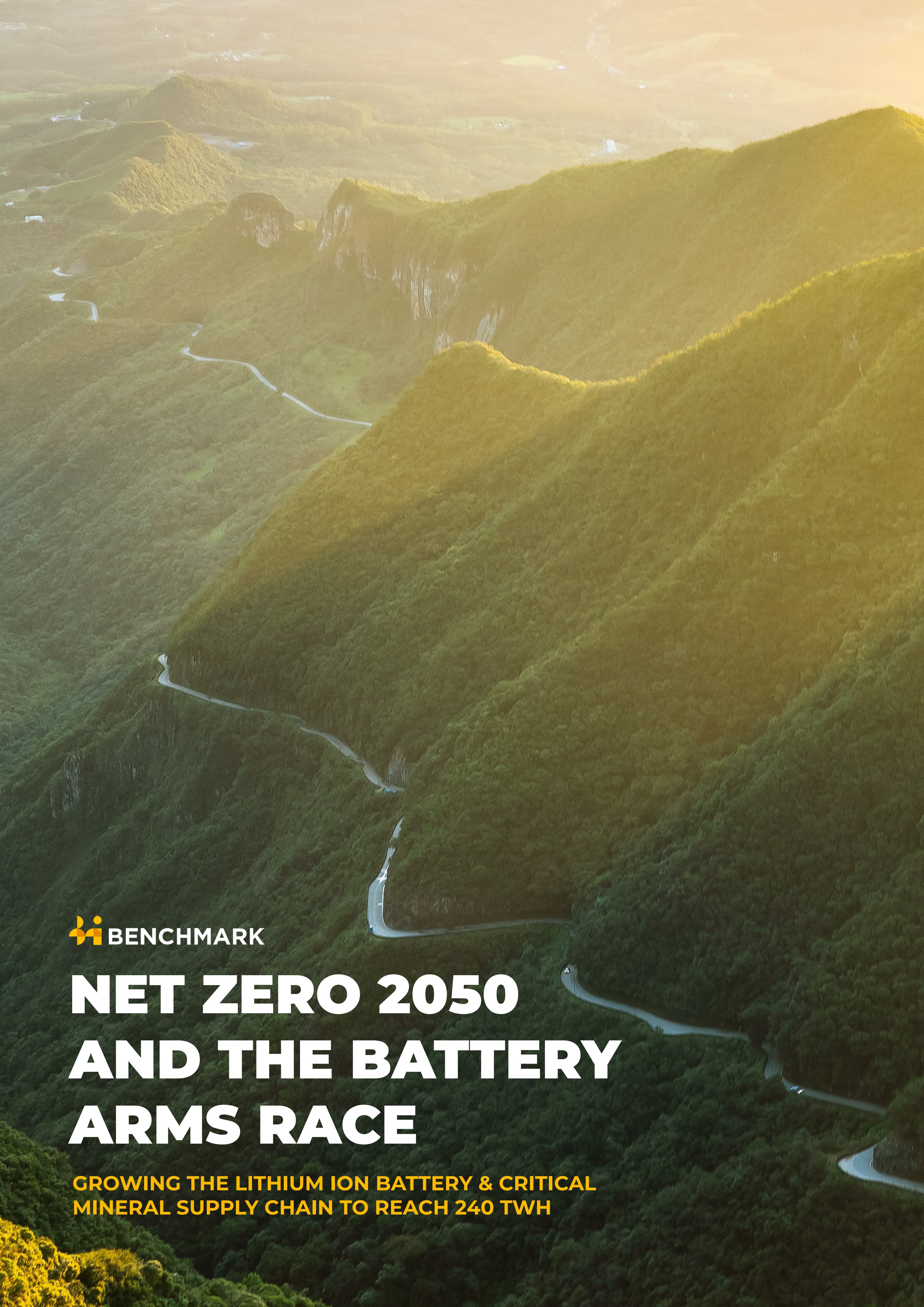


BENCHMARK

NET ZERO 2050 AND THE BATTERY ARMS RACE

GROWING THE LITHIUM ION BATTERY & CRITICAL MINERAL SUPPLY CHAIN TO REACH 240 TWH

Every destination needs a roadmap, and Team Benchmark is happy to provide a template for the path forward.

How can the world reach Net Zero with lithium ion batteries?

The forward march of the energy transition is one of the global megatrends of our time.

The need to transition towards non-fossil fuel energy, in particular wind and solar, is nothing new. The world woke up to this a decade ago. But the ability to store this energy on a wide scale, efficiently and economically, will be a revolutionary development.

The rise of pure electric vehicles demonstrates the lithium ion battery is becoming better, lower cost and more abundant. This means it is here to stay. Yet making batteries at scale and building the corresponding critical mineral supply chains is a huge challenge.

The lithium ion battery and the core supply chains that feed into it are under an ever intensifying spotlight.

Why is this the case? Recent comments from policymakers, international organisations, and, earlier in the year, Tesla CEO Elon Musk, have fuelled Benchmark's thinking on how big the lithium ion battery ecosystem needs to become. Musk estimates that the world requires 240TWh of deployed batteries - batteries in the wild, installed and operating - for a sustainable energy future. This has provided a quantifiable target that the industry can work towards.

Benchmark data shows that in order to achieve this 240TWh Net Zero goal by 2050, the industry will need to scale from 1.1TWh of annual lithium ion battery output in 2023 to nearly 15TWh in 2050.

This 15x increase in battery cell output isn't really the central challenge. Rather, it is building the critical mineral supply chains of lithium, nickel, graphite, cobalt, and manganese that provide the raw material foundations to support this increase.

We believe Benchmark's 'Net Zero 240' concept provides a valuable framework for the industry and guides how to think about its sustainable energy goals.

While it is important to acknowledge the potential of alternative battery chemistries, we have chosen to concentrate this analysis on lithium ion batteries due to their long-term tailwinds. Battery chemistry will not be static, but neither will the requirements for a clean energy future.

This Benchmark report outlines how big the lithium ion ecosystem, from mine to end-market, needs to become to reach Net Zero.

Contents

04 **Main Findings**

05 **What did Elon say?**

07 **Bigger than Giga:**
The global battery arms race reaches new heights Batteries & Gigafactories

09 **The Rush for Raw Materials:**
Are we scaling quick enough?

10 **Lithium:**
From niche to mainstream and the need for a bigger stage

11 **Graphite:**
The largest input into a lithium ion battery needs tonnage and diversity

12 **Nickel:**
Battery big hitter needs to step up to the plate

13 **Cobalt:**
Cathode mainstay needs invaluable supply boost

14 **Manganese:**
The overlooked input becoming a crucial factor to battery evolution

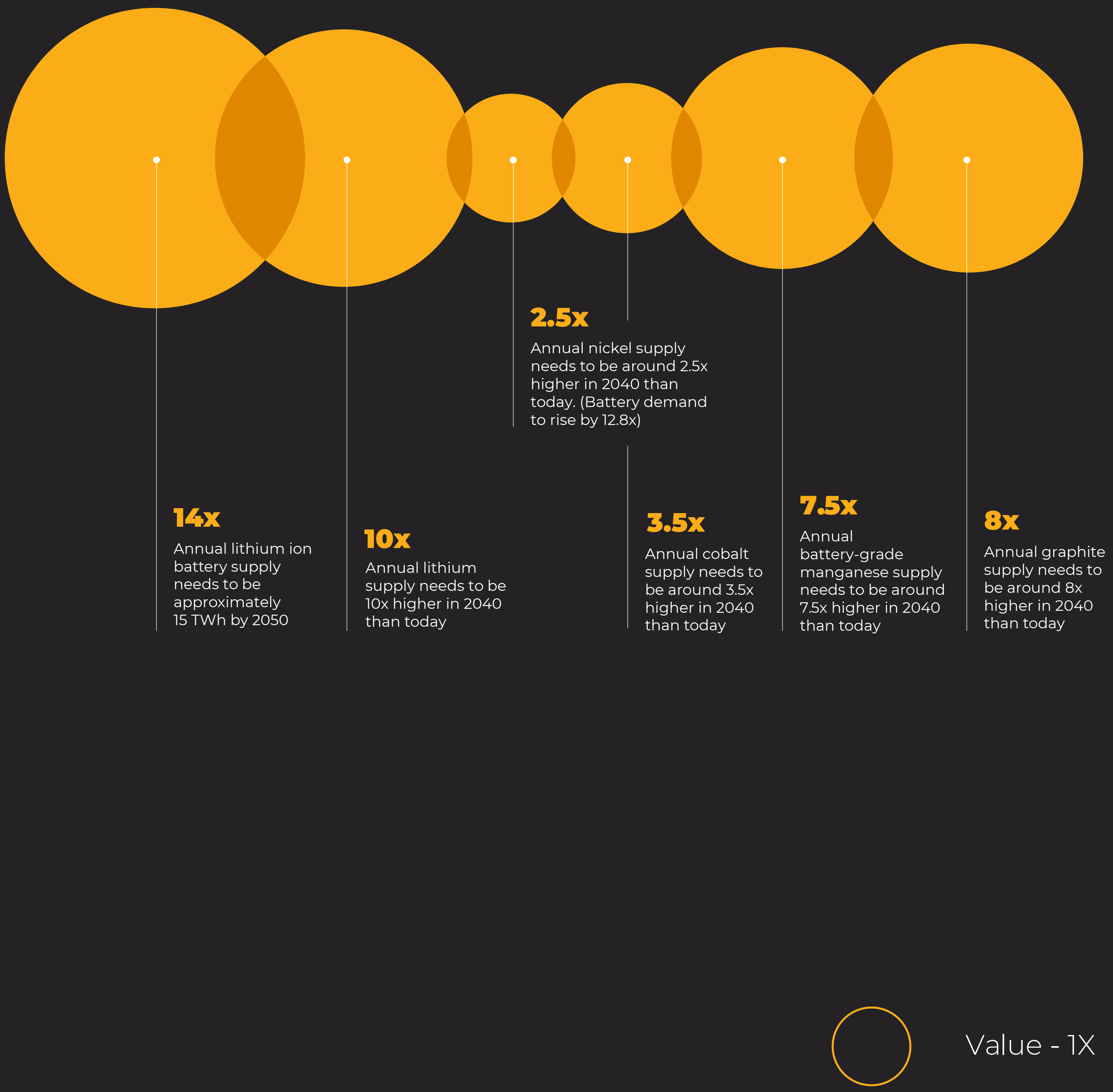
15 **What could go wrong?**

16 **Summary**

17 **About Us**

Main Findings

Predictions for annual supply



What did Elon say?

When Elon Musk speaks, the world listens.

His pioneering work as the CEO of Tesla has placed him at the forefront of the energy transition movement and what he says matters.

Tesla's Investor Day 2023 took place at the beginning of March and encompassed Musk's long-awaited 'Master Plan 3' vision for the future of the company and the wider industry.

The presentation contained the important estimate that 240TWh of deployed battery capacity would be required to achieve a sustainable energy economy.

Musk had previously floated a figure of 300TWh, but settling on the lower number has now provided some much-needed clarity on the level of ambition and expansion required in the lithium ion battery critical mineral supply chain.

The target provides a welcome wake-up call for the entire industry and presents a useful direction of travel for the coming decades.

It is the first time such an end game goal for total energy storage has been published.

The breakdown of the 240TWh target figure was heavily skewed towards electric vehicles, which made up 115TWh of the total.

The remainder consisted of planes and ships, the renewable energy grid, heat pumps and high-temperature thermal. The ramp up of lithium ion battery use through the increased utilisation of these end-products would help to transform the new energy economy.

Master Plan 3 was widely expected to contain detail on how Tesla planned to expand its own operations upstream into the critical mineral supply chain, but fans of the brand were left with unanswered questions on that point. Instead subsequent annoucnements from the company have focussed on pragmatic, near-term realities of scaling to meet burgeoning western EV demand. Tesla's efforts will be an important example for the industry to follow, but will ultimately be only one part of a bigger picture. The real challenge is to galvanise the industry into growing in unison.

Miners, component suppliers and the manufacturers of finished products will all have to rise to the challenge.

“The real challenge is to galvanise the industry into growing in unison.”

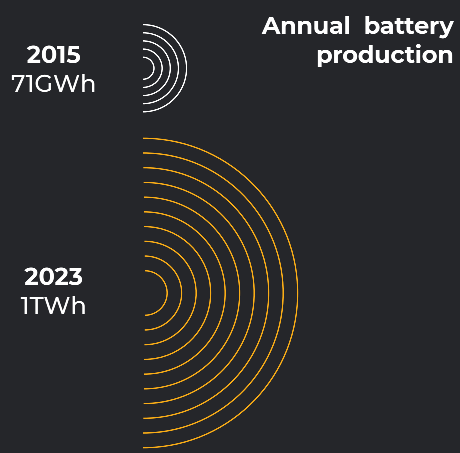
Bigger than Giga:

The global battery arms race reaches new heights

Batteries & Gigafactories

Benchmark forecasts that the annual supply of lithium ion battery cells needs to rise from last year's 786GWh (0.79TWh) to 6.71TWh by 2030 and 11.13TWh in 2040 before reaching average annual production of 14.85TWh over the following decade to meet the projected demand necessary for the achievement of Net Zero 240 by mid-century. New battery supplies will be crucial in replacing end-of-life cells during this period, which Benchmark forecasts will total 124GWh in 2030 climbing to over 2.3TWh by 2040.

The current forecast is for annual battery cell supply to reach 3.83TWh by 2030, 4.45TWh by 2040 and 5.16TWh by 2050. This indicates that the pipeline for supply would need to roughly double its current trajectory through to 2040 before scaling this run rate by more than an additional 50% for the proceeding decade. According to Benchmark estimates, the number of gigafactories, a relatively new type of production facility designed to produce batteries at scale, will need to rise from 234 this year to 460 in 2030, 583 in 2040 and 735 in 2050. These targets show that a renewed sense of urgency and ambition is required across the industry if Net Zero 240 is to be achieved by 2050.



The lithium-ion battery is the battery technology that dominates the modern electric vehicle industry. It derives its name from the fact that lithium is used as the charge carrier in the battery cell and is the core raw material required for its manufacture. Lithium-ion batteries are rechargeable and provide energy density, life cycle and performance improvements on previous generation batteries.

The industry has grown an order of magnitude in the last eight years.

Batteries are getting better, cheaper, and more abundant. Annual production has risen from 71GWh (0.07TWh) in 2015 to more than 1TWh this year. Cell level costs have dropped from $280/kWh to $115/kWh in the same timeframe for Nickel-Cobalt-Manganese (NCM) chemistries. This significant drop in costs, part of a wider 25-year downward trend, has been a key ingredient in growing the market for end products such as electric vehicles.

But the last two years have marked a reversal with lithium ion battery cell prices rising instead of falling. Supply chain growing pains, particularly around the availability and cost of lithium and nickel, are driving the change. A rise in the number of gigafactories has resulted in raw materials becoming a much larger portion of the lithium ion battery's costs. The minerals, metals and chemicals that are the core building blocks of a lithium ion battery have risen from 40% of total cost in 2015 to as much as 80% in 2022.

This unexpected cost surge for lithium ion battery inputs has raised the prospect of alternative battery types gaining more market share.

Technologies such as sodium ion batteries and flow batteries could begin to play a larger role in stationary markets as a result.

2022

0.79TWh
CURRENT

2030

75 %↗

3.83TWh
PREDICTED

6.71TWh
NEEDED

2040

150 %↗

4.45TWh
PREDICTED

11.13TWh
NEEDED

2050

190 %↗

5.16TWh
PREDICTED

14.85TWh
NEEDED

The Net Zero 240 target can only go as fast as its slowest component and that is mining.

The Rush for Raw Materials: Are we scaling quick enough?

The march of the gigafactories and the huge increase in the adoption of electric vehicles will often grab the biggest headlines in the world of the lithium ion battery economy. But without the critical mineral raw materials powering this development, everything grinds to a halt.

Understanding the upstream dynamics, all the way to the mine, is central to working out whether rapid scaling is possible and how quickly we can achieve Net Zero. It takes 24 months to build a gigafactory, but upwards of 10 years to develop and build a critical mineral mine and chemical processing plant.

From a geological perspective, there is no shortage of lithium, nickel, cobalt, manganese and graphite. The challenge is financing and building enough mining and refining capacity for each of these supply chains that all feed into lithium ion battery production and finding the skills and knowledge to do so quickly.

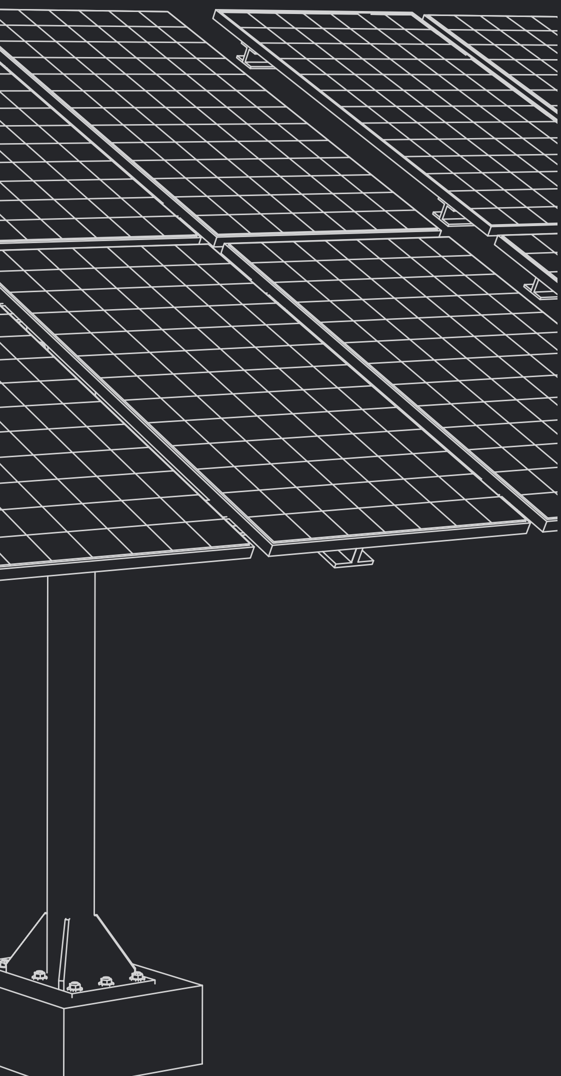
Lithium ion battery recycling will help greatly in reducing the burden of mine level supply, but it will never replace mining as the primary source of minerals.

The supply chains of tomorrow must be financed and scaled in the right volumes and qualities and delivered in the right timeframe. Too much volume would depress the market and drag the wider industry down with it. Too little volume and extreme price spikes will hurt the downstream consumer by pushing the cost of lithium ion batteries and electric vehicles higher.

A balance of speed and economic stability is something that the lithium ion battery supply chain needs to tackle.

The Net Zero 240 target can only go as fast as its slowest component and that is mining.

An increased supply of lithium is crucial to the achievement of the Net Zero 240 vision by 2050.



Lithium: From niche to mainstream and the need for a bigger stage

An increased supply of lithium is crucial to the achievement of the Net Zero 240 vision.

The majority of the world's lithium is already consumed by the battery industry, and these energy storage requirements will only intensify if we are to reach any type of clean energy future.

In 2022, the lithium ion battery industry consumed more than 540k tonnes of lithium. This volume is expected to increase ten-fold on the industry's current demand trajectory, before having to scale to more than 8.5m tonnes annually in the decade to 2050. The current forecast for total annual supply is just 2.53m LCE tonnes in 2030 and 3.93m LCE tonnes in 2040.

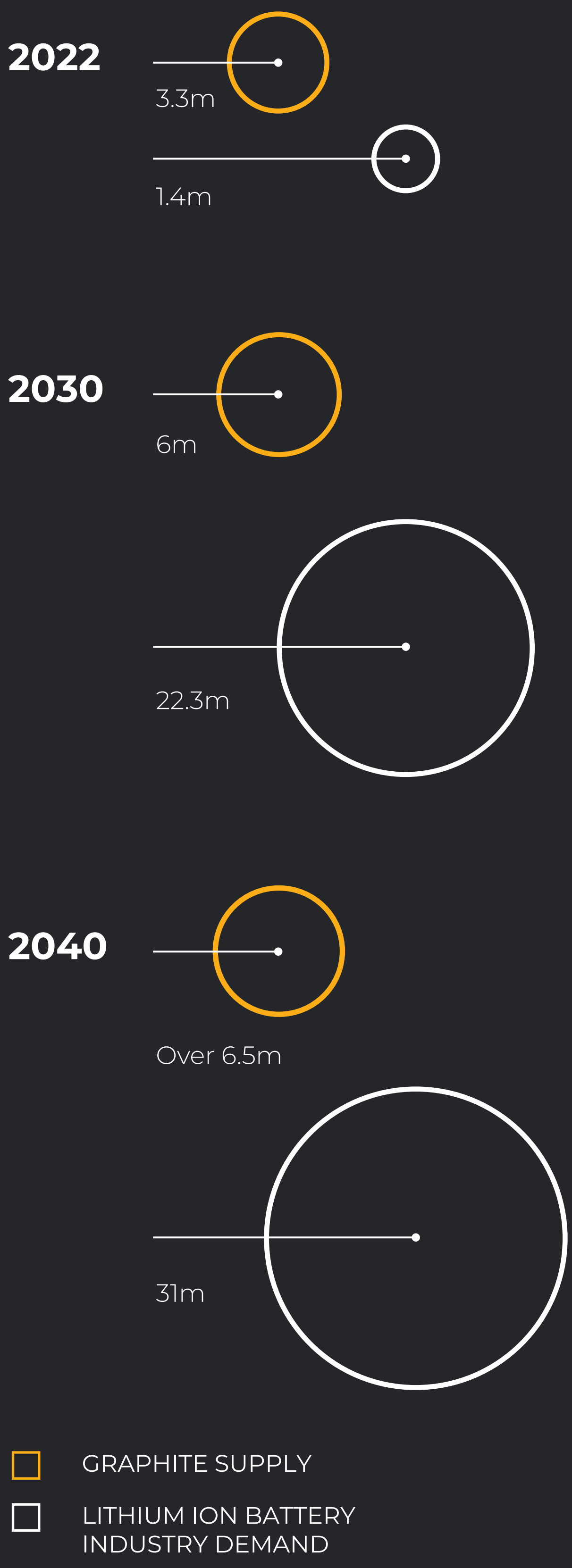
The Net Zero 240 pathway would push total demand across all industries to 5m LCE tonnes as early as 2030. Total demand would be around double the annual supply that is currently forecast at each key milestone.

Due to its lightweight properties, lithium is an essential element for the majority of portable energy storage devices. All modern electric vehicles use lithium ion batteries as their core source of energy storage. Lithium's light-weight characteristics allow for it to store and distribute energy at the scale and power required for transportation. Lithium-ion batteries outperform traditional rival technologies in many aspects such as energy density, longevity and voltage delivery, making them a superior overall alternative. Electricity is generated in a lithium ion battery when the lithium ions move from the anode to the cathode, prompting a circulation of electrons. Charging occurs when the process is reversed.

Consumer electronics such as tablet computers and mobile phones require lithium-based batteries as well as items such as power tools, medical equipment and pharmaceuticals. Smaller forms of transport such as bikes and increasingly popular urban scooters use lithium-ion storage along with mobility aids such as wheelchairs.

Beyond the chemical's use in lithium ion batteries for EVs, portable devices and, in some cases, stationary storage, there are other industrial applications which will continue to compete for material in the market, with a lack of substitute materials across many glass, ceramic and lubricant products.

Graphite supply vs Lithium ion battery industry demand
(million tonnes)



Graphite: The largest input into a lithium ion battery needs tonnage and diversity

The lithium ion battery industry is gearing up to drive a huge leap in demand for graphite over the next few decades and the potential graphite supply crunch is arguably one of the most acute and underappreciated across all battery raw materials.

Graphite supply, across both natural and synthetic feedstocks, hit 3.3m tonnes in 2022 and is expected to rise to 6m tonnes by the 2030s. Demand from the lithium ion battery industry was 1.4m tonnes in 2022, but would climb to more than 30m tonnes by 2040 if Net Zero 240 is to be achieved.

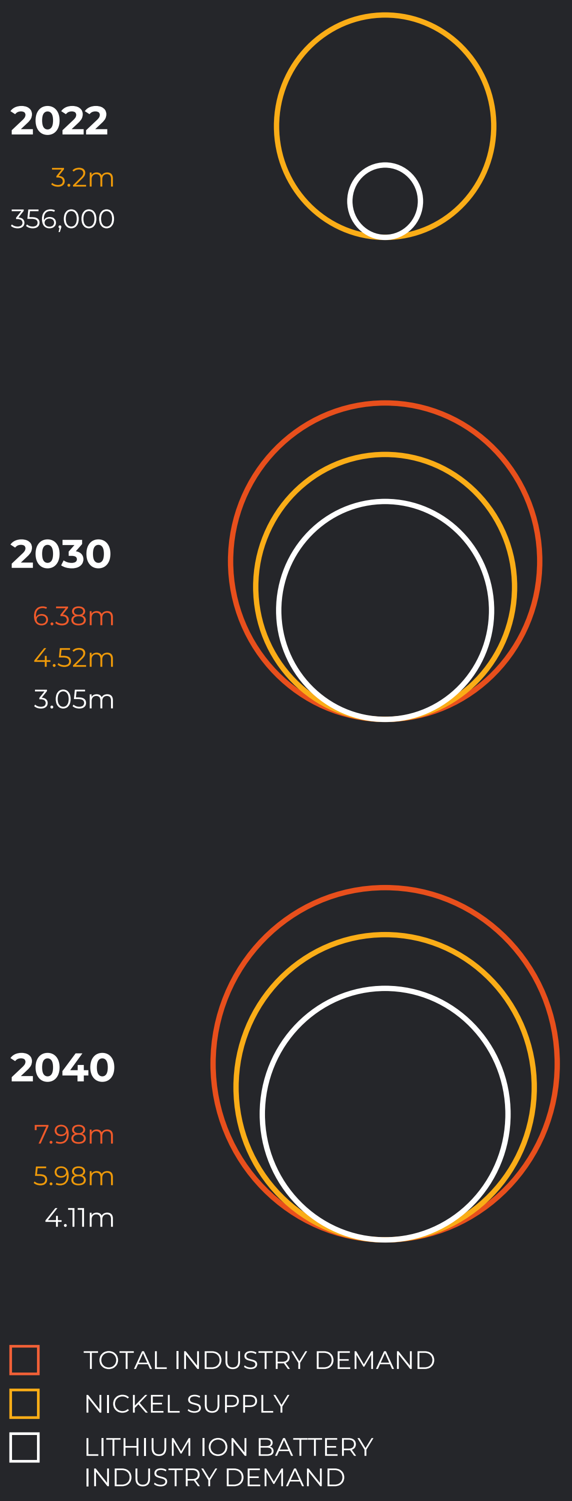
This shows that following the Net Zero 240 vision would see battery-related demand out-stripping forecasted annual supply by 4x in 2030 and by around 9x in 2040.

The supply equation for graphite material inputs into the battery anode market is made even more complex by the fact that not all material is suitable for batteries. For natural graphite a -100 mesh material is the optimal specification for batteries materials, while for anode graphitisation a low-sulphur coke is what has traditionally been the optimal input.

Graphite's conductive properties and low-cost mean it will remain the dominant anode material in the lithium ion battery market for the foreseeable future, even with the emergence of silicon doping, or lithium metal anodes used in solid state batteries in the future. Away from the battery industry, natural graphite is commonly used for refractories, brake linings, foundry facings and lubricants.

Today, there is a preference for synthetic graphite feedstocks for anode materials, however as demand diversifies to Western markets, and consumers seek to optimise the cost and performance metrics of anode material, graphite's are increasingly being blended leading to a more even balance between the two inputs in the future.

Nickel supply vs Lithium ion battery industry demand (tonnes)



Lithium-ion batteries use several key raw materials, but with a single car requiring around 30-40kg of nickel, the metal is typically one of the largest inputs by mass into the cathode.

Nickel: Battery big hitter needs to step up to the plate

The lithium ion battery industry currently uses a modest amount of the total nickel supply, but is expected to increase its hunger for the material on the path to achieving Net Zero 240 by 2050.

The global supply of refined nickel hit 3.2m tonnes in 2022 and is expected to rise to 4.52m tonnes by 2030, according to Benchmark data. This climb is forecast to continue to 5.98m tonnes by 2040. The lithium ion battery industry consumed only 356k tonnes of material in 2022, but Benchmark forecasts that to reach Net Zero 240, demand would have to rise to over 3m tonnes by 2030 and more than 4m tonnes by 2040.

When factoring in non-battery markets, this could see the industry scale to 6.38m by 2030 and 7.98m by 2040.

This illustrates that the current supply trajectory is far from meeting the ambitions and requirements of the energy storage industry, a task made more daunting by the reliance on new technologies to facilitate further expansions.

The nickel supply chain has transformed in recent years with new production routes emerging and Indonesia rising to dominance. In 2015, Indonesia accounted for 6% of refined nickel supply, with that figure now at around 50% of the market. Such a large reliance on a single country poses risks to the market, particularly considering nickel's key role in electric vehicle batteries and the path to Net Zero. Environmental, social and governance (ESG) concerns in relation to some Indonesian producers persist which threatens the position of some parts of the supply chain to serve Western markets – as a result, the market may bifurcate due to ESG considerations, or even driven by policy such as the US Inflation Reduction Act (IRA).

A small part of the nickel market has long been geared towards energy storage. More recently attentions have shifted to nickel's use in lithium ion battery cathodes, particularly as high-nickel chemistries emerged as the industry attempted to thrift the use of cobalt whilst increasing energy density.

Cobalt: Cathode mainstay needs invaluable supply boost

The cobalt industry supplied 191,000 tonnes of material to the market in 2022 and Benchmark forecasts that will rise to 327,000 tonnes by 2030 and 479,000 tonnes by 2040. The lithium ion battery industry accounted for 131,000 tonnes of consumption in 2022, but would require 547,000 tonnes by 2030 and 593,000 tonnes by 2040 to hit the Net Zero 240 target.

These figures show that demand on the Net Zero 240 pathway would require approximately double the current annual forecasted cobalt supply at the key decade markers.

While this supply uptick appears far less daunting than the challenges faced in other critical mineral markets, cobalt's by-product nature, matched with ESG risks, means there is added uncertainty over the volumes available to battery makers.

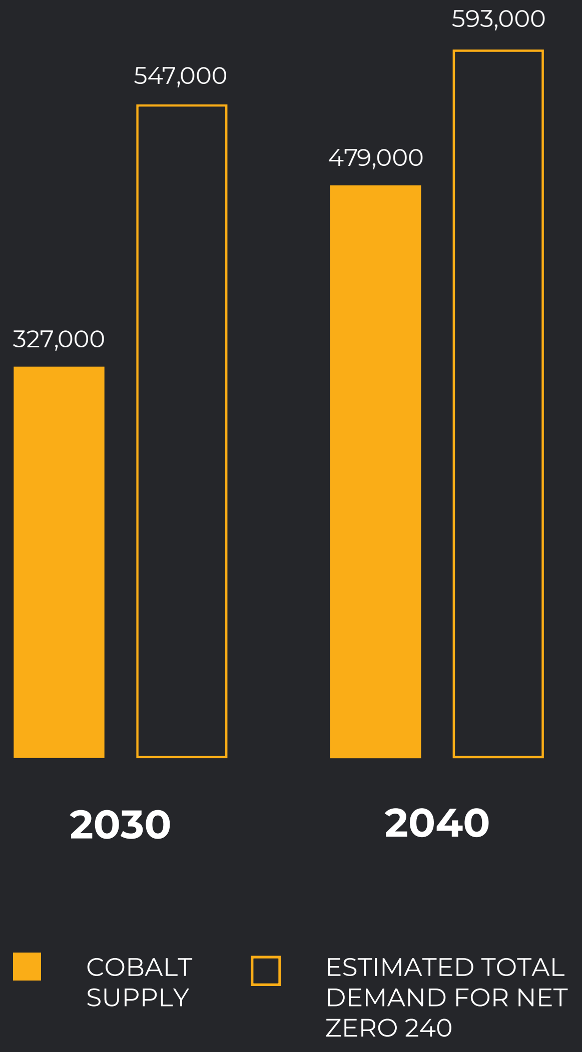
Cobalt played a significant role in the commercialisation of lithium ion batteries in portable devices, with high cobalt-containing LCO chemistries favoured for devices such as smartphones. More recently, the metal's use in both Nickel-Cobalt-Manganese (NCM) cathodes and Nickel-Cobalt-Aluminium (NCA) cathodes make it an essential input for the modern battery industry.

While cobalt is not the largest input into the cathode by mass, it is marked out because it is typically the costliest of the raw materials on a unit basis. This alongside the responsible sourcing and sustainability concerns over cobalt production from areas such as the Democratic Republic of the Congo (DRC) have seen battery producers lower cobalt intensities where possible, although the structural stability it provides in nickel-based chemistries means it will continue to play an important role in the future battery market, particularly as nickel ratios increase

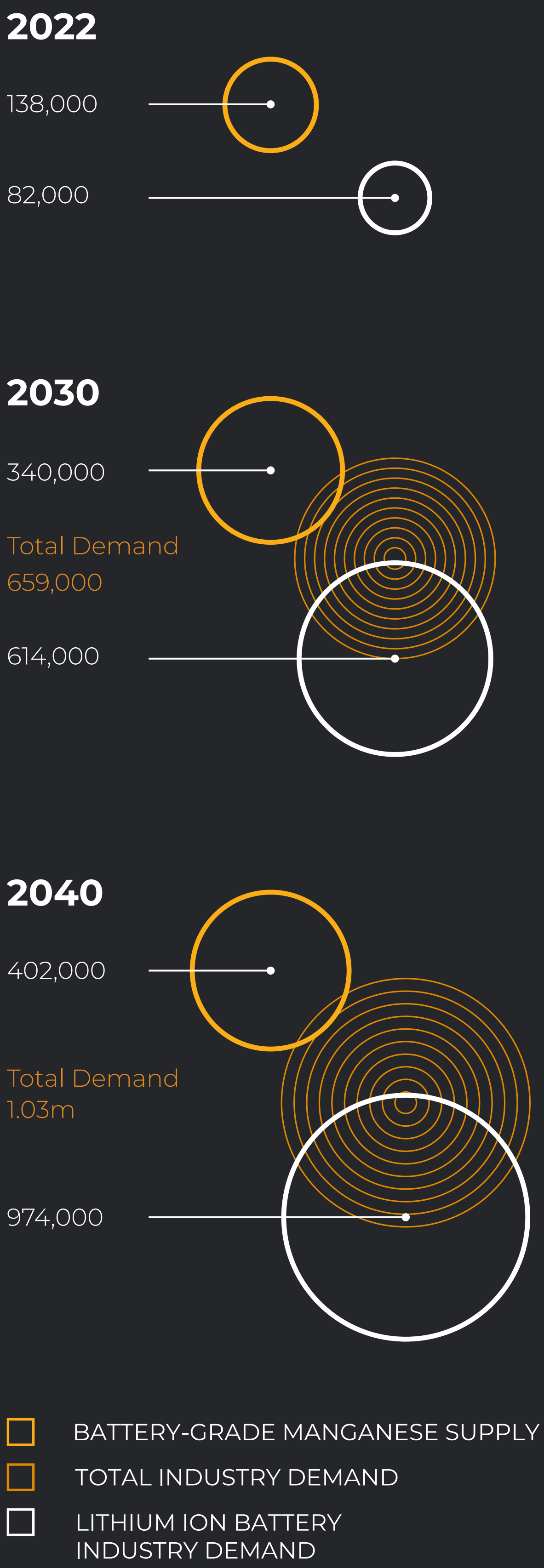
Cobalt is highly reliant on a single country for mined supply, the DRC, to an even larger degree than nickel is on Indonesia – the DRC accounted for 74% of mined cobalt supply in 2022. There is similar single-nation dependence in cobalt refining, with 76% of production in China alone. These factors increase cobalt supply risks with the industry already exposed to copper and nickel as its primary associated minerals. These concerns and the volatile nature of the cobalt market can deter potential supply investment.

Outside of batteries, cobalt has a variety of other uses. Some of those include superalloys for gas turbine engine parts, catalysts for petroleum and chemical industries, magnets, high-speed steels and drying agents for paints.

Cobalt supply vs Total industry demand (tonnes)



Battery-grade manganese supply vs Lithium ion battery industry demand and total industry demand (tonnes Mn contained)



Manganese: The industrial commodity becoming a crucial input to battery evolution

High-purity manganese chemical supply in 2022 was 138,000 tonnes, accounting for 70% of global consumption. These tonnages will be required to scale rapidly on the path to Net Zero, particularly as manganese-rich chemistries rise in popularity.

If Net Zero 240 is to be reached, the battery industry will become the leading consumer of speciality manganese products, and while they wouldn't account for the same proportion of total mined supply that we expect in lithium, cobalt or graphite, the industry would emerge as the primary growth driver for new supplies over the next several decades.

The majority of the world's manganese is ore is converted into ferroalloys for use in the manufacturing of iron and steel. At present, battery grade manganese is only 0.5% of the total supply of manganese. Over the Net Zero 240 path this share will likely rise to between 5-10% by 2040, making the industry a meaningful participant in the broader market for the commodity.

Battery-grade manganese is one of the core ingredients in the battery chemistry of a lithium ion battery cathode, most notably in the popular Nickel-Cobalt-Manganese (NCM) chemistry, as well as emerging man manganese-rich cathode variants. The material primarily acts as a stabilizing agent within the cathode.

Players across the lithium battery supply chain are enthusiastic about greater intensity of use of manganese in cathodes in the future as a way to reduce cost without sacrificing on performance. High-manganese cathodes, such as NMx and LMNO, can facilitate the significant reduction, or elimination of cobalt. Uptake of high-manganese cathodes means that demand growth for battery-grade manganese products is expected to outpace that for other battery-grade raw materials.

What could go wrong?

Mapping the required expansion of the lithium ion battery critical mineral supply chain is naturally vulnerable to the inherent perils of forecasting. The industry contains multiple moving parts ranging from technical to economics and geopolitics. Possible headwinds can largely be grouped together under three main headings: raw materials & chemicals; cell making and macro issues.

The two most common chemical compositions in a lithium ion battery are Nickel-Cobalt-Manganese (NCM) and Lithium-Iron-Phosphate (LFP). NCM made up 46% of market demand in 2022 and LFP accounted for 36%. Changes in demand for these popular variants will be an important component in supply chain development. Additionally, evolution in lithium ion chemistries, pack design and production processes will also play a key role in the direction of the industry.

The direction of technology will also play an important – and hard to predict – role in future supply chain requirements. Even developments within the existing lithium ion ecosystem – with the use of silicon anodes, for example – have the ability to alter the trajectory of the supply chain. The emergence of silicon as a key input will be a trend to watch closely.

Equally, the development of new technologies such as solid state has the potential to shake up the industry's trajectory, along with the improvement of raw material intensities and the wholesale change in extraction methods.

Variables around cell making could include changes to the manufacturing process, including cost. The prospect of gigafactories getting bigger on a single site is a real possibility and could bring with it knock-on effects for the manufacture of battery cells. Possible macro headwinds include a reversal of clean energy ambitions - particularly in the West where demand growth is at an inflection point. Meanwhile from an energy standpoint, the role of lithium ion batteries in stationary applications could be derailed by a push to pair renewables with alternative forms of energy storage such as sodium ion or flow batteries, or a switch to new energy generation platforms such as nuclear or hydrogen.

Summary

The achievement of Net Zero 240 and a sustainable energy future will require a colossal effort up and down the lithium ion battery critical mineral supply chain. Bigger and bolder thinking is required by everyone from miners and refiners to governments and manufacturers. The required supply multiples detailed in this report paint a picture of the size of the task ahead.

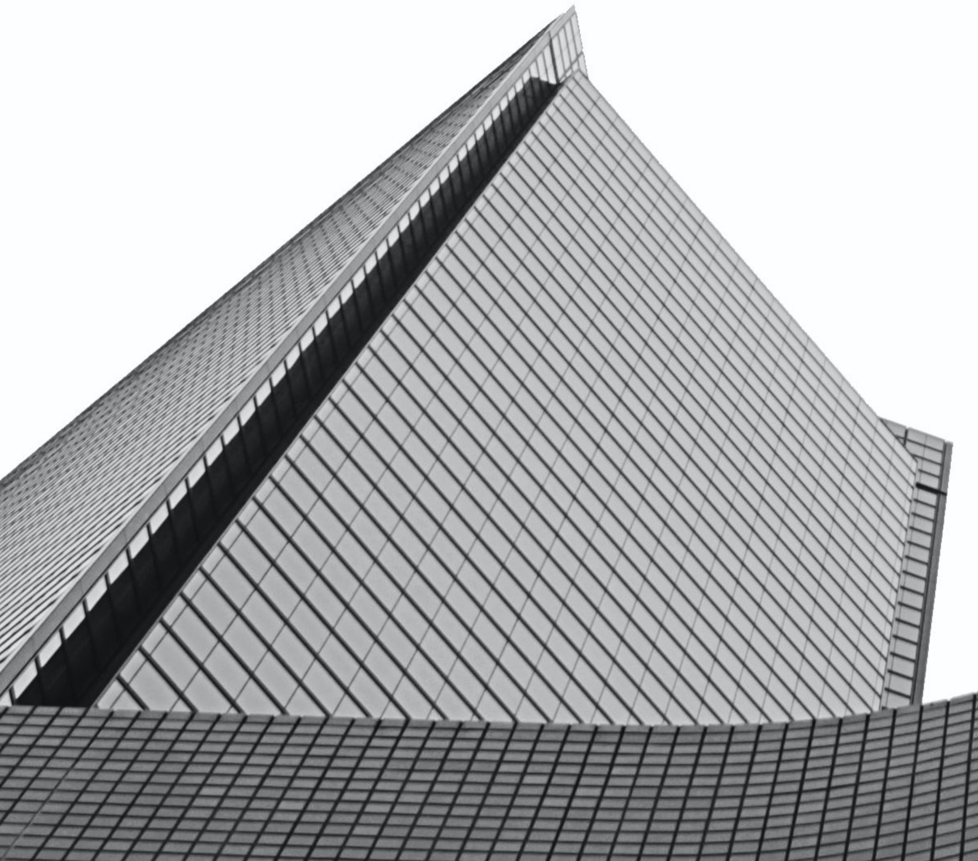
This effort will require closer collaboration across the entire industry. While individual companies can make some impact, cooperation between firms will be vital in the years ahead.

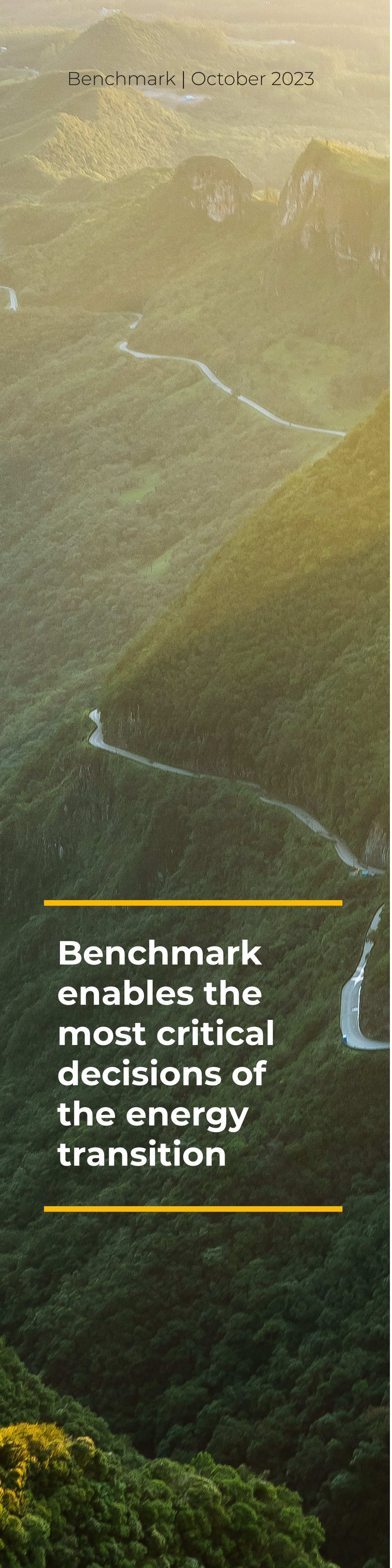
Investment is crucial to the realisation of the Net Zero 240 goal and Benchmark estimates that the lithium ion battery industry will need $3-5 trillion to achieve it. This means that capital providers such as private equity houses, governments and banks will be key players in pushing this sustainable agenda forward. The industry can only flourish if those with capital commit to its aims.

It is also important to focus on the sustainability of the growth required. The achievement of Net Zero 240 is in danger of losing its shine should the means of getting there have excessive environmental costs. Recycling should play an important part in the supply chain and the development of new facilities should be as sustainable as possible. A green goal should have a green pathway.

Net Zero 240 represents the chance for the lithium ion battery industry to achieve something remarkable.

Companies that take the goal seriously need to start thinking today about how they will assist in making it a reality.





Benchmark enables the most critical decisions of the energy transition

About Us

Benchmark provides unrivalled prices, data & insight from critical mineral mine to platform technology: lithium ion batteries, electric vehicles, energy storage and rare earth permanent magnets.

Benchmark Mineral Intelligence was formed in 2014 by a new generation of industry experts who strived for a robust, independent way of collecting market sensitive information.

We specialise in assessing market prices, supply chain data, forecasting and strategic advisory for the technologies and supply chains central to the energy transition.

Our unique approach to supply chain analysis gives Benchmark unrivalled insight into the opaque worlds of lithium ion batteries, electric vehicles, energy storage, and rare earth permanent magnets.

Benchmark's fast-growing influence extends beyond the active industry into the highest level of political and financial spheres.

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