller amount, because while less alloying elements like chromium and magnesium are required in line with reductions in iron and aluminium, there is an increase in the use of materials like phosphorus and manganese in the increase battery demand.

When we remove ICE vehicles from the model in **Figure 32**, it reduces the annual materials requirements for both tier 2 and 3 materials until the mid-2030's where values return to the same levels. As EV developments use the same structural metals, tier 2 and 3 trends are largely the same for ICE and EV developments – the difference is in tier 1 materials demand. When removing ICE vehicles there is no change to demand for tier 1 materials as all these materials, including lithium, graphite, and cobalt are used in EVs alone, thus no comparison figures are provided.

For simplicity, ICE vehicles are excluded from the final analysis and indicative scenarios, but these can be added into modelling simply using the interactive dataset.

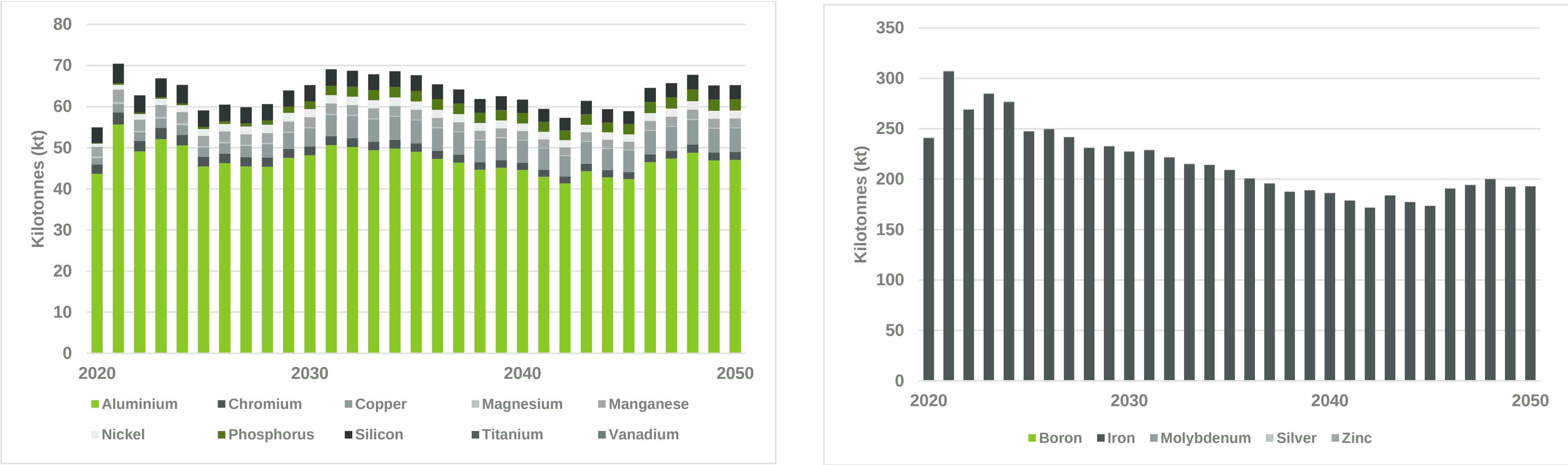


Figure 31: Annual materials requirements of vehicles (including batteries) under CCC Demonstration emissions reduction pathway (tier 2 – left, tier 3 – right)

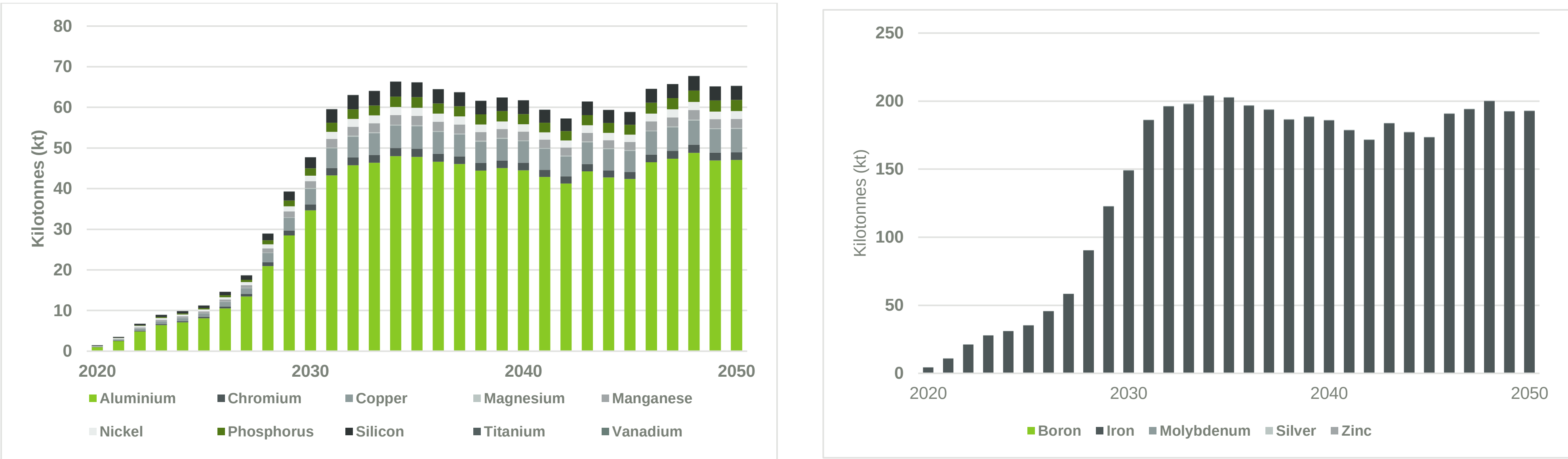


Figure 32: Annual materials requirements of vehicles (excluding ICE, including batteries) under CCC Demonstration emissions reduction pathway (tier 2 – left, tier 3 – right)

6.5 Open-Cycle Gas Turbine Peakers

OCGT units act as peaking plants during periods where baseload or intermittent renewable generation is not sufficient to service NZ's electricity demand. The Climate Change Commission scenarios do not project a material increase to the peaker fleet over time, nor have any technological developments been modelled. There is potential that peakers may be retrofitted to use hydrogen or biogas, but this is unlikely to have a significant impact on the materials required. We have included their material requirements in the analysis so they can be considered in customised scenario analysis beyond the scope of this report.

OCGT units, like geothermal units, are mostly made up of structural elements. The exception is the use of high-temperature nickel alloys required to withstand the heat of combustion within the unit. The overall materials requirements by mass are much lower than alternative technologies (approximately 3.6 tonnes per MW across the unit and foundation). **Figure 33** provides a comparison of the total mass of materials required for a functional unit of each generation type.

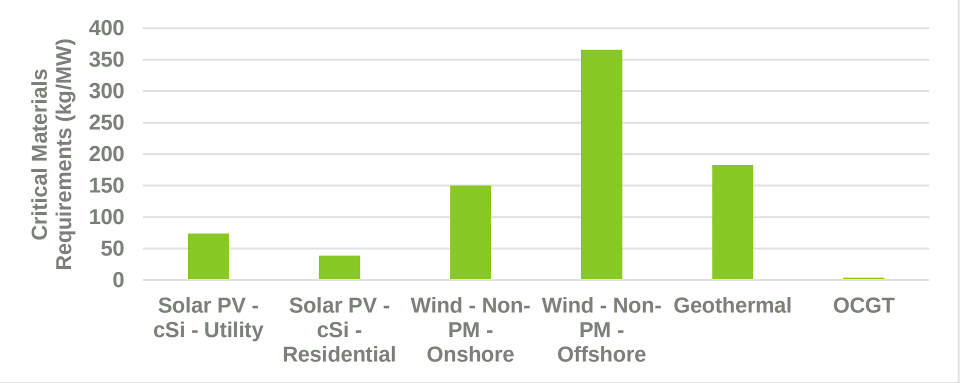


Figure 33: Comparison of materials requirements for different electricity generation technologies

Gas turbines have the smallest materials requirements when compared to other renewable electricity generation technologies considered in this exercise. Some of this difference is due to the scope of components included for each technology. For example, solar PV and wind generation includes inverter/transformer requirements. We expect that even when considering the balance of plant, the OCGT units will have a smaller materials requirement than the construction of renewable generation.

We note that this reduced materials requirement excludes the resources needed to operate this generation, which is considerably higher than renewable alternatives. These trends are in line with analysis from IEA and the World Nuclear Association[29], who quote:

> *"The lower energy density of intermittent renewable energy compared with fossil fuels and nuclear energy translates directly and inexorably to a greater mineral/material demand per unit of energy. Estimates vary but producing electricity from wind and solar typically increases the quantities of materials requiring extraction, processing and handling by a factor of at least 10."*

This insight is like what was seen for vehicles in **Section 6.4** through **Table 9**, where there is a compromise between upfront investment and environmental impacts from increased materials demand, and the medium-long-term decarbonisation benefits of cleaner technologies. In both cases, to claim the emissions reduction benefits of RETs, a larger upfront material demands (especially critical materials like those in CSIRO's tier 1) is required.

A potential takeaway from this is that renewable energy in the current production system still requires non-renewable resources to produce it. Circular economies, re-use, and recycling are covered briefly in the discussion (**Section 8.3**) which touches on how this compromise can be reduced through extending the use of these materials.

It's important to note that in NZ, gas turbines don't act as a direct alternative to renewable energy generation, instead acting primarily as peakers to support the electricity system when renewable energy is not available. In this case, NZ's largely renewable grid allows industrial processes to be decarbonised (from thermal coal in many cases), and peakers act as a backup to ensure all users still have access to electricity when demand is high and generation from intermittent sources is limited. In this way, they can partially support the further development of the energy transition.

7 Results

This report includes three indicative overall system scenarios for analysis. These three scenarios are designed to reflect a range of futures aligned with the CCC and BCG decarbonisation pathways – described in **Table 10**. The first, “BAU” looks at the baseline scenarios, with no new technologies in place. The “Net-Zero” scenario includes some basic technological developments, and the middle-of-the-road growth scenarios. This second scenario is our ‘standard’ scenario, as it models an energy transition aligned with NZ meeting its climate goals as set out in the Paris Agreement, and the Climate Change Response Act. The final scenario (Rapid Decarbonisation) includes our sensitivity analyses for new technology deployment, and the most aggressive growth scenarios possible. **Table 10** describes the variables used in the dataset to produce these system scenarios. They can be recreated in the dynamic dashboard if desired. Data is presented for both stocks (cumulative materials requirements in the system), and flows (annual additions “flow-in” and removals “flow-out” from the system).

All scenarios include residential PV battery storage and T&D infrastructure. ICE vehicles and OCGT generation are not included in these indicative scenarios but can be added by the user in the dataset. As such, not all possible combinations of overall growth and market shares have been included in this report. Users can prepare a custom combination of results using the accompanying dataset workbook.

Figure 34, **Figure 35**, and **Figure 36** over the following pages show the resulting metal demand for these indicative scenarios. Following this, **Section 7.1** provides analysis of each of these scenarios, covering overall materials demand, and insights related to this.

It's noted again that this model is a series of estimates based off both existing research and datasets, and some indicative numbers from Aurecon’s internal experts. These estimates involve numerous uncertainties and limitations (covered in **Section 4.5**), and results shouldn’t be used in isolation for decision making. The orders of magnitude of the numbers, and the trends in the results, are more important to understand, and are likely more useful than specific numbers. It’s also stressed that underlying data sources have their own sets of uncertainties, and are driven by factors that can change rapidly, making predictions very difficult. Similar historical estimates have underestimated the growth of RETs (as described in **Section 3**), so it is likely figures from this exercise are also underestimates.

Technology	BAU	Net-Zero	Rapid Decarbonisation
Solar PV – Utility	CCC Reference, c-Si Dominates	CCC Demonstration, Thin-Films Take Lead	CCC HTHS, Perovskite Sensitivity Analysis
Solar PV - Residential	CCC, c-Si Dominates	CCC, Thin-Films Take Lead	CCC, Perovskite Sensitivity Analysis
Wind – Onshore	CCC Reference, Non-PM Rapid Decline	CCC Demonstration, Non-PM Rapid Decline	CCC HTHS, Non-PM Rapid Decline
Wind – Offshore	N/A	N/A	CCC, Offshore Sensitivity Analysis
BESS	BCG Business as Usual	BCG Smart System Evolution	BCG Green Export Powerhouse
Road Vehicles	CCC Reference	CCC Demonstration	CCC HTHS
Road Vehicle Batteries	CCC Reference, LFP Scenario	CCC Demonstration, LFP Scenario	CCC HTHS, PLIB Scenario
Geothermal	CCC Reference	CCC Demonstration	CCC HTHS

Table 10: Technology growth and development variables used for selected energy transition scenario

Figure 34: Estimated materials requirements of an energy transition - indicative Reference scenario

Figure 35: Estimated materials requirements of an energy transition - indicative Net-Zero scenario

Figure 36: Estimated materials requirements of an energy transition - indicative Rapid Decarbonisation scenario

7.1 Findings

This section presents the results from the indicative energy transition scenarios and discusses the drivers behind the estimates. The annual and cumulative demand for materials in all energy transition scenarios is included in Table 11 and Table 12.

Technology	CSIRO Tier 1	CSIRO Tier 2	CSIRO Tier 3	Draft NZ Minerals Strategy
Reference	15.2	103	262	5
Demonstration	12.5	86.4	204	4.2
HTHS	8.9	105	242	15.9

Table 11: Annual critical materials requirements of the energy transition in 2050 (kt)

Technology	CSIRO Tier 1	CSIRO Tier 2	CSIRO Tier 3	Draft NZ Minerals Strategy
Reference	1,299	3,410	4,890	183
Demonstration	265	2,090	5,650	90.4
HTHS	220	2,410	6,320	260

Table 12: Cumulative critical materials requirements of the energy transition in 2050 (kt)

7.1.1 Net-Zero Scenario Materials Requirements

The Net-Zero scenario for NZ's energy transition is in line with CCC's Demonstration emissions reduction pathway – reaching NZ's net-zero 2050 targets. The indicative scenario includes mostly business as usual technological developments, except for modelling the increase in use of thin films in solar PV generation, as outlined in Table 10. In general, this scenario models a modest increase in solar PV, wind, and geothermal generation, supported by a small buildout of BESS. For vehicles, the CCC's models a complete electrification of vehicles entering the fleet by the early 2030's, and a gradual drop in overall numbers of vehicles entering the fleet each year.

- Tier 1 materials show the largest growth during the modelling period of 2020 to 2050 from **0.238kt** in annual demand to **12.5kt** (an increase of approximately **53 times**) – shown in Figure 35. Most of this demand is in graphite, which is the largest contributor by mass to the materials requirements of most battery developments considered. These batteries are used across BESS, residential solar PV-tied storage, and electric vehicles. The battery requirements of EVs are the more significant contributor to the total tier 1 materials requirements, shown through the plateauing of the increasing in demand towards the end of the modelling period – overlapping with the reduction in annual fleet increases. This drop in materials requirements isn't quite as large as the fleet reductions because the fleet is still transitioning from ICE vehicles and HEVs and PHEVs to full BEVs at the same time – which have a greater tier 1 material demand.
- Tier 2 materials increase in annual demand by a much smaller amount over the modelling period, from **15.3kt** to **86.4kt** (approximately **5.6 times**) – as shown in Figure 35. Within this tier, aluminium dominates by mass, but increases much less than materials like manganese, nickel, and silicon. This is because the structural aluminium demand in vehicles decreases over time with the reduced fleet additions, while other materials continue to increase through additional buildout of batteries, and solar PV generation. As with tier-1 there is a distinct curve to the annual demand, gradually increasing up to the mid-2030's, dipping for approximately a decade, and continuing to increase. From 2035, Figure 30 shows CCC have modelled that all vehicles entering the fleet are EVs (which have a larger materials requirement across all tiers), and that there is a small increase in fleet entries towards 2050 following decades of reductions. This sensitivity of the model to vehicles is one of the core findings of this exercise.
- Tier 3 materials increase in annual demand by the smallest amount of all the material tiers, from **4.58kt** in 2020, to around **204kt** in 2050 (an increase of around **44.5 times**). Iron accounts for almost all the materials requirements in tier 3 (Figure 35) and is used extensively across all RETs included in this exercise. Throughout Section 5 there is a documented trend of steel alloys, and therefore iron, dominating the materials requirements of all RETs by mass. With this trend also true for vehicles, and with vehicles dominating the overall materials requirements, we see a large increase over time. If ICE vehicles were included

in this scenario, we would expect this increase to be smaller, or to even decrease over time as the overall annual fleet additions decrease.

- Materials listed in the Draft NZ Minerals Strategy follows the trend of tier 1 materials because of the overlap in materials included in these two categories. Baseline materials requirements are **0.05kt** in 2020, increasing to **4.17kt** in 2050, an increase of just over **83 times** (Figure 35). It is larger than the tier 1 increase because it also includes materials like Phosphorus which is used in large amounts in LFP batteries. When considering only the materials that are present in both the Draft NZ Minerals Strategy, and the CSIRO tiers, the mass of materials covered by domestic production account for approximately **1.4%** of the total materials requirements in 2050. Excluding iron and aluminium from this calculation, the materials included in the Draft Strategy account for around **12.6%** of the total 2050 materials requirements by mass. These materials would substantially displace the materials requirements in CSIRO's tier 1, accounting for **33.6%** of the demand of tier 1 materials by mass. This suggests that assuming NZ could supply all this material demand domestically, it would still be a small proportion of overall material requirements by mass.

7.1.2 BAU Scenario Materials Requirements

The BAU scenario represents 'business as usual', where energy generation and vehicle fleet numbers remain at current trends. There are no additional technological developments considered in this scenario. Table 11 shows that the annual material requirements across all categories are greater in the reference case compared to the pathway to net-zero. This is in line with the findings for the demonstration pathway, where the total materials requirements are heavily skewed by the number of vehicles entering the fleet. With CCC modelling far more vehicles entering the fleet in the reference case (as shown in Figure 9), the result is a greater materials requirement – even while the electricity generation buildout is smaller.

The larger materials requirements in the BAU scenario are much greater for tier 1 materials than for other materials as outlined in Table 12. As the electrification rate is similar across all scenarios (Figure 9), but the overall fleet additions are far greater, by 2050 the number of EVs in the fleet is far greater in the reference scenario. This further shows the influence of vehicle numbers on the overall material requirements of an energy transition. It's worth noting the reduction in fleet numbers (particularly EVs) not only directly reduces materials requirements overall but would reduce the requirement for electricity generation buildout – creating a further reduction in materials requirements.

Technology	CSIRO Tier 1 (kT)	CSIRO Tier 2 (kT)	CSIRO Tier 3 (kT)	Draft NZ Minerals Strategy (kT)
Reference	2.5	604	939	3.7
Demonstration	3.6	640	1,260	5.4
HTHS	4.2	650	1,420	6

Table 13: Cumulative materials of the energy transition (excl. vehicles, kt)

The removal of vehicles from accounting shows the materials requirements increase slightly between the energy transition scenarios. This shows that the decrease in materials requirements from BAU to Net-Zero previously was due to the inclusion of vehicles, and the reduction in fleet numbers modelled by the CCC. In the BAU case, this is a reduction of **98.6%**, **69.4%**, and **77.7%** for tier 1, 2 and 3 materials respectively. For the default Net-Zero scenario, considering the smaller fleet sizes modelled by CCC, these differences are **99.8%**, **82.3%**, and **80.8%**. The percentage of tier 2 and 3 materials attributed to vehicles is smaller for the demonstration pathway because of the smaller fleet, while there is still use of this materials in electricity generation. This is not true for tier 1 materials which are used primarily in EV batteries, so removing vehicles from the estimates almost entirely reduces the tier 1 materials requirements.

7.1.3 Rapid Decarbonisation Scenario Materials Requirements

The Rapid Decarbonisation scenario represents a more aggressive decarbonisation of the energy system compared to the Net-Zero scenario – utilising new technological developments and introducing systems to change demand habits. In this scenario, not only are fleet additions at their lowest, but more electricity generation is built utilising developments like perovskite solar PV panels, offshore wind generation, and post-lithium-ion batteries.

Table 11 and Table 12 shows an increase in materials requirements in the Rapid Decarbonisation scenario (from the Net-Zero scenario) for tier 2 and 3 materials, but a reduction for tier 1 – which contrasts with the overall reductions from BAU to Net-Zero. The tier 1 reduction is explained by further fleet reductions modelled by CCC (Figure 9), but the increase in tier 2 and 3 is likely driven by the increase in materials requirements from the PLIB battery scenario. In this development market share, solid-state lithium-ion batteries enter the market and begin to displace the historic LFP, NMC, and NCA developments. These batteries offer improved energy density and safety – making them a suitable development for EVs, but also have a much higher materials requirement – as shown in **Table 8**.

This effect of technological developments on the materials requirements of the energy transition is another core theme of the findings and is relevant to all scenarios. Another potential example of this is if sodium-ion batteries. In this case, the materials requirements of batteries (for those materials in **Appendix 10.1**), would be greatly reduced – removing lithium and graphite requirements altogether. This is a reminder of the sensitivity of these estimates to the projected development market shares, and the influence this can have on the overall numbers. It also presents the opportunity for a "win-win" scenario, where utilising new technologies and systems, greater emissions reductions can be achieved through the energy transition, while requiring a smaller number of critical materials.

With increased materials requirements compared to the Net-Zero pathway, this stresses an opportunity for the re-use and re-manufacturing of waste products exiting the system. **Figure 36** shows that RET assets installed within the modelling period begin to reach their end of life in the mid-2030's, potentially introducing large amounts of critical materials into the waste systems. This circular economy opportunity could allow the reduction of virgin materials requirements for assets past this period. It's important to note that while some of these assets produce renewable energy, the materials needed to produce these assets in the first place are not renewable. Without the re-use and re-manufacturing of these wastes back into new assets, there will be a point at which there are simply not enough materials left to manufacture these assets anymore – posing a significant problem not only for NZ, but for the world.

7.2 Environmental Risk Summary

This section presents environmental risks associated with extraction and refining of key materials and minerals considered in this study. Cultural, geopolitical, economic and other supply chain risks were out of the scope of this report. This summary provides an overview of key environmental risks for different materials and should not be considered comprehensive.

7.2.1 Environmental Risk Overview

The identification and summary of environmental risks has been conducted through a review of the key literature and risk assessments undertaken for materials critical to the energy transition, by organisations such as the International Energy Agency (IEA), the International Renewable Energy Association (IRENA) and the Energy Transitions Commission (ETC). Materials identified in these documents have been combined with those in the Draft NZ Minerals Strategy to develop this prioritised list of representative materials for environmental risk assessments. Where information gaps from these documents exist, academic and industry literature has been used, and is cited directly. We have summarised the risks associated with two key areas of the materials supply chain and have chosen these areas due to the different risk profiles of each:

1. **Resource extraction** accounts for the physical mining or extraction of raw resources, and the beneficiation (or concentration) of raw ores to a product suitable for refining. These processes are often more diesel-intensive than downstream refining but can have wider environmental impacts associated with physical resource extraction such as open-cast mining pits.
2. **Resource refining** covers the downstream processing of these materials, including separating materials that occur in the same orebody, the smelting of metals, and the purification of products so they can be used in further manufacturing processes. These processes are often pyrometallurgical or hydrometallurgical and can require significant energy inputs.

Within each of these two stages, there are different categories of environmental risks. These are as follows:

7.2.2 Physical Impacts

Like many resource extraction activities, mining and refining disrupts the natural landscape. Different materials are extracted in different ways – a material excavated in an open pit mine will generally impact a larger area than one from an underground mine, and a mine in an area of tropical rainforest for example, may have larger biodiversity impacts than an equivalent mine in a desert. Impacts go beyond the mine or refinery itself and expand to areas such as the disposal of overburden and waste tailings – and are dependent on characteristics such as ore quality and rock-metal ratios. In well-managed operations, these areas will be stabilised and reclaimed once mining has ceased, alleviating some of the physical impacts.

7.2.3 Contamination Impacts

Environmental contamination brings risks to ecological systems, as well as human health. The mining, beneficiation and refining processes all contribute to these risks in different ways, with two main ones being the following:

Contamination from waste rock or tailings – the process of mining brings metals and minerals to the surface that often don't occur naturally in these quantities. This, of course, is the whole point – but not all these materials are useful. During the beneficiation and refining processes, contaminants and waste are stripped out and disposed of, resulting in stockpiles of material that need to be managed directly so that contaminants such as heavy metals, acids, or eutrophying minerals don't leach into the environment.

The key risk factor for this type of contamination relates to how 'mobile' they are, or how these materials relate to the biological world. As an example, when heavy metals are locked up in a mineral, they are often not water-soluble and cannot be absorbed by plants or animals and can't bioaccumulate up the food chain. But the processing steps used in beneficiation or refining can mobilise these metals, make them water-soluble, and increase the risks of environmental or human harm.

These risks need to be managed actively, with different treatments for different waste materials. Slag waste from smelting is generally less at-risk and more stable, but tailings waste from refining is highly risky due to being finely crushed and therefore easier to dissolve in water. Tailings impoundments should be protected from leakage by using interventions such as impermeable clay or membrane linings, however older infrastructure, or facilities located in countries with reduced environmental standards, may not implement best-in-class environmental controls.

Another key risk is acid rock drainage (ARD). This is where metal salts such as sulphides are oxidised along with water to become acidic, which can then dissolve heavy metals and mobilise them, transporting them so they can accumulate in sediments or groundwater and cause harm to the environment or human health. This is especially significant where mines are below the water table, meaning natural flows through exposed ores need to be actively managed – groundwater contamination is particularly challenging.

Contamination of the air – the refining steps for many metals involve processes that use significant volumes of coking coal, electricity derived from coal-fired electricity, or that produce significant direct emissions, including particulates, metal vapours, NOx or SOx. Environmental controls on smokestacks and flues can help alleviate some of these challenges, but they remain significant for the local environment, and the health of workers and the populations that live near to facilities. Smelters and refineries are especially significant here, as they are more likely to be located nearer to urban areas than mines themselves.

7.2.4 Water Consumption

Water is used throughout the value chain for metal and mineral production, notably during the beneficiation stage. Actual water usage can depend on what is being mined, the type of orebody the material is in, and the processing technique that is being used. In some flotation-based separation processes for example, significant volumes are required. In many cases, this water is recirculated and recycled, but evaporative losses occur, as do losses where materials absorb some of the water.

Hydrometallurgical processes often involve using water-based acidic solutions, some of which involve open-air spraying, significant direct water consumption, and further evaporative losses. Freshwater impacts are not exclusive to direct freshwater usage, however.

Water can also be consumed indirectly, such as in lithium brine extraction. Here, saltwater brine is removed from underground aquifers that can then be refilled by freshwater sources, lowering the water table and reducing the availability for other uses. These can include direct human consumption, or ecosystem services.

The IEA[30] highlight that resource extraction often takes place in areas exposed to significant water stress. This means that direct consumption in these areas has a larger impact than an equivalent volume in an environment with more water availability. The ETC[31] suggest this is especially significant for materials such as copper, lithium, some REEs, and Australian iron ore.

7.2.5 Summary

Table 14 presents a qualitative risk summary for a representative subset of identified materials. We have chosen this subset to include relevant minerals from the Draft NZ Minerals Strategy, as well as the highest-priority materials identified by bodies such as the IEA, which covers a selection of production pathways. It is illustrative only and does not consider how potential risks could change over time, whether they increase or decrease. For some materials, lower-risk supply chains do exist, but the most common supply route has been assessed.

For domestic production of materials in the Draft NZ Minerals Strategy, refining has been assumed to occur offshore, as proposals to date are focussed on mining and resource extraction. For materials that have multiple proposed production routes, such as for seabed mining and land-based extraction of vanadium and titanium iron sands, the higher-impact route has been chosen as a conservative approach. We also note the qualitative nature of this summary – environmental risks are challenging to compare across impacts such as energy usage, pollution risk, or water usage, and we are not using a formal assessment methodology to score these risks.

	Identified Key Material	Resource Extraction & Beneficiation	Resource Refining & Smelting
CSIRO Tier 1	Lithium	M	M
	Graphite	L	H
	Cobalt	M	M
	Rare Earth Metals: Praseodymium, Neodymium, Terbium & Dysprosium	M	H
CSIRO Tier 2	Silicon	L	H
	Nickel	M	M
	Copper	M	M
NZ Minerals Strategy	Lithium (local supply only)	L	L
	Phosphorous (local supply only)	H	M
	Titanium (local supply only)	H	M
	Vanadium (local supply only)	H	M
	Rare Earths (local supply only)	L	H
	Antimony (local supply only)	M	M
Scoring Key:		L Lower Risk	M Medium Risk / H Higher Risk

Table 14: Qualitative environmental risk scoring for key materials across resource extraction & beneficiation and refining/smelting supply chain stages

7.3 Environmental Risk Deep Dive

As discussed above, environmental risks have been identified for key materials from the CSIRO lists, as well as from the NZ Minerals Strategy. These key materials have been selected through a synthesis of existing literature such as the International Energy Agency's 2021[32] and 2024[30] Critical Minerals reports, or the Energy Transitions Commissions' 2023 material requirements report[31], and cover both Tier 1 and Tier 2 materials in the CSIRO list. We have selected these materials as they encompass a representative set of extraction and refining processes for commonly used materials, as well as those with potential local production growth. Risks are assessed against two stages of the supply chain: mining and refining.

	Material	Resource Extraction & Beneficiation	Resource Refining & Smelting
Tier 1	**Lithium**	**Medium Risk** Current lithium production uses two main routes: brine-derived lithium from South America, and rock-based spodumene from Australia. They have major differences in their environmental impacts. Salar brines are extracted from underground deposits and are concentrated using natural evaporation over several months. Between 100-800m^3 of brine is evaporated[33] per tonne of lithium carbonate, with an additional 20-50m^3/t of freshwater used for chemical delivery and purification. Although much of the water used is highly salty and generally unfit for drinking or other purposes, this usage has indirect impacts on freshwater sources. Freshwater aquifers can be impacted by this extraction as groundwater levels decrease, meaning local wells can run dry, and saltwater intrusion can occur for nearby freshwater aquifers. Spodumene rock-sourced lithium has a very high rock-metal-ratio, which is partially influenced by lithium being such a light metal, and spodumene containing much heavier elements such as aluminium. This means high rates of waste rock generation. It's challenging to beneficiate spodumene ore, and it needs multiple steps including gravity, magnetic, and in some cases flotation separation to concentrate it. This 75% spodumene concentrate is exported[34] (generally to China) for refining, at about 6% Li_2O concentration. Gangue wastes can be contaminated with flotation chemicals.	**Medium Risk** Hard rock lithium refining is dominated by China, mainly from beneficiated spodumene concentrate imported from Australia. This process involves[35] coal-powered ore roasting, sulfuric acid leaching, then further roasting. This makes the lithium water-soluble, with the remainder 94% by mass disposed of as gypsum sludge formed using lime to neutralise the acid from roasting. This gypsum sludge contains contaminants including[36] aluminium, iron, calcium, potassium, and phosphorous, and must be disposed of safely. The coal-fired roasting process generates significant NOx, SOx, and carbon emissions. Lithium hydroxide[37] is used for nickel-rich NMC811 cathodes, currently favoured by US and EU manufacturers. Traditionally it has been more expensive than carbonate, which is commonly used in LFP (e.g. BYD). For the brine-based lithium production process, the concentrated lithium brine is refined by treating it with lime to precipitate magnesium and boron contaminants, and then soda ash to precipitate the lithium carbonate.

	Graphite	**Lower Risk** Graphite production has two main routes – natural mined graphite and synthetic graphite. China dominates the **mined**[30] supply, with 80% of current production. As well as beneficiation processes such as **flotation**[38] separation, this process involves spheronisation (rounding off) of the natural flake product so that it can be used in battery anodes. This process can have product losses of up to 50% Impurities can be partially removed through the flotation process, and with further processing with **sodium hydroxide**[39], acid treatment or chloride-based thermochemical means to remove the remainder. Although non-toxic on its own, this process can produce significant dust and particulate emissions, and the chemical usage can pose environmental risks, especially from hydrofluoric acids and the chloride-based off-gassing from thermochemical processing. Synthetic graphite is produced from byproducts from the coal or petrochemical industry, namely **petroleum pitch and coal tar**[40].	**Higher Risk** Synthetic graphite production has significantly **higher environmental impacts**[41] than natural production, mainly related to the high-impact electricity supplies of the main production regions. Inner Mongolia, which makes up almost **half**[42] of Chinese production is especially **significant**[43] as it is dominated by coal. The calcination processes used to refine pitch and tar emit volatile compounds and sulphur oxides. If scrubbers are not installed, this can significantly increase acid rain-related environmental risks. Production requires very high temperatures of up to 2,500°C, but some processes have been developed that reduce the environmental risks associated with synthetic graphite production, including **closed-furnace**[44] and partially-renewable production, or bio-based sources such as NZ's **CarbonScape**[45] which are claimed to be carbon-negative. As synthetic graphite is projected to increase as a proportion of supply over time (reaching **80% of the market**[30] by 2040, according to the IEA) these challenges will only intensify.

	Cobalt	**Medium Risk** Cobalt is primarily produced as a byproduct[46] of copper (55% of production) or nickel (25%) mining. This market has traditionally been dominated by the Democratic Republic of the Congo (DRC) but Indonesia is emerging[47] as a significant player alongside its nickel expansion, rising to be the second-largest producer in 2023. Cobalt-copper mining occurs at both underground and open cast sites. For the latter, mining requires significant overburden and gangue extraction per unit of copper, making these types of open-cast mines especially impactful on local environments. Emerging Indonesian supplies are especially at-risk for rainforest deforestation, with one source assessing that 30% of habitat destruction since 2019 is directly attributable[48] to the nickel and cobalt industries. Additionally, the iron sulphide cobalt-bearing ores (such as those from copper mining) are especially at-risk for rock acid leaching, meaning that tailings and mine works need significant active controls to prevent water contamination, metal contamination and acidification, and failures here are likely to have negative consequences. Some orebodies also have contaminants in the tailings such as arsenic or uranium. Artisanal & small-scale mining (ASM) is especially significant[49] for the cobalt industry, which has come under intense criticism for the human rights, worker safety, and child labour abuses linked to the practice. It's a complex[50] ethical issue, with variable participation rates that have historically been aligned with price fluctuations. The international price spike of cobalt in 2022 increased the role of the sector, but recent suppressed prices due to the LFP boom, along with global output increases, have decreased the rate of ASM cobalt mining. The IEA projects this to be only 2% of total demand in 2023, although total volumes are expected to increase over time, even if rates do not.	**Medium Risk** Cobalt is generally produced as a byproduct of other metal production, meaning that recovery occurs after concentration of copper or nickel in a combined stream. The specific processing steps are dependent[51] on the geo-metallurgy of different ores, with 6 different process flow types, following two main categories: Hydrometallurgical processes can include steps such as acid leaching (high-pressure acid leaching (HPAL) or heap leaching), sulphate roasting, and organic solvent extraction. Laterite ores that have nickel coproducts are focussed on this route, which is 2-5 times more[51] energy-intensive than hydro processing of copper ores. Pyrometallurgical processes are used for some sulphidic ores (including copper and some nickel sulphides) and include roasting and smelting in an electric arc furnace, or in a flash furnace using coal. This process removes iron and sulphur from the matte and require significant flue-gas scrubbing to prevent SOx emissions to air. Some smelters built in the 1950s are still in use in the DRC, due to their age, these facilities likely have significantly higher direct emissions from roasting and smelting than more modern facilities, especially from other jurisdictions.

	Rare Earths: (including praseodymium, neodymium, terbium & dysprosium)	**Medium Risk** Rare earth elements generally occur in in mixed orebody deposits – light rare earth elements (LREEs) such as neodymium and praseodymium often occur together, and heavy rare earths (HREEs) such as terbium or dysprosium are generally separate. China, Myanmar, the US, and Australia are the dominant mining countries, with very different ore types. China has the largest, rare earth mine, the Bayan Obo complex in Inner Mongolia. This is a bastnaesite/monazite-based orebody in sedimentary rock. Myanmar deposits are ionic adsorption clay (IAC) based, with lower ore quality, but are easier to mine, and produce fewer radioactive byproducts. These clays are much softer, do not require crushing, and therefore use less energy to beneficiate than rock-based ores. After mineral extraction, the clays are generally inert and can be used as backfill, with tailings dams or dry stacking not required. IAC-based supplies are a growing segment of the market, but China still has a significant role in its extraction. Hard rock beneficiation generates concentrations of radioactive elements such as thorium and uranium that need careful handling and long-term tailings management. However, only a small **number**[52] of REE mining companies align with international standards on tailings management.	**Higher Risk** Hard rock REE sources need high-temperature ore roasting and acid leaching to extract the metals. IACs can be heap-leached, at a much-reduced energy requirement, although at an increased risk of acid leakage. Significant radioactive thorium **contamination**[53] has been detected around the Bayan Obo mine and refineries in Baotou City, especially within the refinery tailings dam. Radioactivity levels were 35x higher in the dam than in the surrounding region, and 1.3x higher in the surrounding region than neighbouring districts. Heavy mineral sands are an emerging REE supply, often focussing on existing monazite-containing tailings that have already been concentrated. Australia is **investing**[54] in concentration plants and refineries to produce rare earth oxides onshore from these stockpiled resources, although current supply chains are based on domestic concentration, with refining conducted in **Malaysia**[55]. Australian-mined hard-rock resources are **lower-emissions**[56] than equivalent Chinese supplies, despite the lower grades of REE ores, due to the high-emissions electricity used in China. The IEA (2021) shows that water usage per kg of REE is almost as high as lithium extraction and refining, which is especially among the highest intensity of the critical minerals assessed.

Tier 2	**Silicon**	**Lower Risk** Silicon for electronics and PV usage is produced from high-purity silica quartz. Raw material supplies are relatively dispersed globally, although Chinese **supplies**[57] are lesser grade, meaning production here uses a mix of domestic product that requires more processing, and imported product. Most of the emissions and associated environmental risks within the high-purity silicon supply chain come from refining, but there are significant **risks**[57] within the silica supply chain regarding illegal mining, including potential supplies from Cambodia or North Korea. Illegal mines are much less likely to conform to environmental standards, which is especially significant for tailings from gravity, flotation, and magnetic separation techniques.	**Higher Risk** Refining silicon dioxide/silica sand to ultra-high purity silicon wafers is extremely electricity intensive and involves **multiple**[58] steps. Metallurgical grade silicon is smelted in a furnace with coal to produce Si and CO_2. This is then refined further into polysilicon using HCl, H_2, and extremely high temperatures in electric furnaces over several days. Finally, this polysilicon is melted to grow a single monocrystal ingot to be sliced and used for wafers. High electricity usage in this sector is dominated by coal-fired plants, **primarily**[59] in the Xinjiang region of China. All major polysilicon factories in this region are either **collocated**[60] with, or within 2km of coal-fired power plants. This results in **significant**[61] upstream environmental impacts, including air pollution from fine particulates, NOx and SOx, as well as local impacts from open-pit coal mining and tailings from electricity generation. High volumes of water are also used for coal ash and smelter tailings disposal, which is important in an arid climate such as Xinjiang where water supplies are already stretched. Labour and human rights are also a significant issue in this region.

	Nickel	**Medium Risk** Indonesia is both the largest and fastest growing supplier of nickel in the world, with laterite deposits being the focus for development. This is significant, as current sulphide-based resources used for battery-grade nickel are usually extracted using underground mining, whereas laterite deposits are open-cast. This means a larger physical footprint of mine works in regions that have significant rainforest cover, and that biodiversity impacts of this extraction may be larger than other mining types. One source assessed that 30% of the rainforest deforestation in Indonesia since 2019 is directly **attributable**[48] to the nickel and cobalt industries. They also demonstrated mining within 100 metres of the ocean, and other environmental impacts including runoff.	**Medium Risk** Laterite deposits have historically only been used for lower-grade nickel products used in stainless steel production, rather than high-purity nickel for battery cathodes, but these resources can be processed to upgrade their overall quality. The HPAL (high pressure acid leaching) route is projected to make up most of this increased supply, rather than the traditional coal-fired rotary kiln and electric furnace (RKEF) processing route, as it is cheaper to operate. HPAL projects require the storage of significant volumes of fine-grained tailings from processing waste, which are especially **challenging**[62] to handle in steep, high-rainfall, seismically active and soft-soil environments. As well as increasing geotechnical risks, these factors make tailing storage much riskier from a leaching perspective. Earlier projects, including large smelters, had discharged tailings into the ocean, but this process has been **banned**[63] since 2021. Recent projects have addressed some earlier concerns (IEA 2021) that the increased capital requirements of new HPAL facilities, and historic patterns of cost overruns could slow supply growth.

	Copper	**Medium Risk** Copper production is among the highest-pressure resources on biodiversity impacts when using the MiBiD impact category (IEA, 2021) due to low-grade ores requiring significant open-cast mine footprints. Copper ore quality has been declining steadily over the last few decades, with the current rock-to-metal ratio sitting above 500:1, including overburden. The total volume of rock moved for copper extraction is second only to iron production annually, at 9.4 billion tonnes per annum. The low ore grades require significant beneficiation to remove gangue and make it economic to transport ore. This is primarily done through flotation for higher-quality ores. Concentrates are then sent to refineries for smelting. Especially low-grade ores are treated in a process called **heap leaching**[64] where crushed rock is laid on a pad and is sprayed with a sulfuric acid solution over a period of months to years, depending on the mineralogy, achieving yields of 70-90%. These pads can reach 20m thick and $1km^2$ in size. Acidic leakage from HDPE-sealed leach pads has been **assessed**[65] at 500 litres per ha per day at a 50% probability, and a 98% probability the volumes are less than 1000 litres/ha/day.	**Medium Risk** Copper refining results in significant volumes of sulphidic tailings that are especially susceptible to acid rock leaching. This can mobilise contaminants such as heavy metals including arsenic into the environment, if ponds and tailings piles are not treated effectively. Copper **tailings**[66] make up 46% of all tailings volumes produced globally, more than twice the next most significant metal, gold (21%). The ETC note that copper production has disproportionately high human toxicity and ecotoxicity impacts when considering both tailings impacts, and the high sulphur emissions from smelting. Copper is generally produced pyrometallurgically, with **different**[67] specific processes used at different smelters. Some require ore roasting, others use electric arc furnaces or electrowinning, and others require an additional 'conversion' stage to remove sulphur impurities. This requires significant flue-gas scrubbing to prevent SOx emissions to air. The lowest-emissions process is currently an emerging technology that smelts directly to metallic blister copper, although it still requires coal.

NZ Minerals Strategy	NZ Lithium	Lower Risk	Lower Risk
		The exploration of local lithium resources has been concentrated on geothermal brine extraction, in conjunction with other brine processing techniques. Geo40 is the most notable company looking at this. These processes are markedly different to standard brine extraction – they do not require large settling or evaporation ponds but use Direct Lithium Extraction (DLE) and sorbents to rapidly **concentrate**[68] lithium from the brine. A key enabling step for this is the extraction of colloidal silica from the geothermal brine – this was the original target for Geo40, as silica can build up in the reinjection wells, reducing efficiency and requiring wells to be replaced more regularly. Silica removal is also required for CO_2 reinjection. This form of lithium extraction is unlikely to have significant environmental risks compared to either spodumene mining, or traditional brine extraction, however volumes of lithium extracted locally are not likely to be significant.	As of 2024, Geo40's lithium brine extraction from geothermal fluid is in the pilot stage of development and requires silica removal to occur first. This technology is more mature and is already operating at scale at multiple NZ geothermal power stations. For the lithium refining process more generally, we suggest silica and lithium are coproducts of a similar refining process and will discuss both methods here. Detailed information on the lithium refining process is not available, so it is challenging to obtain specific risks of its implementation. Geo40's silica removal technology **requires**[69] reverse osmosis filtration at pressures up to 10 bar, with acidified geothermal fluid. Significant electricity usage, as well as dispersant and anti-scalant chemicals are used in conjunction with these acids to process a large volume of effluent from geothermal power stations. Once silica has been removed, lithium extraction can occur. This requires a hydrogen manganese oxide **sorbent**[70] which is then separated from the lithium-depleted solution. Acids then strip the lithium from the sorbent, with bases used to refine the lithium liquor. The sorbent is regenerated in a furnace at high temperature over several hours to then be recycled. The lithium can then be separated from the enriched brine with evaporation or reverse osmosis filtration techniques.

	NZ Phosphorous	Higher Risk	Medium Risk
		The local phosphate resource identified in the **Draft Minerals Strategy**[10] is on the Chatham Rise, a seabed-based nodule deposit between mainland NZ and the Chatham Islands. Chatham Rock Phosphate (CRP) has long proposed the exploitation of this resource, with consents **lodged**[71] in 2014. Over a 35-year period, CRP sought consent to mine over 1,000km^2 of seabed, at depths of 250-450m. This mining process involves a drag-head and suction pump to extract phosphorite nodules and sediment gangue, beneficiation on board the mining vessel, then a sediment discharge pipe diffusing the waste 10m above the seabed. This consent was not approved, with the EPA noting "significant and permanent benthic effects" including wider environmental impacts on the trophic food web and pelagic animals. They also found that sediment deposition would have 'destructive effects' on the marine environment, including on areas adjacent to mining blocks, that could not be mitigated. Phosphate seabed mining has been **proposed**[72] in Namibia, with consent approvals postponed while a moratorium has been put in place. Environmental risks are many and include sediment plumes, increased turbidity issues, large-scale permanent habitat loss, significant disruptions to the carbon pump that may release significant CO_2 emissions, and disruptions to nutrient balances and the nitrogen cycle.	CRP has positioned the phosphate resource as being **aimed**[73] at the fertiliser industry, and not for use in energy transition technologies such as LFP batteries. It is theoretically possible that these nodules could be refined into high-purity phosphoric acid for use in LDP batteries, with facilities being built in **Morocco**[74] and **Australia**[75]. Both facilities use the Turner process, which is significantly more energy-intensive than wet processing and requires fossil fuels such as coal for process heat. The Turner process also produces large volumes of gypsum-based waste product that would need handling. If New Zealand were to set these phosphate resources aside for use in the energy transition, we would be competing against raw materials extracted cheaply from land-based sedimentary resources, and refined close to market in large facilities, often co-owned by battery manufacturers to reduce costs.

	NZ Titanium	**Higher Risk** New Zealand's titanium resources mainly occur as a heavy mineral sand component, with ilmenite ($FeTiO_3$) iron sand deposits being especially significant. Titanomagnetite deposits used for steelmaking are extracted from West Coast beaches near Auckland, with titanium making a significant proportion of the waste slag materials. This is not currently economic to extract, however. Other heavy mineral sands are already commercially extracted[76] from ancient sand dunes on the West Coast and exported as mixed concentrates. This extraction occurs as an open-pit mine close[77] to the Blind River and Silverstream wetland, with mitigations in place to help minimise environmental impacts on these sensitive areas. The site is identified as being close to at-risk and threatened bird species such as the kororā (little blue penguin) and the fairy prion, with specific management plans in place to reduce risks. They are, however, not zero-risk. Further consent requirements relate to limiting extraction to above groundwater level, testing concentrates for radioactivity, and testing wastewater discharge for heavy metal contamination. Titanomagnetite iron sands are being explored for extraction using seabed mining, with significant environmental risks, similar to the phosphorous risk as discussed above. Currently extracted non-seabed sources will likely reduce the overall risk rating, but a conservative approach has been used here.	**Medium Risk** New Zealand does not currently produce titanium in any meaningful quantity. Avertana has been exploring ways to refine[78] steelmaking slag into titanium dioxide (TiO_2) pigments, but this form of titanium is not commonly used within the energy transition. Furthermore, NZ Steel production is moving away from iron sands-based feedstock by introducing a recycled steel stream in 2027. This electric arc furnace will reduce[79] the slag available for any repurposing by half. Common TiO_2 processing methods include smelting in coal-powered furnaces, with metal being further processed from this intermediate product. Titanium metal and its related alloys are mostly used in the aerospace industry, although there may be a role in the emerging hydrogen economy. This use case is outside the scope of this report. Pure titanium metal for use in alloys is a very small part of the global market, with the most common production process being Kroll process. This uses magnesium as a reactant to form a 'sponge' at very high temperatures using coal and chlorine. This is then cast into ingots, with the magnesium salts reprocessed to be reused. Significant environmental impacts relating to the electricity usage of this refining process have been identified[80], especially given the dominance of China as a producer.

	NZ Vanadium	**Higher Risk** Like other focus metals, NZ vanadium resources occur mainly as a component of mineral sands, specifically, titanomagnetite resources currently extracted at North Head in the Waikato. Trans-Tasman Resources has previously sought consent to extract vanadium-rich iron sand using a seabed mining technique off the coast of the Taranaki Bight, with **consents**[81] initially granted, then appealed in the Court of Appeal, High and Supreme Courts. A key factor was that the harm caused by sediment discharge would be material, that it was polluting, and **environmental harm**[82] could not be prevented through the provision of regulation or conditions. The environmental impacts of this seabed mining are very similar to those discussed above in the phosphorous section. The high-risk rating is based on this extraction methodology, with terrestrial mineral sand deposits representing lower-risk resources.	**Medium Risk** Vanadium production in New Zealand occurs as a byproduct of the steel industry, where vanadium-bearing slag is tapped from the steel production process. This is then sold as an **intermediate**[83] product for use overseas; it is not refined further locally. As NZ Steel transitions away from iron sand-based feedstock, this will significantly reduce the vanadium slag byproducts available for export. Current international vanadium production occurs in a similar way to local production, where **steelmaking**[84] is used to separate iron from titanium and vanadium slags, and further ore roasting, leaching, and precipitation steps are used to refine the vanadium pentoxide product in a hydrometallurgical process. Specific environmental risks for local production are relatively low, given the well-established facility in Glenbrook. However, vanadium as-produced locally is not fully refined. A whole-of-supply-chain process so that local supplies could be used directly (such as in a vanadium flow redox battery) would introduce additional environmental risks due to the added hydrometallurgical processing required.

	NZ Rare Earth Elements	**Lower Risk** Rare earth elements (REEs) have been identified as a minor component of Heavy Mineral Sands (HMS) deposits, most notably in Barrytown[85] on the West Coast. These are very low concentration, with ilmenite (for use in titanium production) and garnet (an industrial abrasive) being the primary resources for extraction. Estimates of the natural concentration of rare-earth bearing monazite are around[85] 0.1-0.2%. As a comparison, ilmenite ($FeTiO_3$), the primary resource extracted from these deposits, makes up 14% of the raw ore. A further comparison is with commercial REE extraction in Bayan Obo in China, where the concentration[53] is between 4-6% RE_2O_3. We suggest that given these low concentrations, New Zealand REE resources are unlikely to play a significant role in supporting the local or global energy transition. As discussed as part of the titanium mining section above, these HMS-based resources likely have lower environmental impacts relating to extraction compared to alternative supplies. For the REE supply chain, these would include hard-rock deposits, as well as ionic adsorption clay supplies, such as those in Myanmar.	**Higher Risk** Much of the environmental impacts associated with REE production occur in the refining stage, rather than the extraction stage. Reuters suggests[55] this has been exploited by China to incentivise mining developments, offshore while it consolidates refining domestically, where it makes up 92%[86] of current refined output.
	NZ Antimony	**Medium Risk** As of 2024, NZ does not currently mine or export antimony, however a large stibnite (Sb_2S_3) deposit has been identified[87] on the West Coast near Reefton. Historic antimony contamination has been identified[88] from old mine and smelter sites, highlighting the risks that Sb can be dissolved and transported into soils kilometres away, if not handled appropriately. Siren Gold[89], who have identified the large deposit, have a concept design for a plant in Reefton based on an existing facility in Victoria. It produces gold-rich gravity concentrate stream, and a gold-antimony concentrate using flotation separation. They do not propose local antimony refining.	**Medium Risk** Antimony refining usually involves roasting the sulphidic stibnite ore and converting it to an oxide, which is then reduced in a blast furnace to metallic antimony. These processes[90] involve the use of coal-fired smelters, and roasting releases significant SOx emissions that can have negative acidification impacts. Chinese smelters have been repeatedly closed in the last 10 years because of lax compliance with environmental standards. Byproducts[91] from the resulting arsenic-alkali smelting slag can include[92] lead, arsenic, and zinc.

8 Key Insights

The primary insights that result from this analysis can be grouped into the three core dynamics of the energy transition, as identified in **Section 3: Background**.

8.1 Ever-present: Resource Use is Driven by Innovation

The technologies that use the resources that have been modelled are changing rapidly, and increased production can have its own impact on overall demand. Manufacturers get better at producing components, designing out expensive or risky materials and making their products cheaper. This in turn drives further demand growth, and further improvements to efficiency. Growth can disrupt supply chains for some materials, and others may not be impacted so significantly. Our analysis has identified materials in both these camps.

- Tier 1 materials outgrow structural metals: The largest increases in demand in the Net-Zero scenario is for tier 1 metals and minerals, with a **53 times** increase in annual requirements between 2020 and 2050. As shown in **Section 7.1**, these increases flatten off due to EVs saturating the vehicle market through the 2030s. Meanwhile, by mass, tier 2 and 3 materials like aluminium and iron, make up most of the overall materials requirements on a mass basis, while growing at a much smaller pace than tier 1 materials. Given the increase in demand for tier 1 materials from New Zealand will be mirrored in the global economy and the environmental risks associated with them, tier 1 materials represent the main risk to New Zealand's energy transition.
- Demand for critical materials is dominated by the transport sector: As discussed in **Section 7.1**, the vehicles sector accounts for **99.8%**, **82.3%**, and **80.8%** of tier 1, 2 and 3 material requirements respectively in the Net-Zero pathway. Tier 1 material demand is almost entirely driven by EV batteries, especially by the graphite used in lithium-ion battery anodes. The reference pathway has far greater annual fleet additions, causing the overall materials requirements to be larger than the demonstration pathway – while building lower amounts of renewable energy generation.
- Material tiers are relevant to different aspects of the energy transition: Proportional mass breakdowns show that tier 1 materials are mostly used in batteries and for producing magnets. Graphite used in battery anodes dominate this tier. Tier 2 includes a large component of aluminium used in structural requirements across RETs, but also includes metals used in alloying structural elements, and metals used in RETs like batteries, and solar PV generation like phosphorus and silicon. Tier 3 is almost entirely iron, which is the most used material in the energy transition for different steel alloys, forming the structural balance of all RETs to some degree.

Scenario analysis suggests that more aggressive decarbonisation can also have a smaller materials footprint: The most ambitious transition scenario developed by the CCC is driven by both technological and policy changes. Technological developments that drive faster adoption can achieve this in a self-reinforcing cycle by using less critical materials for the same function. This means that the mechanisms to achieve faster rollouts may also reduce overall demand for critical metals and minerals, replacing them with low-risk materials, or dematerialising more generally. The ambitious scenario also shows that policy changes to reduce the vehicle fleet size can make a significant difference to metal demand.

8.2 Current paradigm: Physical Constraints, Supply Chains and Risk

Current-state fossil resources need to be continually extracted to maintain energy security, whereas the new energy paradigm extracts minerals to meet the needs of growth and change on a one-off basis. As an example, resources used to produce solar panels or wind turbines will remain in those assets across their lifespan, generating energy with minimal additional inputs. Fossil resources extracted for energy use are consumed immediately, meaning that continual extraction is needed for a consistent energy supply. Another difference is that the supply chains associated with these new resources are different to the current state; they involve different countries, manufacturers, processes, and environmental risks.

- **Global supply chains identified across materials share common environmental risks**: two significant stages in the supply chains for critical metals and materials are the mining & beneficiation processes, and the refining & smelting processes. Although different materials have their own distinct supply chains, the analysis of environmental risks highlighted common themes.
  - **Mining and Beneficiation**
    - Direct Environmental Effects

Ore grades are declining for many materials globally, requiring more rock extraction per tonne of metal, and larger mines.

Mine expansion into rainforest areas has a significant impact on biodiversity – Indonesia's growing nickel industry is a significant example.

- Water Use Impacts

  Lithium brine extraction in arid areas of South America lowers the water table, introducing salt into freshwater aquifers.

  Hydrometallurgical processing and beneficiation can use significant volumes of water, with some supply chains concentrated in areas with high water stress.

- Pollution Impacts from Tailings Storage and Mine Sites

  Acid rock drainage is a challenge, especially for sulfidic ores and materials processed using acid leaching. This can mobilise heavy metals or acidify surrounding areas if not contained with resilient and well-maintained infrastructure over long periods of time.

– **Refining and Smelting**

- Direct Environmental Effects

  Refining and smelting processes often use coal-fired ore roasters or coking coal. These emit significant carbon emissions, among other pollutants.

  Sulfidic ores and acid-leached concentrates emit significant levels of SOx emissions when smelted, which require scrubbing and active environmental controls.

- Indirect Environmental Impacts

  If not powered directly by coal, many electrified furnaces and refining processes use significant quantities of electricity. For China especially, these grids are often powered by coal.

- **Resources identified in the Draft NZ Minerals Strategy play a relatively minor role in the local energy transition**: When considering all the assessed materials required for the energy transition to 2050 resources identified in the Draft NZ Minerals Strategy play a minor role on a mass basis. When considering the demonstration scenario, they make up **1.4%** of total demand in 2050. As with other scenarios, structural metals do dominate the assessment on a mass basis.

  Although NZ does produce steel and aluminium, they are not included in the Draft NZ Minerals Strategy. When we remove these structural materials from the calculation, there is a relatively minor contribution from NZ Minerals Strategy-identified minerals at **12.6%** of total demand in 2050. Out of the materials identified, phosphorus, lithium, and REEs are the most significant materials on a mass basis and are mainly used in EV batteries and motors.

- **Resources identified in the Draft NZ Minerals Strategy have varying environmental risk profiles, aligned with different extraction techniques**: Four primary resource extraction techniques have been identified from a review of the Draft NZ Minerals Strategy and the materials assessed have correspondingly different environmental risk profiles.

Land-based Mineral Sands

– Titanomagnetite deposits are currently mined at North Head in the Waikato and Heavy Mineral Sands mined on the West Coast.

– Beneficiation is generally low-impact, using magnetic, gravity-based or flotation methods, with sand often replaced back on dunes.

– Concentrates exported at varying levels: REE levels from the Barrytown deposit are 25x lower than Australian or Chinese deposits; they are essentially a minor byproduct.

Future Seabed Mining

– Seabed mining has highly uncertain environmental impacts, primarily related to local effects on the seabed itself.

– The NZ Supreme Court has blocked a mining consent on environmental grounds, and a moratorium on phosphate seabed mining is also in place in Namibia.

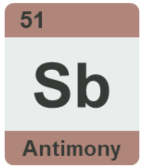
- Phosphorous resources investigated on the Chatham Rise are not pure enough for battery use without significant and environmentally intensive refining processes, and this has not been proposed for local production as of 2024.

Geothermal Brine Extraction

- Potential NZ lithium supplies are focussed on direct lithium extraction from waste geothermal brine using sorbents.
- Large-scale local production is less likely than expanding the brine extraction technology offshore and utilising it in higher-concentration deposits.
- The energy demand for this process is unclear, but likely lower risk than the significant fossil energy demand for the spodumene rock route, or the water consumption from traditional salar brine extraction.

Underground Rock Mining

- A large stibnite deposit has been identified near Reefton, where antimony will likely be a coproduct of gold mining.
- Underground extraction is proposed, with a flotation-based ore concentration process. Tailings can include other heavy metals and require active management.



8.3 Emerging Dynamic: Circular Economy

Technological change isn't the only way to reduce resource demand. Critical mineral and metal resources are often used as stocks within technological systems rather than flows, as they can be recaptured and processed at the end of life. Asset lifetimes can be expanded, and materials can be repurposed, reducing or even removing the need for continual extraction of these minerals and metals.

- **The circular economy will become especially important through the late 2030s**: Material recovery and reuse can play a role in reducing virgin material demand during the latter stages of the energy transition.

  NZ has time to scale the infrastructure to recover or process these resources, as the volume of Tier 1 and 2 materials reaching end-of-life is less significant through the early 2030s. Tier 2 materials have a much sharper spike in demand due to the fixed asset lifespans assumed in the analysis, and the 2020 baseline year. Due to assets developed prior to 2020, there will be a more gradual increase in available materials for secondary usage, but this is outside the scope of this study. We have not modelled specific end-of-life pathways for materials and technologies, just the mass of materials in products and infrastructure reaching this stage – this would be a key addition to further the development of this driver.

9 Conclusions

The energy transition is a multi-faceted problem that incorporates shifting patterns of environmental impacts, geopolitical risks, international trade, economic growth, recycling, and consumer habits.

Materials Footprint of the Energy Transition

The energy transition requires an increased buildout of renewable electricity generation, and electrification of the vehicle fleet. By mass, iron and aluminium account for most of this, however the rate of increase is relatively small compared to the over **5000%** increase in annual demand projected for Tier 1 materials. The estimates have shown that technological developments across these technologies seek to replace the requirements for these critical materials with more readily available alternatives. Through innovation, the requirement for critical materials is reduced, even when significantly increasing the buildout of renewable energy systems.

Transport as the Driver of the Energy Transition

Through the analysis, vehicles have been identified as the leading contributor to the overall mass of materials that are required as part of the energy transition. In addition to this, vehicle electrification itself is a driver of the increased capacity in electrical generation, so a reduction here would have a compounding effect on the requirements for technologies like solar PV and wind generation.

Environmental Trade-offs

While installing renewable energy generation and electrifying NZ's vehicle fleet are ultimately positive for NZ's climate goals, and for the global response to climate change, the immediate compromises of mineral extraction and refining must be made. The environmental risk summary describes how these materials are mined and processed to a point where they can be manufactured into these finished goods, and what toll they take on the environment.

Waste Streams of Critical Materials

Assets considered here have a defined useable lifespan, (typically 10-30 years), and even after maintenance and re-commissioning, these assets reach their end of life. These assets that have reached their end of life are no longer producing the output required of them, but still contain the critical materials that required harvesting to make them. As these materials are non-renewable, and often in short supply, it is important that the materials can be extracted from the waste stream and re-used to produce similar assets. While there is a general difficulty in extracting specific elements from alloys and compounds, there should be a focus on the design of technologies to be disassembled. Similarly, there must be infrastructure in place to efficiently deconstruct finished goods into their consistent materials, or at least into complete subsystems that can be directly re-manufactured into new goods.

9.1 Potential Next Steps

- **Supply chain risk deep dive**: This exercise has identified the materials required for NZ to achieve its energy transition under different decarbonisation scenarios. While it has touched on environmental risks associated with these materials, there are a range of broader cultural, geopolitical and economic risks associated with meeting these targets. It's recommended a future piece of work looks at these broader risks.
- **Circular economy barriers and opportunities**: This report has touched on waste stream quantities and estimates when these will reach significant levels. In line with analysis, there is an opportunity to reduce future materials requirements, and reduce environmental and other risks through circular economies – as well as support economic development. It's recommended that this is investigated further in the future to bridge the gap between these research exercises and real-world action.
- **Future domestic manufacturing**: The background in this report outlines the economic benefits of being vertically integrated in the manufacturing of RETs. The extraction and beneficiation, regardless of if NZ can contribute to this, is not a significant contributor to economic gain. If NZ could be integrated across the supply chain, it's worth exploring a future where NZ is not as import dependent on RETs, reducing supply chain risks. It's recommended an economic cost-benefit analysis and feasibility study around this is completed.

10 Appendix

10.1 Material Tiers

Tier 1 Critical Minerals

3	6	27	78
Li	C	Co	Pt
Lithium	Graphite	Cobalt	Platinum

59	60	65	66
Pr	Nd	Tb	Dy
Praseodymium	Neodymium	Terbium	Dysprosium

Rare Earth Elements (REEs)

Tier 2 Critical Minerals

12	13	14	15	22
Mg	Al	Si	P	Ti
Magnesium	Aluminium	Silicon	Phosphorous	Titanium

23	24	25	28	29
V	Cr	Mn	Ni	Cu
Vanadium	Chromium	Manganese	Nickel	Copper

Tier 3 Critical Minerals

5	25	30
B	Fe	Zn
Boron	Iron	Zinc

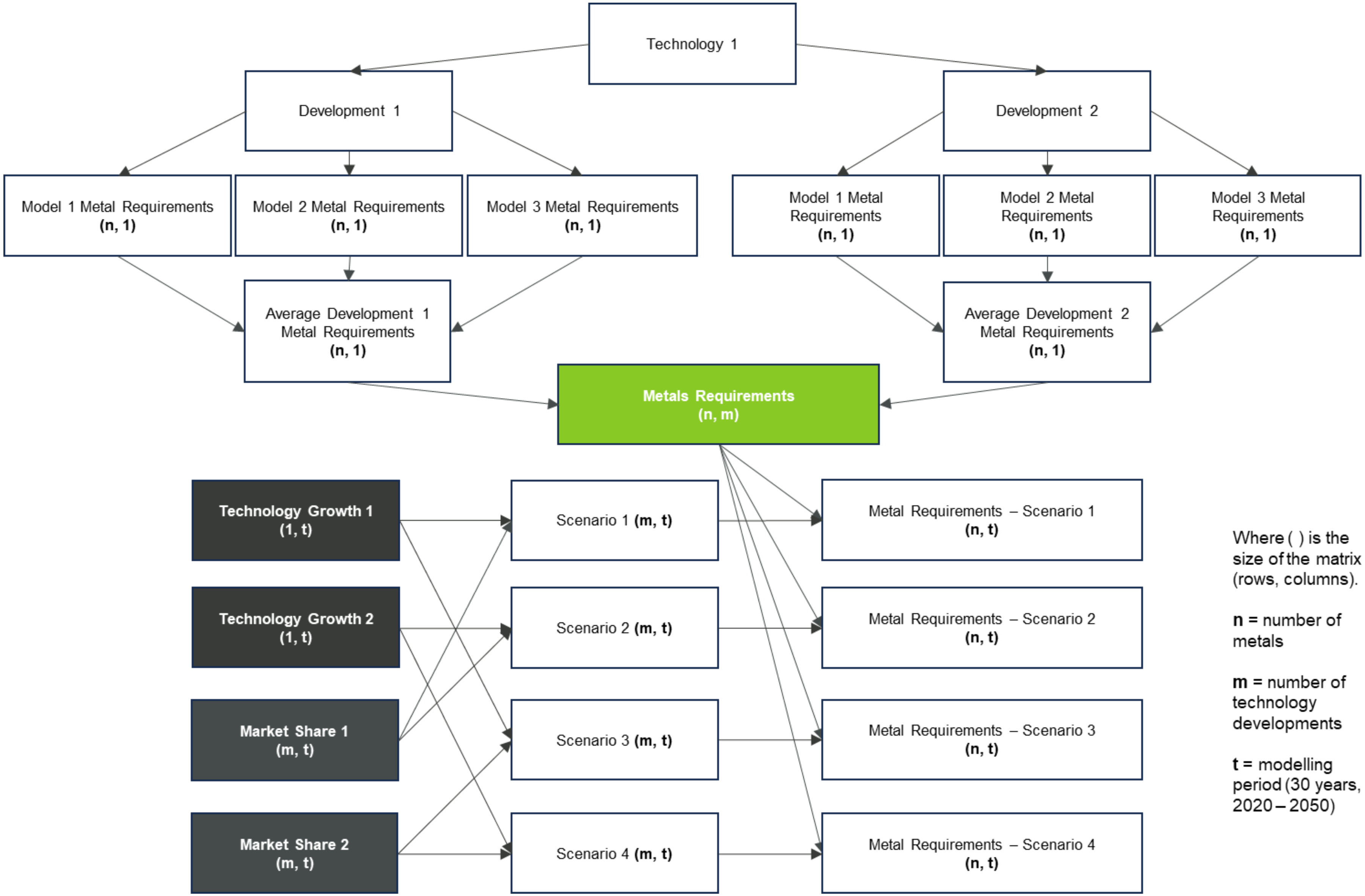
42	47	77
Mo	Ag	Ir
Molybdenum	Silver	Iridium

NZ Mineral Strategy

3	15	22
Li	P	Ti
Lithium	Phosphorous	Titanium

23	59–66
V	REE
Vanadium	Rare Earths

10.2 Model Methodology



Where ( ) is the size of the matrix (rows, columns).

n = number of metals

m = number of technology developments

t = modelling period (30 years, 2020 – 2050)

10.3 Model Sources

A list of the data sources used in this research exercise.

Source	Information Used
U.S Environmental Protection Agency (EPA) - National Renewable Energy Laboratory (NREL) - Renewable Energy Materials Properties Database (REMPD) - Aug-23	Materials requirements for solar PV electricity generation (non-panel requirements including electrics and structural elements) and wind generation (non-gearbox/generator components).
International Energy Agency (IEA) - Photovoltaic Power Systems Programme (PVPS) - Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems - Dec-20	Materials requirements across c-Si, CIGS, and CdTe PV modules (excluding auxiliary components).
"The resource demands of multi-terrawatt-scale perovskite tandem photovoltaics" - L. Wagner, J. Suo, B. Young, D. Bogachuk, E. Gervais, R. Pietzcker, A. Gassmann, J. C. Goldschmidt - Elsevier Joule - Apr-24	Materials requirements for PSC-PSC-tandem PV module – for sensitivity analysis.
"Evaluating metal constraints for photovoltaics: Perspectives from China's PV Development" - K. Ren, X. Tang, M. Hook - Elsevier Journal of Applied Energy - Nov-20	Projected future market share scenarios across c-Si and thin-film PV technologies.
He Pou a Rangi Climate Change Commission - Modelling and analysis to support the draft advice on Aotearoa New Zealand's fourth emissions budget - Apr-24	Overall technology growth scenarios across all technologies except battery energy storage systems.
"Comprehensive Review of Crysalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques" - P. Chen, W. Chen, C. Lee, J. Wu - MDPI Sustainability - Dec-23	Projected useable life of c-Si PV panels.
"Thin Film Solar Panels" American Solar Energy Society - Feb-21	Projected useable life of thin-film PV panels.
"Sustainability in Perovskite Solar Cells" - K. P. Goetz, A. D. Taylor, Y.J. Hoefstetter, Y. Vaynzof - ACS Journal of Applied Materials & Interfaces - Dec-20	Projected useable life of PSC PV panels. Value adjusted based on assumption that PSC panels will only become commercially viable when this life has reached a level comparable to existing technologies.
"Comparative life cycle assessment of electricity generation by different wind turbine types" - A. Schreiber, J. Marx, P. Zapp - Elsevier Journal of Cleaner Production – 2019	Materials requirements of DFIG, DDSG, and PMDDSG wind turbine generator developments.
"Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits" - J. Marx, A. Schreiber, R. Zapp, F. Walachowicz - ACS Journal of Sustainable Chemistry & Engineering - Jan-19	Neodymium magnet scaling factors used to scale materials requirements for PMSSDG to account for PMSG-MS/HS geared generator developments.
"Bridging energy and metal sustainability: Insights from China's wind power development up to 2050" - K. Ren, Z. Tang, P. Wang, J. Willerstrom, M. Hook - Elsevier Journal of Energy - Apr-21	Projected future market share scenarios for wind turbine technologies – for both onshore and offshore developments.

"Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK" - L. Zeigler, E. Gonzalez, T. Rubert, U. Smolka, J. J. Melero - Elsevier Journal of Renewable and Sustainable Energy Reviews - Sep-17	Projected useable life of onshore wind turbines.
"Future material requirements for global sustainable offshore wind energy development" - C. Li, J. M. Mogollonm A. Tukker, J. Dong, D. von Terzi, C. Zhang, B. Steubing - Elsevier Journal of Renewable and Sustainable Energy Reviews - May-22	Projected useable life of offshore wind turbines.
U.S Environmental Protection Agency (EPA) - Argonne National Laboratory - Greenhouse gases, Regulated Emissions, and Energy use in Technology (GREET) – 2023	Materials requirements of lithium-ion battery developments, and for vehicles.
"A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage" - R. Yudhistira, D. Khatiwada, F. Sanchez - Elsevier Journal of Cleaner Production - Apr-22	Materials requirements of lead-acid batteries for vehicles.
"Prospective life cycle assessment of sodium-ion batteries made from abundant elements" - S. Wickerts, R. Arvidsson, A. Nordelof, M. Svanstrom, P. Johansson - Wiley Journal of Industrial Ecology - Nov-23	Materials requirements of sodium-ion batteries.
"Environmental and Preliminary Cost Assessments of Redox Flow Batteries for Renewable Energy Storage" - C.M. Fernandez-Marchante, M. M. Jesus, I. Medina-Santos, J. Lobato - Wiley Journal of Energy Technology - Nov-20	Materials requirements of vanadium redox flow batteries.
"Production of Lithium-Ion Battery Cell Components, 2nd Edition, 2023" - RWTH Aachen University, VDMA - Dec-23	Materials requirements for active cathode/anode materials and electrolytes, and auxiliary components for lithium-ion battery developments.
Boston Consulting Group (BCG) - The Future is Electric – 2022	Overall technology growth scenarios for battery energy storage systems. Annual figures estimated based off summary figures.
"Life Prediction Model for Grid-Connected Li-ion Battery Energy Storage System" - K. Smith, A. Saxon, M. Keyser, B. Lundstrom - U.S EPA National Renewable Energy Laboratory (NREL) - May-17	Projected useable life of lithium-ion batteries.
"Sodium as a Green Substitute for Lithium in Batteries" M. Schirber - American Physical Society - Apr-24	Projected useable life of sodium-ion batteries.
"All-iron redox flow battery in flow-through and flow-over set-ups: the critical of cell configuration" - J. J. Bailey, M. Pahlevaninezhad, H. Q. N. Gunaratne, H. O'Connor, K. Thompson, P. Sharda, P. Kavanagh, O. M. Istrate, S. Glover, P. A. A. Klusener, E. P. L. Roberts, P. Nockermann - Royal Society of Chemistry Journal of Energy Advances - Mar-24	Projected useable life of vanadium redox flow batteries.
"Cradle-to-gate life cycle assessment of all-solid-state lithium-ion batteries for sustainable design and manufacturing" - J. Zhang, X. Ke, Y. Gu, F. Wang, D. Zheng, K. Shen, C. Yuan - Springer International Journal of Life Cycle Assessment - Jan-22	Materials requirements of solid-state lithium-ion batteries.
"Estimating the environmental impacts of global lithium-ion supply chain: A temporal, geographical, and technological perspective" - J. A. Llamas-Orozco, F. Meng, G. S. Walker, A. F. N. Abdul-Manan, H. L. MacLean, I. D. Posen, J. McKechnie - PNAS Nexus - Nov-23	Projected future market share for lithium, and post-lithium-ion batteries.

"Future material demand for automotive lithium-based batteries" - C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker, B. Steubing" - Nature Communications Materials - Dec-20	Projected future market share for lithium-ion batteries, focussing on LFP growth.
Te Manatu Waka Ministry of Transport - Vehicle Fleet Emissions Model (VFEM) - Jun-22	Projected future market share for vehicles in NZ, including electrification rates, and annual flows of vehicles into the country.
Massey University - Environmental Health Indicators NZ – 2023	Projected useable life of an average vehicle in NZ.
Nexans New Zealand Cable Datasheets	Materials requirements of distribution and transmission cabling.
"Sustainability in Transformers: Towards a Low Carbon Power Grid" - B. Das, G. Barrientos (Hitachi Energy) - EEA Conference & Exhibition 2023, 27-29 June, Christchurch	Materials requirements of power transformers.
Orion Asset Management Plan 2024	Projected overall spend on electricity distribution infrastructure.
Vector Asset Management Plan 2024	Projected ratio of spend across different categories of distribution infrastructure.
Transpower Asset Management Plan 2023	Projected spend on different categories of transmission infrastructure.
"Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland" - M. R. Karlsdottir, O. P. Palsson, H. Palsson, L. Maya-Drysdale - International Journal of Life Cycle Assessment - Dec-14	Materials requirements of double-flash geothermal generation unit.
"Life Cycle Based Environmental Impacts of Future New Zealand Electricity Supply" - L. Bullen, Massey University, 2020	Geothermal unit scaling factors for NZ installations.
"Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization" - M. R. Karlsdottir, J. Heinonen, H. Palsson, O. P. Palsson - Elsevier Journal of Geothermics - Nov-19	Projected useable life of geothermal generation units.
"Life Cycle Assessment of a Gas Turbine Installation" - Y. Mozzhegorova, G. Illinykh, V. Korotaev	Materials requirements of OCGT unit.
"Combined Cycle Gas Turbines Power Stations in England: A Historical Overview" - W. D. Cocroft - Discrovery, Innovation, and Science in the Historic Environment – 2021	Projected useable life of OCGT units.

10.4 Report Sources

A list of the in-line references used throughout this report in the order they are mentioned.

- [1]**Ministry for the Environment (MfE)** – NZ Nationally Determined Contribution https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/nationally-determined-contribution/
- [2]**MfE** – Zero Carbon Act emissions reduction targets https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/greenhouse-gas-emissions-targets-and-reporting/#:~:text=Government%20Target%209,megatonnes%20from%202026%20to%202030.
- [3]**MfE** – NZ GHG emissions inventory https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-19902022-snapshot/
- [4]**United States Geological Survey (USGS)** – US Critical Minerals List https://pubs.usgs.gov/circ/c1050/ww1.htm
- [5]**Rocky Mountain Institute (RMI)** - X-Change: Electricity report https://rmi.org/insight/x-change-electricity/
- [6]**RMI** – Cleantech Revolution Report https://rmi.org/wp-content/uploads/dlm_uploads/2024/07/RMI-Cleantech-Revolution-pdf-1.pdf
- [7]**NZ Herald** – "Mercury Energy to expand Kaiwera Downs wind farm after smelter deal" https://www.nzherald.co.nz/business/mercury-energy-to-expand-kaiwera-downs-wind-farm-after-smelter-deal/NVLJXYM2LRBQBJ5L5N7VAV2YHU/
- [8]**Ellen Macarthur Foundation** – Circular Economy principles https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview
- [9]**CSIRO** – Critical Minerals Roadmap https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/Critical-energy-minerals-roadmap
- [10]**Ministry for Business, Innovation & Employment (MBIE)** – NZ Draft Minerals Strategy https://www.mbie.govt.nz/dmsdocument/28387-a-draft-minerals-strategy-for-new-zealand-to-2040
- [11]**MBIE** – Electricity Demand and Generation Scenarios https://www.mbie.govt.nz/assets/electricity-demand-and-generation-scenarios-report-2024.pdf
- [12]**Climate Change Commission** – Emissions Budget 4 https://www.climatecommission.govt.nz/public/Uploads/EB4/supporting-docs/Technical-Annex-Modelling-and-analysis-9-4.pdf
- [13]**Transpower** – NZ current generation capacity https://www.transpower.co.nz/system-operator/live-system-and-market-data/consolidated-live-data
- [14]**Boston Consulting Group** – The Future is Electric report https://web-assets.bcg.com/b3/79/19665b7f40c8ba52d5b372cf7e6c/the-future-is-electric-full-report-october-2022.pdf
- [15]**Ministry of Transport** – Vehicle Fleet Emissions Model https://www.transport.govt.nz/assets/Uploads/Data/Transport-outlook-updated/Vehicle-Fleet-Emissions-Model-Documentation-20220608.pdf
- [16]**Massey Environmental Health Indicators** – Age of vehicles in NZ https://www.ehinz.ac.nz/assets/Factsheets/Released_2023/2023_Factsheet_AverageAgeMotorVehicles.pdf
- [17]**Transpower** – Transmission Planning Report https://static.transpower.co.nz/public/uncontrolled_docs/Transmission%20Planning%20Report%202023.pdf
- [18]**National Renewable Energy Laboratory** – REMPD database https://www.nrel.gov/wind/materials-database.html
- [19]**Argonne National Laboratory** – GREET database https://www.anl.gov/topic/greet
- [20]**International Energy Agency (IEA)** – World Energy Investment https://www.iea.org/reports/world-energy-investment-2024/china
- [21]**Australian Energy Market Operator** – Inputs, Assumptions, Methodologies https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-

assumptions-methodologies/2021/transmission-cost-database-phase-1-report.pdf?la=en

- [22]**PEGuru** – Transformer cost guide https://peguru.com/2019/08/power-transformer/#cost-of-transformer
- [23]**Massachusetts Institute of Technology** - Laser-mechanical drilling https://news.mit.edu/2022/quaise-energy-geothermal-0628
- [24]**IEA** – Technology Readiness Level https://www.iea.org/reports/innovation-gaps
- [25]**IEA** – Clean Technology Guide https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide
- [26]**Joule** - The resource demands of multi-terawatt-scale perovskite tandem photovoltaics https://www.sciencedirect.com/science/article/pii/S2542435124000527
- [27]**National Data Buoy Centre** - Offshore wind resources https://www.ndbc.noaa.gov/education/windspeed_ans.shtml
- [28]**Iberdrola** - Sodium-ion batteries: the revolution in renewable energy storage https://www.iberdrola.com/sustainability/environment/energy-efficiency/sodium-ion-batteries
- [29]**IEA, World Nuclear Association** – Mineral requirements for energy generation https://world-nuclear.org/information-library/energy-and-the-environment/mineral-requirements-for-electricity-generation
- [30]**IEA** – Critical Materials Outlook 2024 https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf
- [31]**Energy Transitions Commission** – Material and Resource Requirements of the Energy Transition https://www.energy-transitions.org/wp-content/uploads/2023/08/ETC-Materials-Report_highres-1.pdf
- [32]**IEA** – Critical Minerals Outlook 2021 https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
- [33]**Nature** – Environmental impact of direct lithium extraction from brines https://www.nature.com/articles/s43017-022-00387-5
- [34]**New York Times** – Australia Tries to Break Its Dependence on China for Lithium Mining https://www.nytimes.com/2023/05/23/business/australia-lithium-refining.html
- [35]**MDPI** – Lithium Production and Recovery Methods: Overview of Lithium Losses https://www.mdpi.com/2075-4701/13/7/1213
- [36]**Albemarle** – Spodumene Concentrate, SC 7.2 standard https://www.albemarle.com/global/en/product/spodumene-concentrate-sc-72-standard
- [37]**S&P Global** – Lithium prices diverge and defy expectations as new EV trends unfold https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/051921-lithium-carbonate-hydroxide-batteries-ev-policy-subsidies-china-eu
- [38]**Asbury Carbons** – Natural flake graphite https://www.asbury.com/resources/education/science-of-graphite/natural-flake-graphite/
- [39]**Journal of Materials Research and Technology** – High efficiency purification of natural flake graphite by flotation combined with alkali-melting acid leaching: application in energy storage https://www.sciencedirect.com/science/article/pii/S2238785422017069
- [40]**Environmental Science & Technology** – Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9979652/
- [41]**Minviro** – Climate Impact of Graphite Production https://www.minviro.com/resources/guides/climate-impact-graphite-production
- [42]**Wired** – The Surprising Climate Cost of the Humblest Battery Material https://www.wired.com/story/the-surprising-climate-cost-of-the-humblest-battery-material/
- [43]**Benchmark Source** – ESG of graphite: how do synthetic graphite and natural graphite compare? https://source.benchmarkminerals.com/article/esg-of-graphite-how-do-synthetic-graphite-and-natural-graphite-compare
- [44]**Vianode** - 90% CO_2 reductions with Vianode's synthetic anode graphite https://www.vianode.com/sustainability/life-cycle-assessment/

- [45]**CarbonScape** – Biographite https://www.carbonscape.com/biographite
- [46]**Global LCA Data Access** - Cobalt, refined (metal); mining, beneficiation, primary extraction, refining, transport; production mix, at plant; 99.8% cobalt https://www.globallcadataaccess.org/cobalt-refined-metal-mining-beneficiation-primary-extraction-refining-transport-production-mix
- [47]**Cobalt Institute** – Cobalt Market Report https://www.cobaltinstitute.org/wp-content/uploads/2024/05/Cobalt-Market-Report-2023_FINAL.pdf
- [48]**Mighty Earth** – Nickel industry costs lives and livelihoods in Indonesia's last nomadic sea tribe https://mightyearth.org/article/from-forests-to-electric-vehicles/
- [49]**OECD** – Trends in Stakeholder Reporting: Mineral Supply Chains https://mneguidelines.oecd.org/trends-in-stakeholder-reporting-mineral-supply-chains.pdf
- [50]**OECD** – Interconnected supply chains: a comprehensive look at due diligence challenges and opportunities sourcing cobalt and copper from the Democratic Republic of the Congo https://mneguidelines.oecd.org/Interconnected-supply-chains-a-comprehensive-look-at-due-diligence-challenges-and-opportunities-sourcing-cobalt-and-copper-from-the-DRC.pdf
- [51]**Minerals Engineering** – Geometallurgy of cobalt ores: A review https://www.researchgate.net/publication/346564949_Geometallurgy_of_cobalt_ores_A_review
- [52]**Benchmark Source** – Why Western rare earths producers must act on radioactive waste https://source.benchmarkminerals.com/article/why-western-rare-earths-producers-must-act-on-radioactive-waste
- [53]**Journal of Environmental Radioactivity** - In-situ gamma-ray survey of rare-earth tailings dams – A case study in Baotou and Bayan Obo Districts, China https://www.sciencedirect.com/science/article/pii/S0265931X15301430
- [54]**Iluka** – ENEABBA https://www.iluka.com/operations-resource-development/resource-development/eneabba/
- [55]**Reuters** - Insight: World battles to loosen China's grip on vital rare earths for clean energy transition https://www.reuters.com/markets/commodities/world-battles-loosen-chinas-grip-vital-rare-earths-clean-energy-transition-2023-08-02/
- [56]**Sustainable Chemistry & Engineering** – Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.7b04165
- [57]**Resources, Conservation & Recycling** - Country-specific carbon footprint and cumulative energy demand of metallurgical grade silicon production for silicon photovoltaics https://par.nsf.gov/servlets/purl/10378317
- [58]**US Department of Energy** – Solar Photovoltaics Supply Chain Deep Dive Assessment https://www.energy.gov/sites/default/files/2022-02/Solar%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf
- [59]**IEA** – Special Report on Solar PV Global Supply Chains https://iea.blob.core.windows.net/assets/2d18437f-211d-4504-beeb-570c4d139e25/SpecialReportonSolarPVGlobalSupplyChains.pdf
- [60]**The Breakthrough Institute** – Confronting the Solar Manufacturing Industry's Human Rights Problem https://thebreakthrough.org/issues/energy/sins-of-a-solar-empire
- [61]**Wilson Center** – Environmental Health Challenges in Xinjiang https://www.wilsoncenter.org/publication/environmental-health-challenges-xinjiang
- [62]**S&P Global** - Indonesia's nickel processing boom raises questions over tailings disposal https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/indonesia-s-nickel-processing-boom-raises-questions-over-tailings-disposal-75180844
- [63]**Mining** – Nickel price: Indonesia halts deep-sea mining disposal https://www.mining.com/web/facing-green-pressure-indonesia-halts-deep-sea-mining-disposal/
- [64]**Extractive Metallurgy of Copper** – Chapter 14 - Hydrometallurgical copper extraction: introduction and leaching https://www.sciencedirect.com/science/article/abs/pii/B9780128218754000031

- [65]**Extractive Industries and Society** – Assessing the risk of leakage from heap leach pads used in mining operations https://www.sciencedirect.com/science/article/abs/pii/S2214790X13000051
- [66]**Global Tailings Review** – CHAPTER II MINE TAILINGS FACILITIES: OVERVIEW AND INDUSTRY TRENDS https://globaltailingsreview.org/wp-content/uploads/2020/09/Ch-II-Mine-Tailings-Facilities_Overview-and-Industry-Trends.pdf
- [67]**Cleaner Environmental Systems** – Comparison of environmental performance of modern copper smelting technologies https://www.sciencedirect.com/science/article/pii/S2666789421000441
- [68]**Geo40** – Geothermal lithium https://geo40.com/geothermallithium/
- [69]**U.S Patent Application Publication** – Reverse Osmosis Filtration https://patentimages.storage.googleapis.com/70/a4/04/501087811aa311/US20170182460A1.pdf
- [70]**European Patent Office** – Process and system for lithium extraction https://patents.google.com/patent/EP4351754A1/
- [71]**Environmental Protection Authority (EPA)** – DECISION ON MARINE CONSENT APPLICATION Chatham Rock Phosphate Limited To mine phosphorite nodules on the Chatham Rise https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000006/Boards-decision/990a6509eb/EEZ000006-CRP-Decision.pdf
- [72]**Fauna & Flora International** – An assessment of the risks and impacts of seabed mining on marine ecosystems https://www.fauna-flora.org/wp-content/uploads/2023/05/FFI_2020_The-risks-impacts-deep-seabed-mining_Report.pdf
- [73]**Chatham Rock Phosphate** – The Project https://www.rockphosphate.co.nz/the-project
- [74]**Benchmark Source** – Phosphate concerns drive Chinese battery investments in Morocco https://source.benchmarkminerals.com/article/phosphate-concerns-drive-chinese-battery-investments-in-morocco
- [75]**Investment Territory** – Territory LFP battery cathode plant reaches milestone https://invest.nt.gov.au/news-and-insights/lfp_battery_milestone
- [76]**Newsroom** - Barging into an ore-some future https://newsroom.co.nz/2023/10/02/barging-into-an-ore-some-future/
- [77]**West Coast Regional Council** – Westland Mineral Sands Co Ltd: Proposed Conditions of Consent https://www.wcrc.govt.nz/repository/libraries/id:2459ikxj617q9ser65rr/hierarchy/Documents/Services/Consents%20and%20Compliance/Publicly%20Notified%20Consents/Black%20Sand%20Mining/Further%20Information/WMS%20-%20Applicant%20Proposed%20Conditions%20of%20Consent%20and%20Schedules.pdf
- [78]**Callaghan Innovation** - Avertana: Turning steelmaking waste into useful raw materials https://www.callaghaninnovation.govt.nz/stories/avertana-turning-steelmaking-waste-into-useful-raw-materials/
- [79]**New Zealand Steel** – Electric Arc Furnace, Process Change https://www.nzsteel.co.nz/new-zealand-steel/electric-arc-furnace/
- [80]**Journal of Cleaner Production** – Environmental impacts analysis of titanium sponge production using Kroll process in China https://www.sciencedirect.com/science/article/abs/pii/S0959652617322527
- [81]**EPA** - Decision-making Committee (DMC) granted consent subject to conditions for Trans-Tasman Resources Limited (TTRL) to extract and process iron sand within the South Taranaki Bight https://www.epa.govt.nz/public-consultations/decided/trans-tasman-resources-limited-2016/the-decision/
- [82]**EPA** – Supreme Court Decision on TTRL to extract and process iron sand within the South Taranaki Bight https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000011/Objections-and-appeals/Supreme_Court_decision_2021-NZSC-127_30Sep21.pdf
- [83]**HERA** – 10 August 2022 | Ep.74 – extractables from steel bi-products https://www.hera.org.nz/stp-ep74-megan-girdwood/
- [84]**Lawrence Livermore National Laboratory** – Production of Pure Vanadium: Industry Review and Feasibility Study of Electron Beam Melt Refining of V-Al Alloys https://pyro.byu.edu/00000183-5bf3-d0b2-a7c7-7ff7f6390001/production-of-pure-vanadium-review-and-feasibility-pdf
- [85]**GNS Science** – Mineral resource assessment of the West Coast Region, New Zealand

https://www.wcrc.govt.nz/repository/libraries/id:2459ikxj617q9ser65rr/hierarchy/Documents/Publications/Natural%20Hazard%20Reports/West%20Coast/Mineral%20Resource%20Assessment%20West%20Coast%20Region%202010.pdf

- [86]**IEA** – Geographical distribution of refined material production for key energy transition minerals in the base case, 2023-2040 https://www.iea.org/data-and-statistics/charts/geographical-distribution-of-refined-material-production-for-key-energy-transition-minerals-in-the-base-case-2023-2040-2
- [87]**Radio NZ** – Reefton could hold 5 percent of world's supply of antimony https://www.rnz.co.nz/news/business/516115/reefton-could-hold-5-percent-of-world-s-supply-of-antimony
- [88]**University of Otago** – Antimony in the New Zealand environment https://www.otago.ac.nz/__data/assets/pdf_file/0031/288742/nzteg_2008_014_craw_slideshow_sm.pdf
- [89]**Siren Gold** – Process Plant https://www.sirengold.com.au/site/process-plant
- [90]**USGS** – 2018 Minerals Yearbook https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-antimony.pdf
- [91]**Journal of Cleaner Production** – Antimony and gold substance flows analysis of pyrometallurgical process for antimony-gold concentrates https://www.sciencedirect.com/science/article/abs/pii/S095965262302543X
- [92]**MDPI** – Present Situation and Research Progress of Comprehensive Utilization of Antimony Tailings and Smelting Slag https://www.mdpi.com/2071-1050/15/18/13947

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