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X-Change: Batteries

The Battery Domino Effect

December 2023

In partnership with:
BEZOS EARTH FUND

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Acknowledgments

The X-Change: Batteries report was produced by RMI in partnership with the Bezos Earth Fund and is a contribution to Systems Change Lab.

We would like to thank the following individuals for their input and expertise: Nigel Topping, Kelly Levin, Mark Dyson, Clay Stranger, Lena Hansen, Joel Jaeger, Tilmann Vahle, Zhe Wang, Carmelita Miller, Aparajit Pandey, James Newcomb, Achim Teuber, Leonardo Buizza, and Stephanie Schenk.

About RMI

RMI is an independent non-profit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all.

We work in the world's most critical geographies and engage businesses, policymakers, communities, and non-governmental organizations (NGOs) to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030.

RMI has offices in: Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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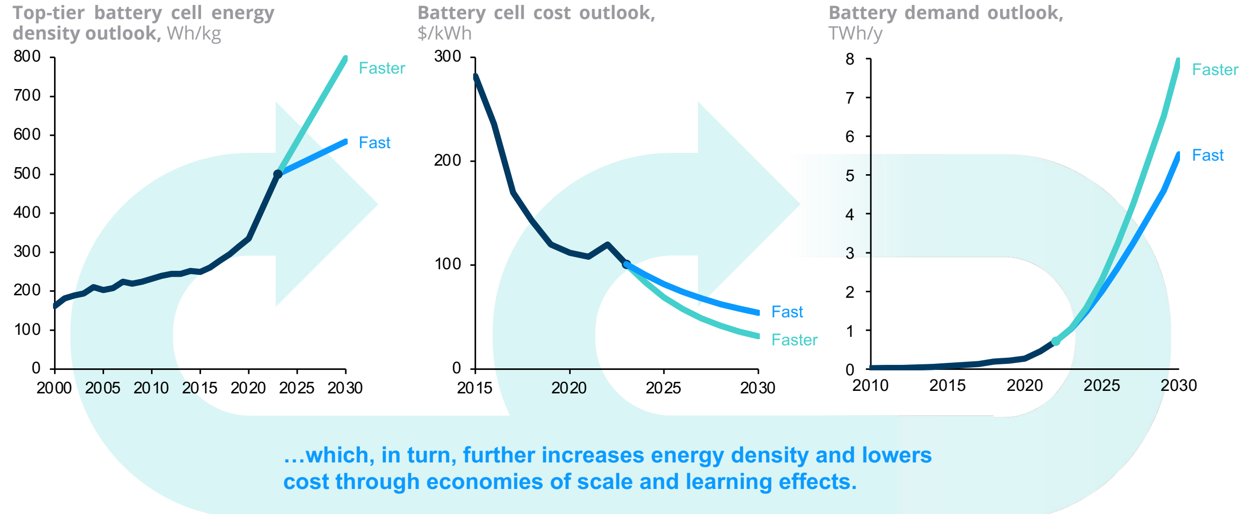
Summary

Battery demand is growing exponentially, driven by a domino effect of adoption that cascades from country to country and from one sector to the next. This battery domino effect is set to enable the phaseout of half of global fossil fuel demand and be instrumental in abating transport and power emissions, propelling us over 60% of the way toward a zero-carbon energy system.

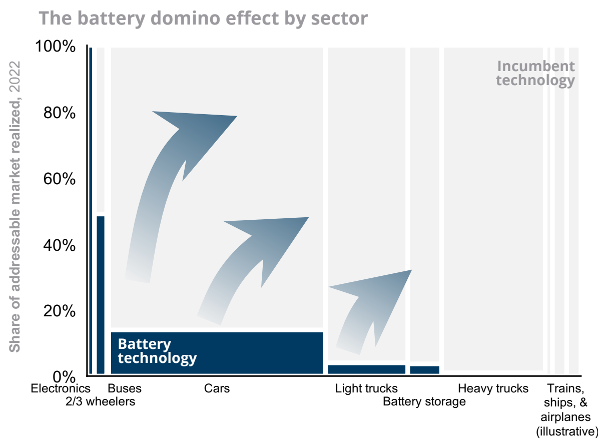
- **Demand is growing on an S-curve**. Battery sales have been doubling every two to three years, and we are on track for a six to eight times increase by 2030, with sales of 5.5-8 TWh per year.
- **A reinforcing feedback loop of scale, cost, and quality.** As the battery market grows, unit cost keeps falling and quality keeps rising. Both battery cost and energy density are on learning curves: for every doubling of battery production, costs fall by 19%-29% and the density of leading batteries rises by 7%-18%. At this rate, by 2030, battery cell costs will fall to $32-54 per kWh and top-tier batteries will have an energy density of 600-800 Wh/kg.
- **The domino effect by sector**. As one sector scales up demand, the cost and quality feedback loops enable batteries to start uptake in the next. Batteries started in consumer electronics, moved to motorbikes and buses, and then into cars. Now they are moving into stationary electricity storage and trucking and will be ready to enter short-haul ships and planes by 2030.
- **The domino effect by country**. Once new battery technology is successful, it jumps geographies. The shift of batteries into the car market was started by early adopters; China is the largest domino to fall; and the transition is now shifting across the rest of the world, from Europe to the US, from Southeast Asia to India.
- **The biggest capacity ramp-up since World War 2**. The race to the top means we are building 400 gigafactories, with capacity to make 9 TWh of batteries a year by 2030 — over 1 kWh for every person on the planet.
- **The largest clean tech market.** In 2022 we spent more on building battery factories ($45 billion) than on solar and wind factories combined; and by the end of the decade, the battery market will be larger than both solar panels and wind turbines.
- **Over half of fossil fuel demand is at risk**. Batteries will enable renewable technologies to replace 175 EJ of fossil fuel demand in the electricity sector and 86 EJ of demand in the road transport sector, and put at risk the remaining 23 EJ of transport demand from shipping and aviation.
- **Batteries put climate goals within reach**. As batteries help phase out fossil fuels, they enable the reduction of global emissions by 22 $GtCO_2$ per year, which is over 60% of global energy-related emissions today. On the current S-curve trend, battery uptake is set to outpace net-zero scenarios.
- **Incumbent modelers are behind the curve**. Current models keep underestimating the speed of change in batteries. If we stay on the current S-curves, battery sales in 2030 will be up to double consensus expectations of around 4 TWh a year.
- **Barriers are soluble**. Although supply chains are stressed, thanks to constant innovation and investment, we have enough raw materials that can be sourced — equitably and sustainably — and can act fast enough to build the charging infrastructure required for the future battery-dominated energy system.
- **Change does not happen by itself.** Batteries got this far through the concerted efforts of companies, governments, researchers, and climate advocates. Continued growth will require continued effort. The path ahead for batteries is clear, but we do still need to walk it.

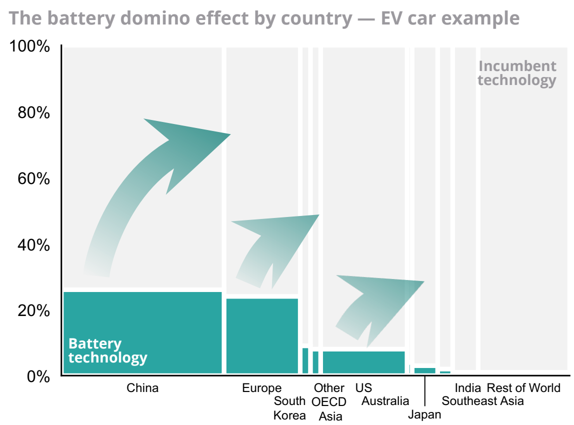
The battery domino effect in seven charts

Battery energy density keeps rising… | **…while battery cost keeps falling…** | **…driving exponential growth of battery demand…**

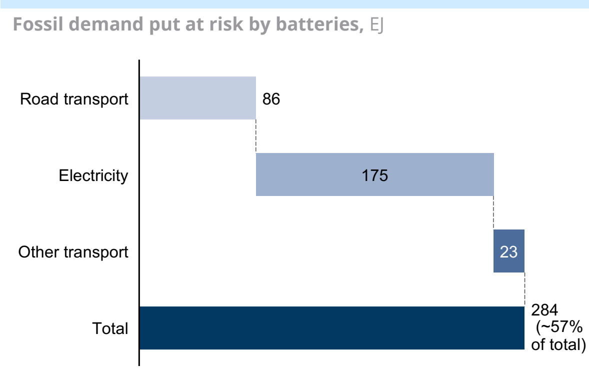


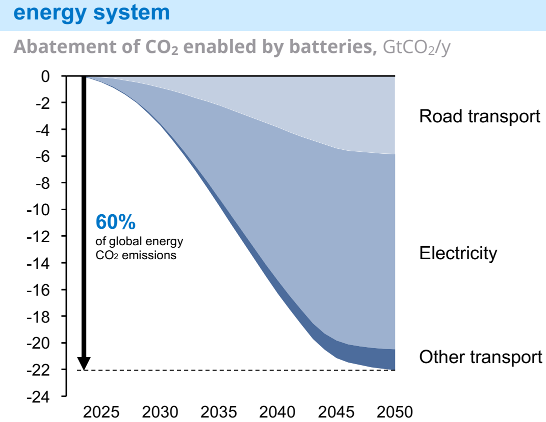
The result is a domino effect of battery uptake across sectors and countries…





…which puts over half of today's fossil demand at risk… | **…and propels us 60% of the way to a zero-carbon energy system**





1 Exponential change so far

Battery demand is growing exponentially. Rising energy density keeps unlocking new uses while declining costs enhance affordability and accelerate market uptake. This uptake, in turn, drives further cost reductions and continuous innovation — a cycle of self-perpetuating progress. The result is a domino effect, whereby batteries enter new markets, from country to country and from one sector to the next. Geopolitical tension has brought new players into the markets, speeding up the race to the top.

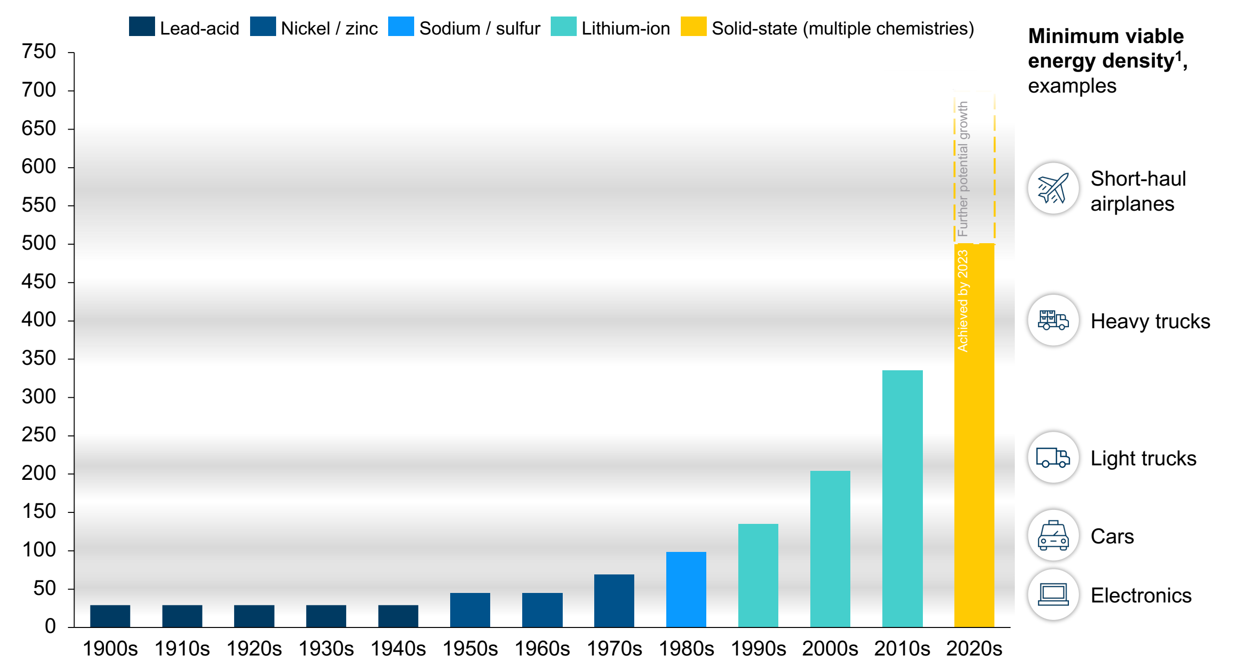
The pace of change keeps confounding experts, who consistently underestimate the potential and exponential growth of batteries. Defying past predictions, batteries now play a key role in the energy transition and their continued rapid growth signals a seismic shift in the energy system to come.

Energy density rose

Batteries have been around for over 200 years. Yet they have only recently emerged as a key technology in the global energy system. For most of their history, batteries were simply too heavy to be practical in sectors that could otherwise have readily used them, such as transport. In the early days of the car, in 1900, over one-third of cars in the United States were battery powered, but their limited range due to battery weight could not compete against internal combustion engine (ICE) cars, so battery cars rapidly faded away.[1]

The development of battery energy density — the amount of energy carried per unit of weight — stagnated for over half a century until the 1970s and 1980s, when innovation in the United States and Japan picked up.[2] In the 1990s, lithium-ion batteries entered the market. Rapid innovation in energy density and cost declines in the decade that followed enabled novel applications in electronics, such as battery use in cell phones and laptops. As energy density rose, battery applications in transport — such as electric motorbikes, cars and light trucks — became useful. Energy density has kept rising ever further, raising expectations that new applications in heavy trucks and even aviation may become possible as well. This is illustrated below by the rise of top-tier battery density over time.

Figure 1: Top-tier battery cell energy density by decade, Wh/kg



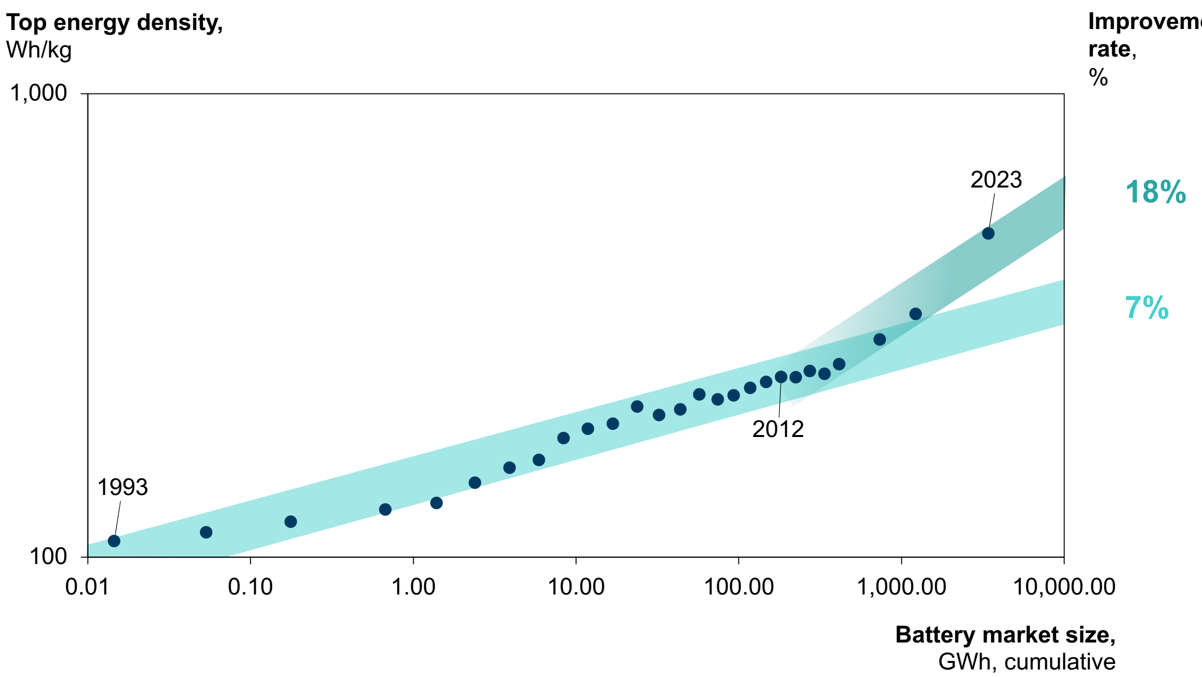
1. Minimum density at which first full battery-electric models are feasible

Source: Zu and Li (2011),[3] for 1900s-2000s, Bloomberg New Energy Finance (BNEF) Long-Term Electric Vehicle Outlook (2023)[4] for 2010s and 2020s

If we look at the development since 1993, top-tier energy density has increased by 7% for every doubling of battery deployment. Since 2012, top-tier energy density has been growing even faster, at 18% for every doubling of deployment.

The innovation potential of batteries is in part driven by the wide range of elements that can make up a battery. Batteries can be made from many different chemical compositions, which means the chemical properties of lithium, sodium, nickel, cobalt, manganese, and many other minerals can be used to improve the technology. When contrasted with, for example, a combustion engine — which effectively only relies on steel (for the engine itself) and hydrocarbons (as fuel) — it becomes clear why battery innovation has so much potential: the solution space is vast, and we have only just started to explore it.

Figure 2: Top-tier battery cell energy density vs. cumulative battery market size



Source: Ziegler and Trancik (2021)[5] before 2018 (end of data), BNEF Long-Term Electric Vehicle Outlook (2023)[6] since 2018, RMI analysis

Costs fell

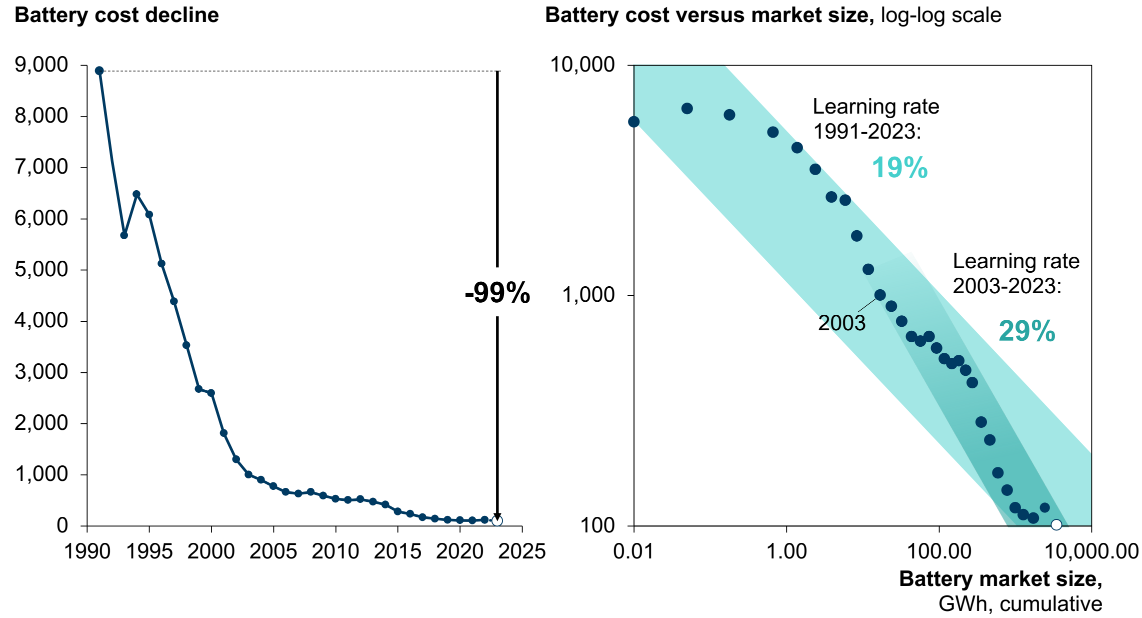
As innovation accelerated and battery uptake rose, so battery costs fell. Battery cost decline closely followed Wright's law over the past three decades — as production grew, economies of scale and R&D learning drove down cost.[7]

The learning rate for battery costs since the first introduction of the lithium-ion battery in 1991 has been 19%. That means that battery prices fell by 19% for every doubling of battery deployment. To arrive at this learning rate for battery cells, we use total battery demand in all applications, including consumer electronics, and look at the average cost decline for every doubling since 1991.[i] The battery cell learning rate has increased over time, and over the past two decades, the learning rate was 29%.

[i] Learning rates for batteries can be calculated for cells or for packs and over different time periods. One further complication is that some analysts such as BNEF do not include consumer electronics in their calculations; the impact of this is to make battery demand lower in early years and so increase the growth rate and thus reduce the apparent learning rate.

As batteries dropped in cost, they did not just improve the economics of existing battery technology — they also enabled competitive market entry in new sectors that were unlocked by rising energy density.

Figure 3: Lithium-ion battery prices, $/kWh (left), $/kWh log scale (right)



Source: Ziegler and Trancik (2021)[8] for 1991-2014, BNEF Lithium-Ion Battery Price Survey (2023)[9] for 2015-2023, RMI analysis

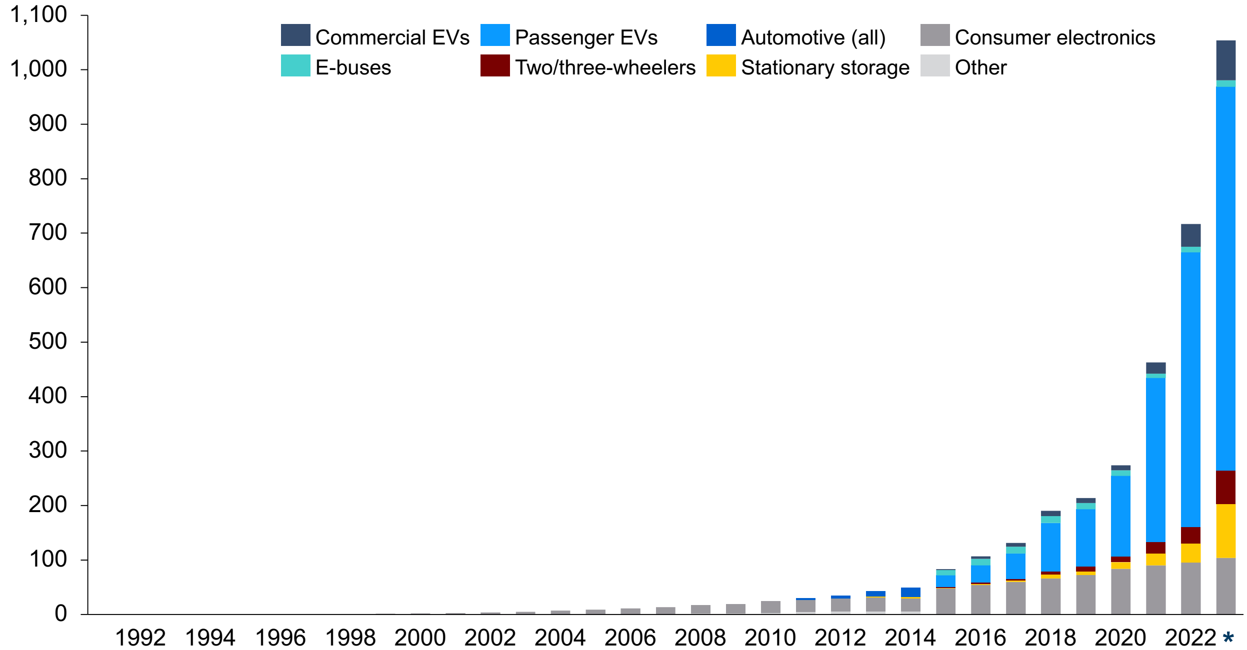
Demand increased

As batteries became more attractive through improvements in energy density and cost, market uptake took off. Battery demand has grown at an average annual rate of 33% for nearly three decades.

Electronics drove early uptake — with camcorders, cell phones, laptops, and other niche applications (such as grid frequency control). As saturation was reached in these sectors and growth started to ease to 20% per year, batteries became a viable technology in the transport market in the 2010s. This led to a resurgence of market growth. Since 2014, battery demand has been growing at an annual average of 41%, doubling every two years.

As the global battery market scaled up, it reinforced the rise in energy density and fall in cost, which in turn accelerated uptake. The result was a rapid, exponential uptake of battery demand.

Figure 4: Battery demand by sector, GWh/y



Source: Ziegler and Trancik (2021),[10] Placke et al. (2017)[11] for 1991-2014; BNEF Long-Term Electric Vehicle Outlook (2023)[12] for 2015-2022 and the latest outlook for 2023 (*) from the BNEF Lithium-Ion Battery Price Survey (2023).[13]

Supply responded

As battery demand rapidly grew, so supply had to respond. It did so by mounting a supply chain scale-up, at a pace not seen since World War 2 (as pointed out by the International Energy Agency (IEA)).[14]

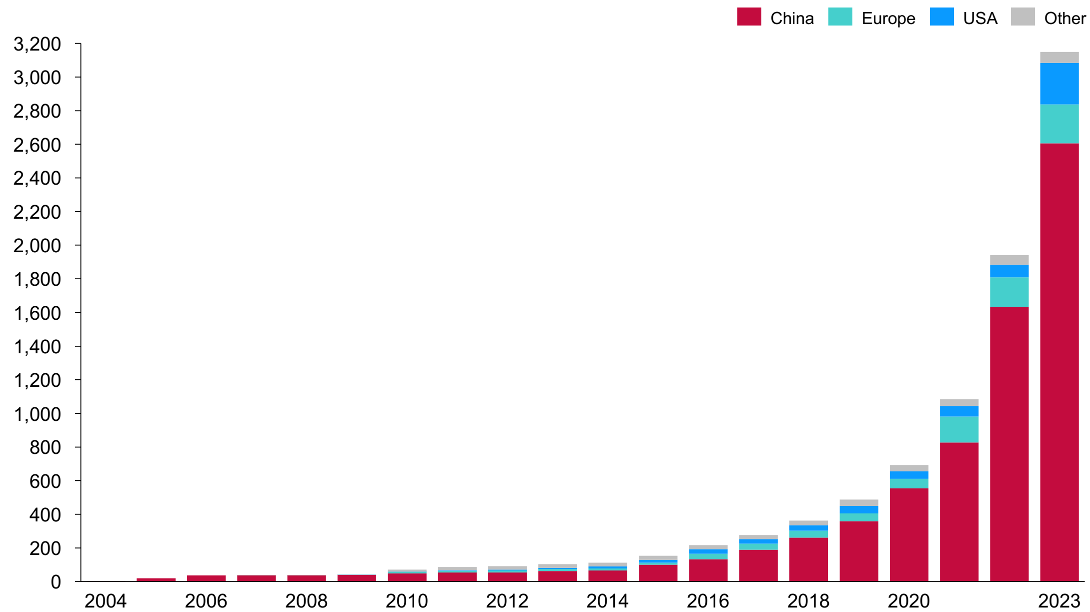
Manufacturing capacity built out

Battery demand grew fast over the past decade, but even so, manufacturing supply has been able to outpace it: demand grew by a factor of 24, yet battery manufacturing capacity went up by a factor of 42. As battery manufacturers are expecting more growth to come, annual manufacturing capacity additions are still rising — today's annual commissions of new factories are more than 18 times those of just five years ago.[15]

As the prospect of rising demand became apparent, investment markets paid attention and made ample capital available.[16] According to Bloomberg New Energy Finance (BNEF), investment in battery factories today ($45 billion in 2022) is considerably higher than investment in solar and wind factories combined ($33 billion).[17]

As capital availability ceased to be the primary limiting factor, the challenge of meeting demand has primarily been an engineering one: factories need time to be built and start operations. Companies are becoming more proficient at building out factories — the first battery gigafactory opened in 2016, and now dozens are under construction. According to Benchmark Minerals, there are now 240 operational gigafactories across the world, and this is set to increase to over 400 by 2030.[18] These factories can be deployed rapidly: in Western countries it usually takes one to two years to build a large battery factory, but in China this can now be done in as little as six months.[ii] With sufficient advance planning and reliable forecasts on expected demand, battery manufacturing has been able to scale up rapidly to meet demand.

Figure 5: Installed battery manufacturing capacity, GWh/y capacity



Source: BNEF,[19] RMI analysis

Mineral mining sectors expand

The rise of batteries disrupted many mineral mining sectors that had long been niche. As battery demand grows at a breakneck pace, these sectors are racing to catch up.

Mining of minerals such as lithium, cobalt, and nickel is undergoing exponential growth. For example, in lithium mining, over 60% of current mining production assets is less than five years old.[20] Investments in lithium extraction is increasing by over 30% annually, and new technologies like direct lithium extraction (DLE) are attracting significant funding. Major companies, including Exxon with its new DLE site in Arkansas, are entering the field, indicating further acceleration of growth.[21]

Batteries have rapidly taken over the role of main demand driver across minerals. According to the IEA, in 2022, EV batteries accounted for 60% of lithium, 30% of cobalt, and 10% of nickel demand.[22]

This scale-up has not been without challenges. Issues such as labor rights, environmental impacts, and the socioeconomic effects on local communities are increasingly coming to the fore. For example, cobalt mining in places such as the Democratic Republic of Congo has raised concerns over ethical sourcing due to reports of hazardous working conditions and child labor.[23] We discuss how these challenges are being tackled in section 2 and provide more detail in the appendix.

[ii] For example, consider Tesla's Giga Nevada (2014-2016), Giga New York (2014-2017), and Giga Texas & Giga Berlin (2020-2021), but also China's Giga Shanghai (2019, 168 working days).

Innovation accelerated

As the battery market grew, so did the R&D budgets that companies and governments were willing to spend on it, driving energy density and cost improvements.

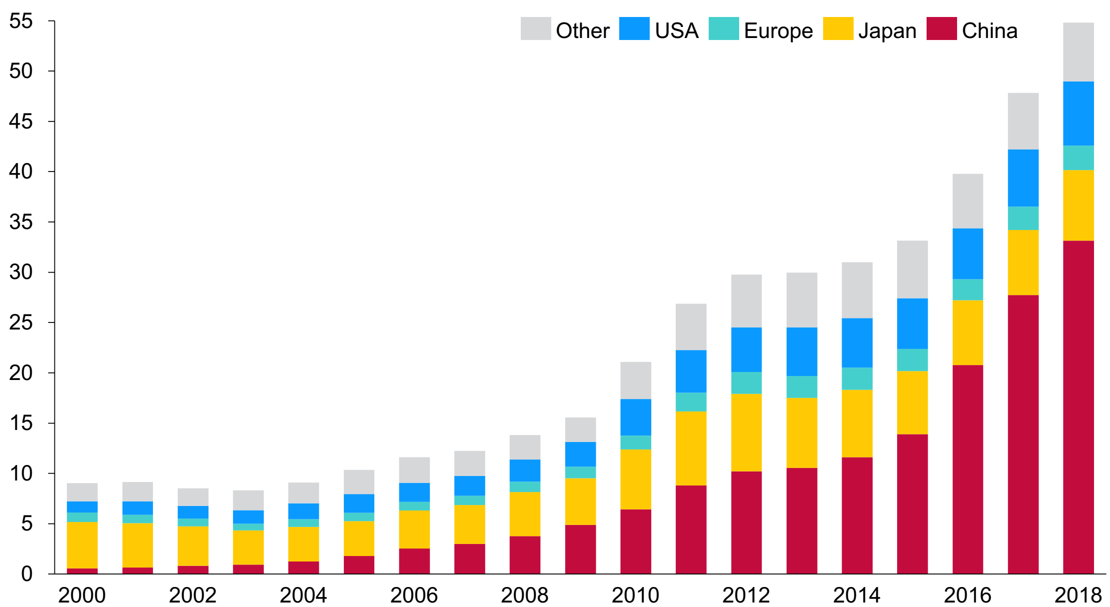
Cell innovation boomed

R&D spending has been essential in improving energy density and battery cost. Analysis by Ziegler, Song and Trancik shows that some 55% of cell cost decline came from public and private R&D — and only 45% from other drivers, such as economies of scale.[24]

New battery models need extensive lab research time and costly testing equipment. Just opening up a battery lab for research can easily come with a $5 million start-up cost.[25] As fundamental battery research got funded, the battery research community grew quickly; academic publications on batteries increased fivefold over the past decade.[26]

As more money came into R&D, the pace of technology breakthroughs accelerated. Annual patent filings on batteries have risen by 15% per year over the past decade. In 2018 (the most recent year with full data), the number of patents filed during the year was more than twice the rate from just seven years before.[27] This suggests that innovation continues to accelerate, and we can expect more breakthroughs in years to come.

Figure 6: Battery patents filed over time by region, thousands of filings per year



Source: IRENA, via Our World In Data[28]

Innovation in design and business and delivery models

Equally important breakthroughs were made in the way batteries were built into technologies, and which business and delivery models were able to make for a better user experience.

Tesla understood early on that batteries are the most important part of the EV. Collaborating with Panasonic, Tesla designed its cars around the battery to optimize EV cost and operational performance. To address range anxiety, Tesla also developed one of the largest EV fast-charging networks in the world.[29] The market valuation of Tesla today eclipses that of all other traditional car manufacturers.[30]

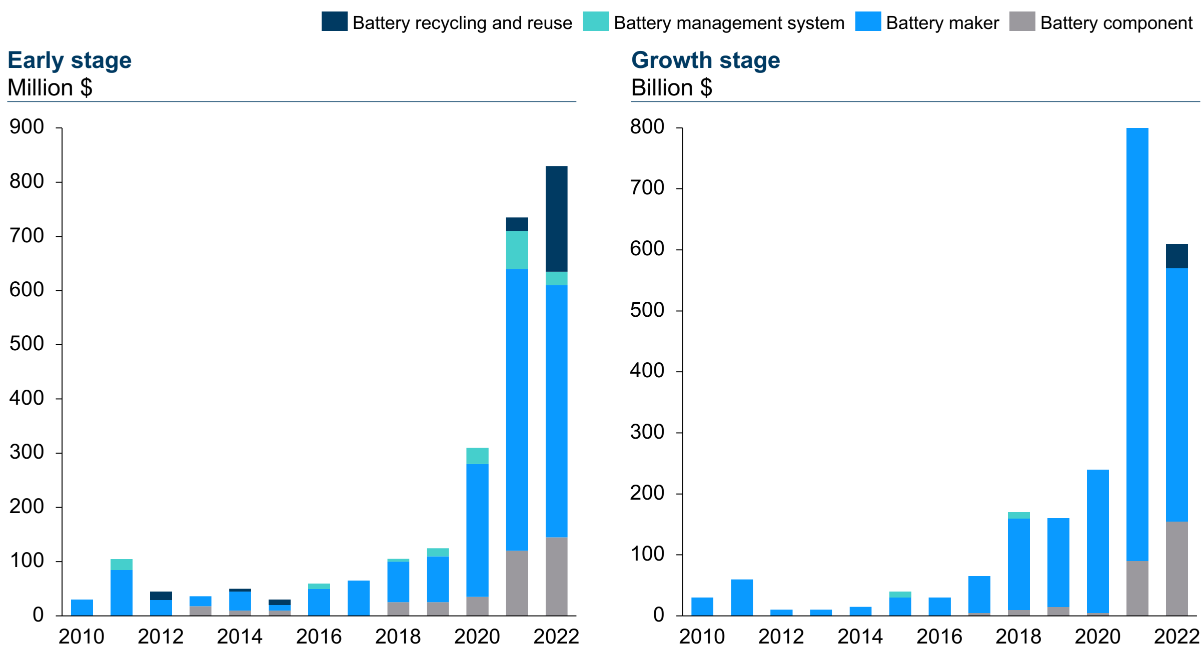
Companies such as Sun Mobility, Gogoro, and Battery Smart have successfully adopted a battery swapping model for smaller vehicles such as scooters and mopeds in India, with companies such as NIO working to bring battery swapping to passenger vehicles in China as well.[31] This reduces charging waiting times, grid constraints and charging anxiety, and is a reimagination of what it means to 'fuel' your vehicle.

Stationary battery companies have found significant cost reductions not only in cell technology but also in construction processes.[32] In the battery-electric aviation sector, companies like Eviation, Airflow, and Beta Tech are rethinking the aviation business model — shifting from traditional flight patterns to shorter, battery-feasible routes.[33]

Investment in innovation increased

Venture capital has been paying close attention. Investments in battery innovation surged over the past decade. Early and growth stage funding are both an order of magnitude larger than just five years ago.

Figure 7: Venture capital investments in batteries



Source: IEA Global Electric Vehicle Outlook (2023)[34]

The battery domino effect

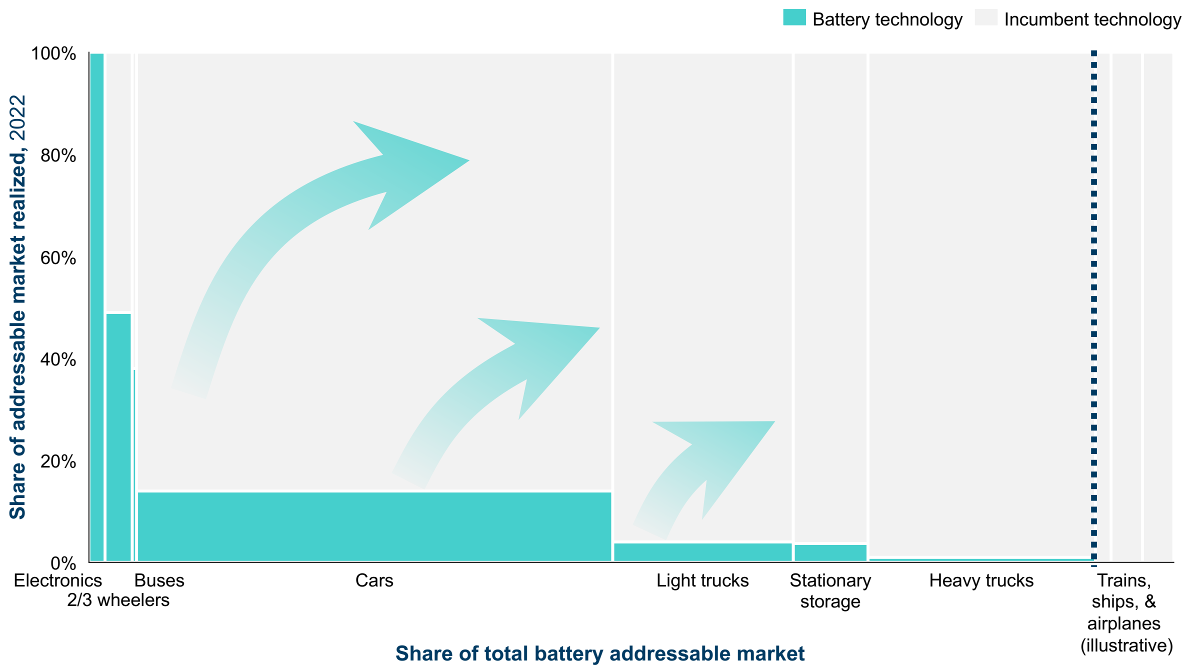
Batteries are adaptable, modular, and can be used across key energy sectors and geographies. Their versatility has enabled scale and innovation in one domain to catalyze initial uptake in others, creating a domino effect of adoption.

The sectoral domino effect

This domino effect started from electronics and then moved to two- and three-wheelers, buses and cars. Today, battery technology already makes up 50% of two-/three-wheelers and 40% of bus sales. The largest domino has also fallen with cars — as discussed in the previous X-Change report on cars, EV cars have hit a tipping point and are set to capture all of passenger cars. Today, most electric passenger cars already are at cost parity with ICEs on a total cost of ownership basis.[35] Sticker price parity is expected to be achieved soon as well.[36] Early 2023 figures show that almost 20% of global car sales are EV today.[37]

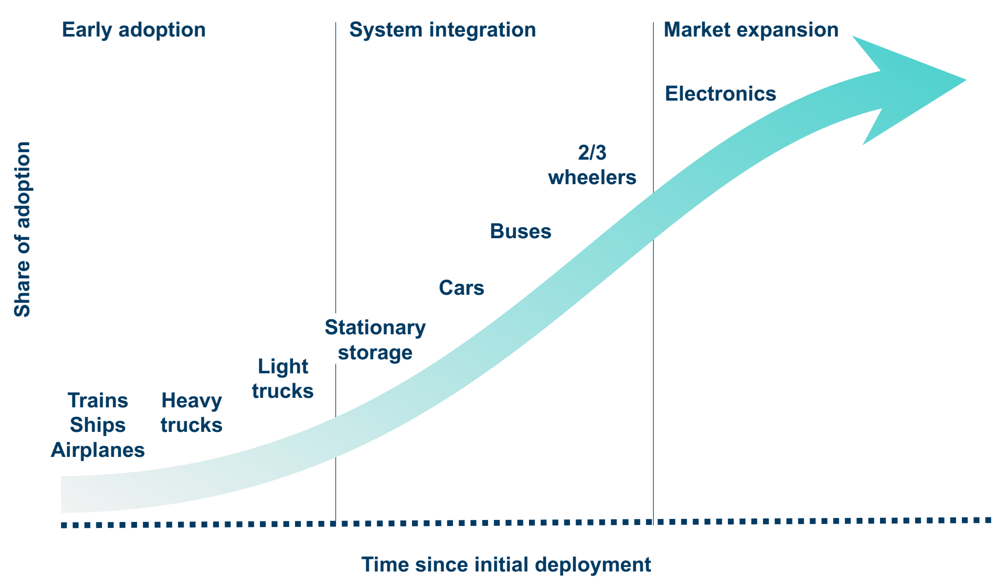
After cars, more sectors are ready to tip as well. We will discuss them in section 2.

Figure 8: The battery domino effect by sector



Source: BNEF[38], RMI analysis; Electronics share of addressable market percentage indicative, transport percentage based on 2022 EV sales share, stationary storage defined as sales volume today divided by peak sales in long term (2050). Trains, ships, and airplane total addressable market sizes illustrative.

Figure 9: Stage of battery adoption by sector — concept chart

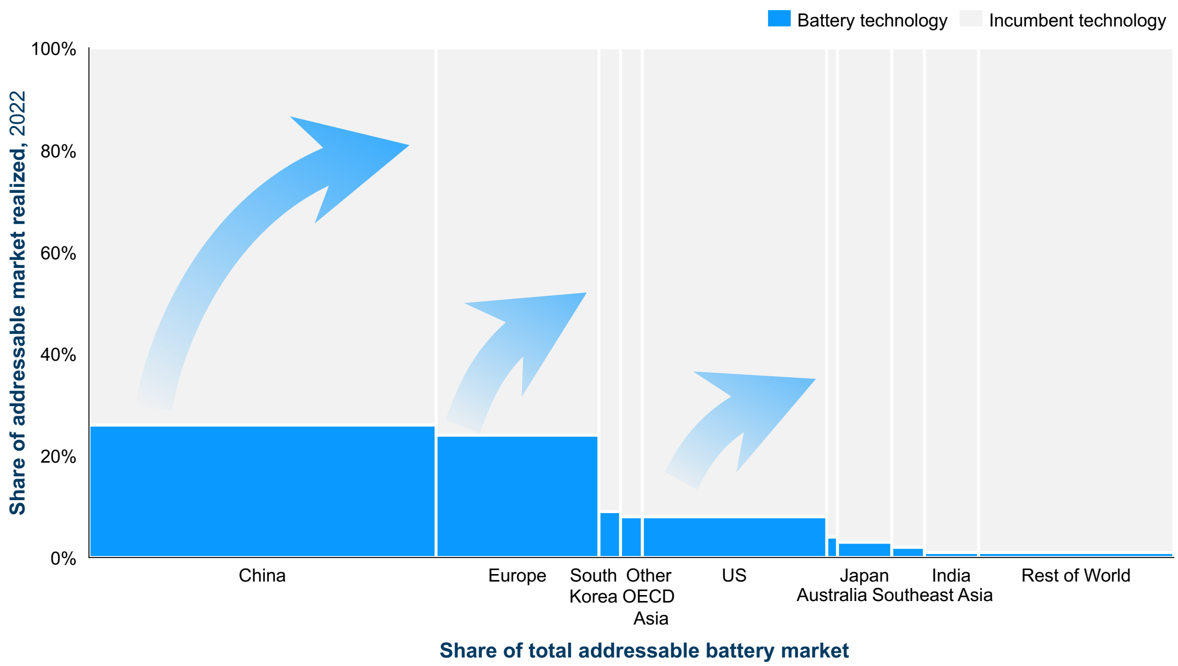


Source: RMI analysis

The country domino effect

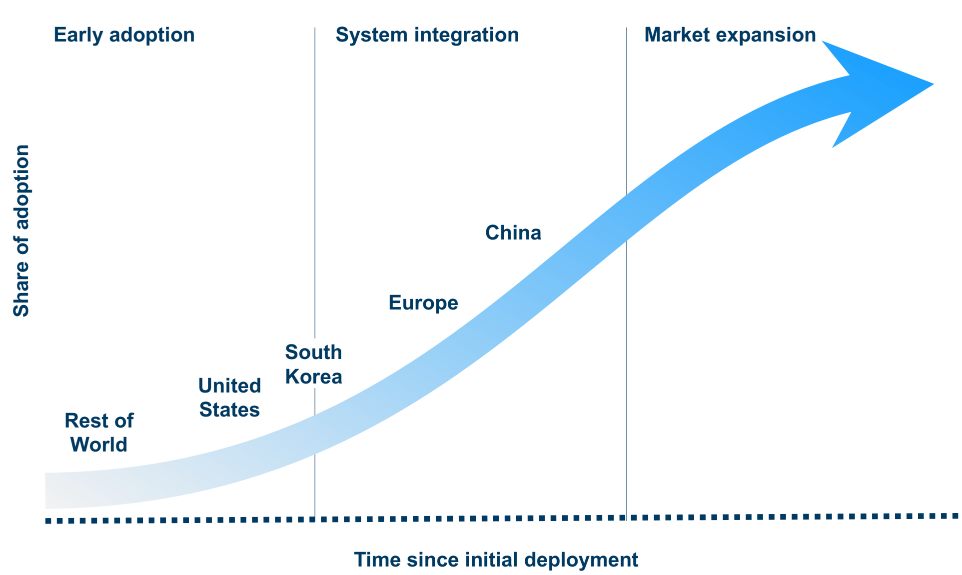
Battery technology growth did not happen uniformly across countries. China has been a clear frontrunner in the battery revolution. But Western countries are catching up. As the battery domino effect gained momentum, governments started to realize batteries are an essential part of their energy future. The geopolitical competition over batteries accelerated innovation and turbocharged the scale-up of batteries.

Figure 10: The battery domino effect by country — EV car example



Source: BNEF[39], RMI analysis; share of addressable market based on sales share in 2022

Figure 11: Stage of EV car battery adoption by country — concept chart



Source: RMI analysis

China leads the charge

China is the frontrunner in battery uptake, leading the EU and United States in battery sales across all key sectors. This is in part because China was early to the game. Already in 2015, EV sales for two-wheelers in China were over 50%, versus 0-1% in the EU and US. Similarly, EV sales for buses were over 50% in China in 2020, compared to about 10% in the EU and US.[40]

Over recent years, one country after another started to catch up. New policies were introduced to promote battery uptake. In the EU, a suite of incentives — including tax exemptions and rebates, alongside non-monetary benefits such as access to bus lanes — spurred the rapid adoption of EVs.[41,42,43] In the US, the Inflation Reduction Act of 2022 also introduced a set of incentives, offering substantial tax credits for electric passenger vehicles and home battery storage solutions.[44]

Subsidies historically focused on lighter vehicles, but in the past year a similar policy push has taken shape for heavy trucks as well. For example, the US Inflation Reduction Act is set to provide incentives for heavy duty electric trucks of up to $40,000 per vehicle, making the cost per mile close to parity with traditional diesel trucks.[45]

Other countries are also trying to enter the race. India is actively promoting the uptake of battery technology by implementing incentives like the FAME-II scheme, the PLI scheme for battery storage, a battery swapping policy, reductions in customs duties for battery materials, and establishing special e-mobility zones.[46]

Meanwhile, China is not sitting still. It has introduced significant incentives such as financial subsidies and tax deductions for EVs. For example, China spent about $57 billion to support electric car purchases between 2016 and 2022, over five times what the United States spent in the same period.[47] National subsidies for EVs concluded in 2022, marking a pivotal transition where the economics of EVs, having reached cost parity, began to drive the market independently of government intervention.[48]

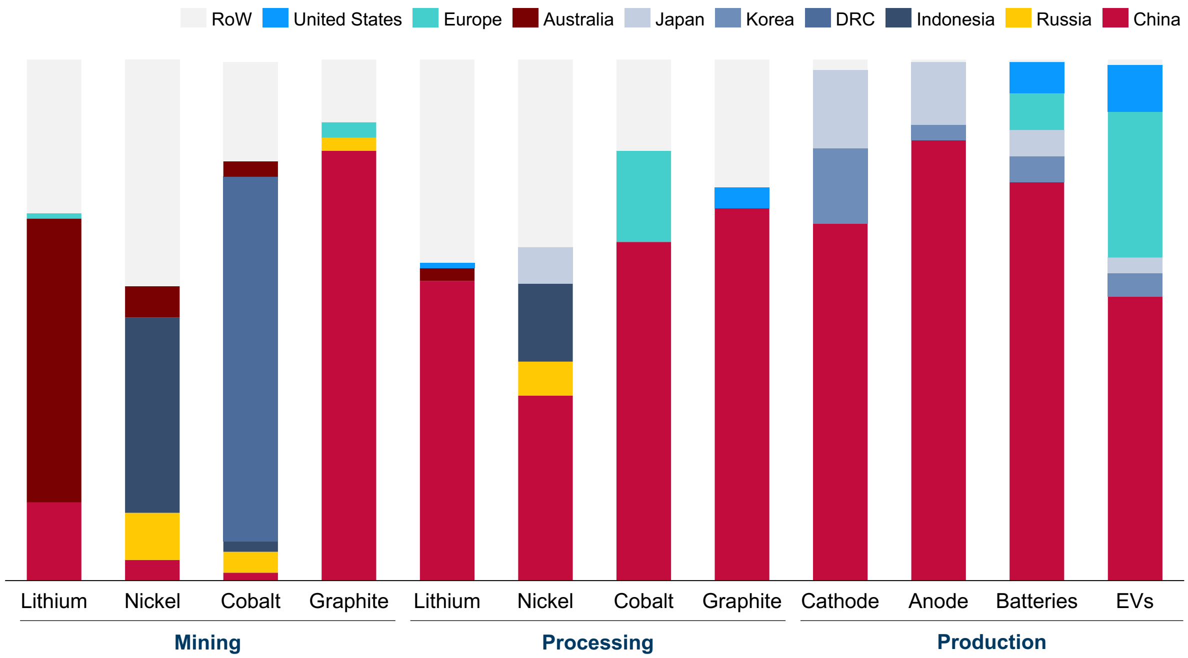
China dominates battery supply

China not only dominates demand, it also leads battery supply. Some 77% of batteries are made in China today.[49] The country's leading position is not limited to sheer volume — China has also made remarkable strides in innovation and lead battery patents today (see Figure 6). A prime example of China's pioneering efforts is the recent unveiling by CATL of its cutting-edge 500 Wh/kg battery cell.[50]

China's dominance in battery technology is a relatively recent development. The origins of lithium-ion batteries trace back to innovation by US oil companies in the 1970s (notably, Exxon).[51] Initial progress was abandoned in the 1980s as oil & gas companies doubled down on fossil fuels. It was not until the 1990s that lithium-ion batteries found commercial success in electronics, thanks to Japanese firms such as Sony and demand from rich OECD countries. It was only in the late 2000s that China ascended to the role of the primary consumer, innovator, and producer of batteries.

Today, Western nations are reentering the fray. Bringing battery manufacturing to home soil has become a focal point of industrial policy in both the United States and the EU.[52] The additional support for R&D and factory development is driving further battery uptake.

Figure 12: Share of battery value chain by region, % of total



Source: IEA Global Supply Chains of EV Batteries (2022)[53]

Energy security concerns boost domestic demand and supply creation efforts

In response to a resurgence in energy security concerns triggered by Putin's invasion of Ukraine, both the EU and the United States have taken legislative actions that promote domestic battery manufacturing and the development of clean energy technologies.

In the EU, the RePowerEU legislation seeks to reduce dependency on imported fossil fuels, especially from Russia. It does so through targeted programs that include promoting EVs to curb oil demand and stationary batteries to replace gas peaker plants.[54]

In the US, the Inflation Reduction Act contains $500 billion in new spending and tax breaks aimed at boosting clean energy. The act provides significant incentives for domestic battery production as part of its broader strategy to catalyze investments in domestic manufacturing capacity and promote the procurement of critical supplies, such as battery minerals, domestically.[55]

The effects of these policies are already apparent. Over the past year, battery investment significantly picked up in the US and EU to re-shore supply. In the United States, 14 new battery gigafactories with a total capacity of over 400 GWh/y were announced since the IRA was passed (a jump of almost 60% versus the year before).[56] The EU is expected to come up with a response to the IRA that will target building an equal amount of capacity in Europe.[57] China's plans for the development of gigafactories remained unchanged since the passage of the EU and US policies; the additional capacity is coming on top of — not instead of — Chinese manufacturing build-out.

Experts keep underestimating batteries

Despite the clear exponential trend batteries have been on for decades, experts kept underestimating the pace of change. A systematic underestimation of the improvement potential of energy density and costs led to battery uptake outlooks that were far too pessimistic. This trend persists today.

Underestimating energy density

It is notoriously difficult to forecast technological advancements, and most experts have been careful not to make explicit assumptions on future energy density. Nevertheless, implicit assumptions on energy density permeate the outlooks of incumbent energy modelers. New battery applications have been dismissed based on low technology readiness levels or the lack of models on the market — all of which implicitly assumed energy densities at the time of analysis would not improve. They almost always did.

This underestimation has followed a clear pattern.

Initially, experts estimate that low energy density will confine batteries to a niche role in a sector. For instance, the first laptops were expected to have limited use except for those who could really benefit, such as the military and traveling salesmen.[58] Similarly, not too long ago, EVs were seen as suitable only for small cars in dense urban areas.

Then, as battery-powered technology continues its ascent, expert outlooks change, acknowledging a significant role for batteries in the sector, except for a final niche that needs even higher energy density. The IEA's 2009 EV technology roadmap envisioned that half of car sales would not switch to EV, even by 2050, due to their limited range.[59] Even in 2017, McKinsey estimated that a third of the car fleet would need hydrogen technology to decarbonize.[60]

Later, the narrative shifts again, with experts predicting a complete takeover by battery-powered technology. The latest IEA EV outlook states that the entire car segment can switch to EV.[61]

This trend has played out in electronics (laptops versus desktops), two-/three-wheelers (EV versus ICE scooters) and is unfolding in real time in cars today.

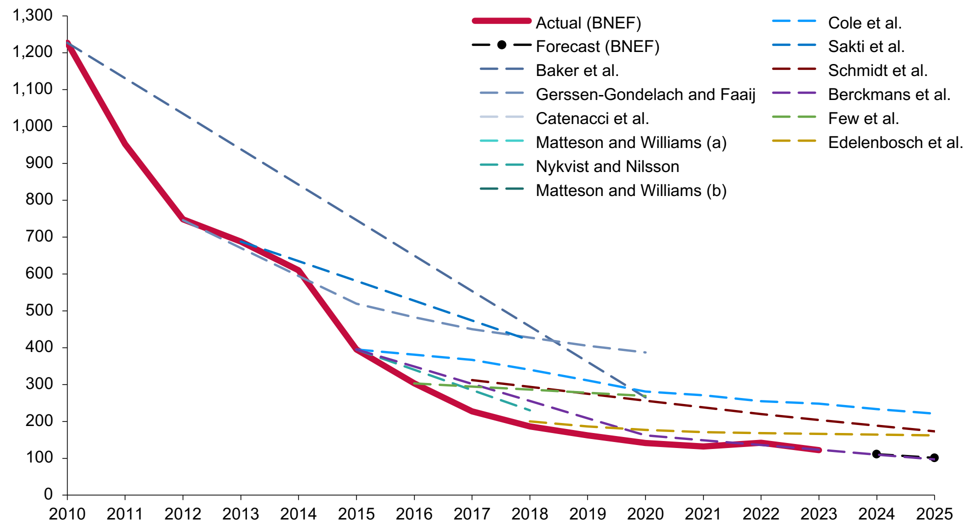
Even when batteries are initially seen as unsuitable for a certain sector, they tend to find their entry in niche or hybrid applications. Many of the early successful EV models, for example, were smaller city cars, or hybrid battery-ICE cars. Once early models are successful and drive further scale, improved energy density and costs enable further market capture.

Overestimating cost

While energy density has been underestimated, costs have consistently been overestimated. Outlooks from as little as five years ago overestimated today's battery cost by a factor of 2. Notably, until 2022 no mainstream forecasts seem to have underestimated cost, showing a clear bias towards conservatism.

Only with the global inflationary pressures of 2022 did costs rise above forecast levels. But battery cell costs have started to fall again – to the lowest-ever level of $107/kWh in 2023 (using real 2023 dollars), according to BNEF's annual Lithium-Ion Battery Price Survey.[62] Monthly prices even fell below $100/kWh in August this year, according to Benchmark Minerals' monthly battery price tracker.[63] And that would put battery costs well below forecasts again.

Figure 13: Battery cell costs, expert forecasts vs. actuals, $/kWh



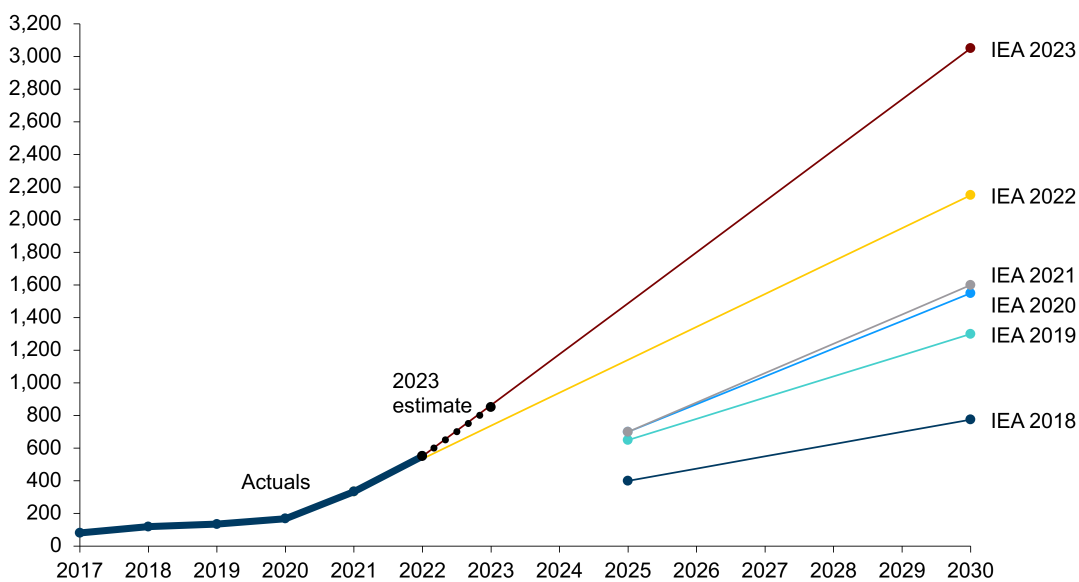
Source: Mauler et al. (2021)[64] for expert forecasts of 2010-2018, BNEF Lithium-Ion Battery Price Survey (2023)[65] for actuals and most recent forecasts.

Underestimating sales

Underestimation of battery energy density and overestimation of cost led to the underestimation of battery demand growth. For example, BNEF battery demand outlooks from as recently as two years ago were off by a factor of two compared to actuals today.[66]

A similar trend is unfolding for near-future outlooks. The IEA only started to publish battery outlooks in 2018, and its first four forecasts (2018 to 2021) all had 2025 battery demand at no more than ~700 GWh/y[67] — but we are already exceeding this level in 2023.[68] Experts keep being surprised by the pace of change.

Figure 14: Automotive lithium-ion battery demand, IEA forecast vs. actuals, GWh/y



Source: IEA Global EV Outlook (2018-2023)[69] current policy scenarios and actuals; BNEF Long-Term Electric Vehicle Outlook (2023)[70] for 2023 estimate. Historical data are similar across the two IEA and BNEF sources, so the 2023 BNEF estimate is shown for comparison.

2 The drivers of change will strengthen

Drivers of rapid change will intensify over the coming decade. Policy action and private sector investments will increase, costs will go down, energy density will go up, new markets will form, supply chains will mature, and barriers will continue to be overcome. The stage is set for continued rapid expansion of batteries.

Therefore, in line with the methodology we have used across the X-Change report series, we set out in the rest of this note two key scenarios for the future, described as 'fast' and 'faster'. Both scenarios assume that battery sales continue to follow S-curves in line with the trend seen in other cheap modular technologies. As explained in more detail in the appendix, the fast scenario assumes a more conservative S-curve and the lower bound of learning rates for energy density and cost, while the faster scenario uses a more aggressive S-curve and learning rates. Our analysis of the forecasting power of S-curves suggests that actuals are likely to lie between these two curves.

Policy action will increase

As batteries continue to rise in significance, so governments will make strategic policies to secure, improve and grow supply. Already today, governments are making targeted policy to accelerate the battery industry, as outlined in the previous section. The battery "arms race" has only just started — one can expect more aggressive policies to accelerate the build-out for more and better batteries in the coming decade.[71]

Despite protective policies from the West, China is expected to continue to lead the battery revolution for the foreseeable future.[72] Chinese companies are adapting their strategy to deal with protective trade policies in the West, for example by expanding battery production to Western shores — although Western countries are also making policy that makes that harder.[73] According to BNEF estimates, China's battery production capacity will remain an order of magnitude larger than that in the West for at least another five years.[74] In the coming decade, Chinese companies are expected to continue to produce the most and the highest quality batteries.

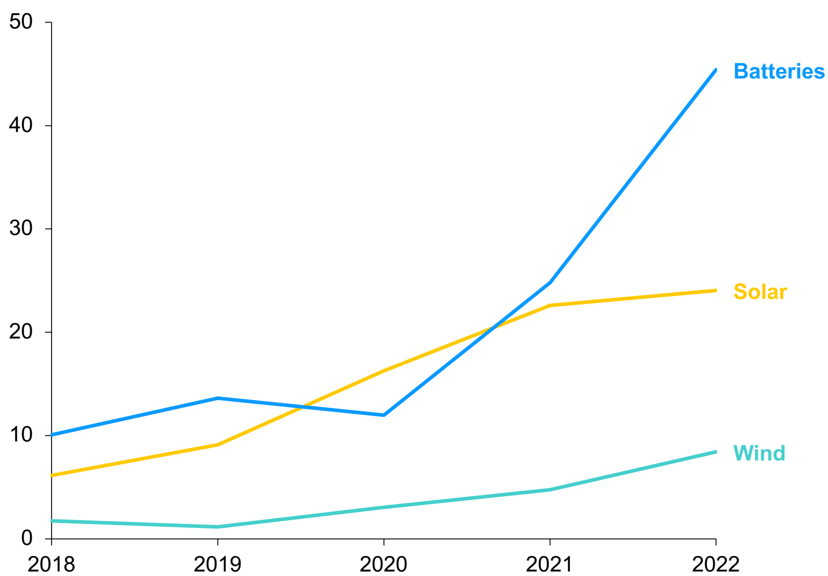
Nevertheless, markets in the United States, Europe, OECD Asia and India will continue to try and catch up. This arms race will speed up the battery domino effect.

Corporate investments will grow

Companies worldwide are competing in an ambition loop to produce the best and most cost-effective batteries.[75] Investments in battery factories and EVs are expected to continue their sharp rise across the world.[76] And investments in new battery start-ups and scale-ups continue to surge. So far this year, several battery start-ups have raised over $1 billion in funding, including: Verkor ($2.1 billion) Redwood Materials ($1 billion in Series D funding) and Northvolt: ($1.2 billion).[77] The total funding going into battery start-ups is expected to exceed $12 billion in 2023 — more than six times as much as only five years ago.[78]

It is notable that investment in battery factories is now the largest part of the capital expenditure on technology in the energy transition, according to BNEF. This trend is set to continue. Battery manufacturers have already committed to hundreds of new factories that will lead to a surge in global manufacturing capacity this decade.[79]

Figure 15: Investment in clean tech factories, $ bn/y



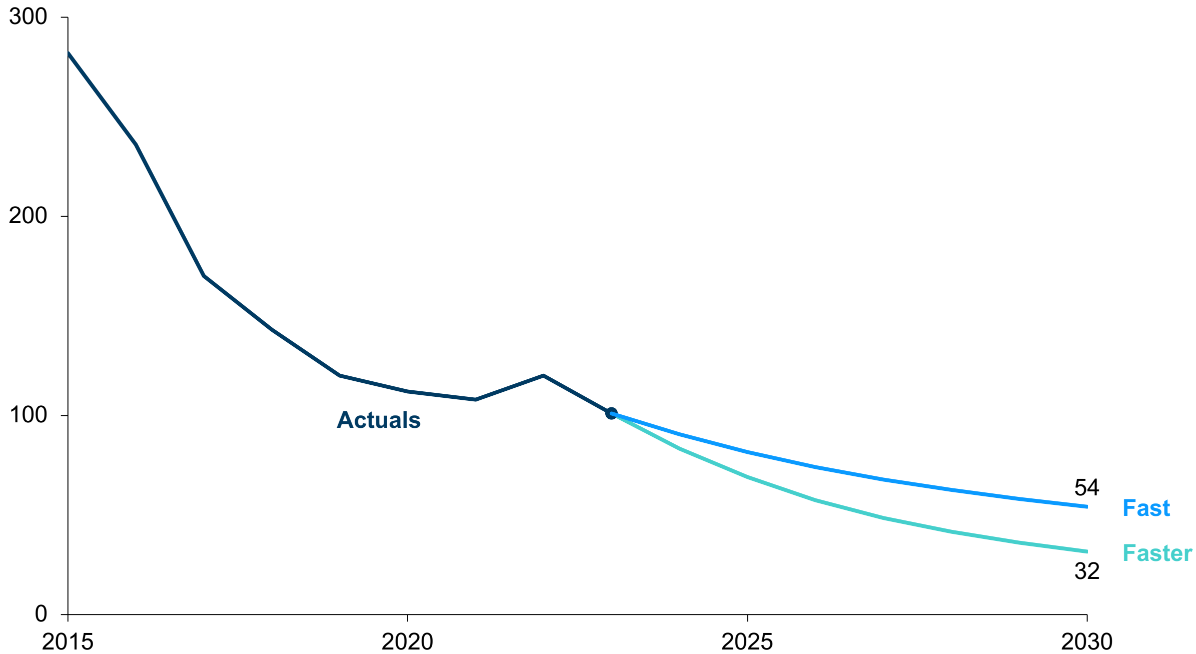
Source: BNEF[80]

Costs will continue to fall

As batteries continue to grow, so costs will fall. Continuing the 19%-29% learning rate identified in section 1 and assuming sales growth of 29%-35%, as we will derive in section 3, would imply that 2030 battery cell costs will end up at $32-54/kWh, depending on the speed of the transition — the faster the uptake, the faster costs will fall due to learning effects and economies of scale.

And, in turn, as costs fall, uptake accelerates. EV cars are already competitive in most regions in the world on a total cost of ownership basis.[81] As cell costs keep falling and reach about $80/kWh, EVs will be at sticker price parity with ICEs.[82] Battery cell prices fell to below $100 USD/kWh for the first time this summer.[83] In both a fast and faster transition, EV car sticker price parity will be achieved by 2025. This will further increase uptake of EV cars, leading to continued technology learning and economies of scale.

Figure 16: Battery cell cost outlook, USD/kWh



Source: BNEF[84], RMI analysis based on and historical learning rates and deployment outlook. Fast assumes demand of 5.5 TWh/y by 2030 and 19% learning rate. Faster assumes 8 TWh/y demand by 2030 and 29% learning rate. Note 2022 USD.

Other cost forecasts

Our projections suggest that 2030 battery cell costs will be only a little lower that prominent forecasts. For example, BNEF predicts a cell price of $56/kWh, based on long-term trends since 1992.[85] Goldman Sachs estimates a slightly higher cost of approximately $60/kWh in 2030, attributing much of this reduction to falling raw material costs.[86] Other recent research estimates are even higher, based on higher assumptions for future mineral costs.[87] The difference between our forecast and those of establishment modelers comes from higher learning rates and higher growth rates in our forecasts.

Energy density will continue to rise

As the battery market and R&D grow, so energy density will keep rising. To get a sense of where top-tier energy density may end up by the end of the decade, we can extend the 7%-18% improvement rate trend (as identified in section 1) to 2030, again using the sales growth rates of 29%-35% derived in section 3.

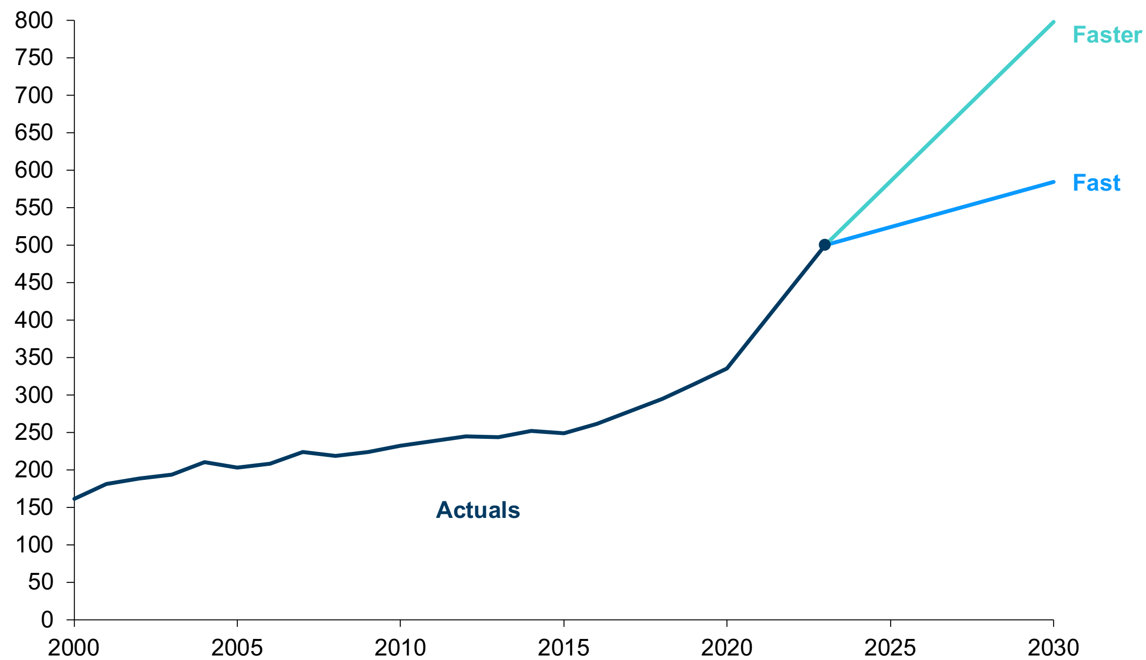
Projecting energy density forward with this improvement rate leads to a 2030 leading battery cell energy density of ~600 to 800 Wh/kg. We focus here on the battery energy density of the leaders, not the average, because the focus is on new applications and markets for batteries, rather than the average across existing applications.

As top-tier energy density rises, new battery applications will unlock. At around 400 Wh/kg, long haul trucking becomes economically attractive.[88] At 500-650 Wh/kg, short haul electric aviation becomes feasible.[89] Both are within striking distance after CATL's 500 Wh/kg battery cell announcement. As more 500+ Wh/kg batteries enter the market over the coming decade, long haul trucks will decidedly tip, and electric aviation can start to take off.

Besides unlocking new applications, higher energy density will also enhance the attractiveness of existing battery technologies. The new generation of (semi-)solid state battery cells of 500+ Wh/kg are set to double EV car ranges compared to today.[90] That would put an end to any residual EV range anxiety.

Not only top tier, but also average energy density will rise. This will be driven by new chemistries and expiring patents. For example, CATL's patents on lithium iron phosphate (LFP) batteries are expiring, making their high energy density batteries more widely available for production, and spurring CATL to further innovate to find a new battery chemistry to patent and use to maintain and capture market share. Already in 2021, CATL introduced its first-generation sodium-ion battery and is continually advancing this technology.[91] Many other companies are following suit.[92]

Figure 17: Top-tier battery cell energy density outlook, Wh/kg



Source: Ziegler and Trancik (2021)[93] for 2000-2016, BNEF Long-Term Electric Vehicle Outlook (2023)[94] for 2017-2023, RMI analysis. Fast assumed 5.5 TWh/y by 2030 and 7% improvement rate. Faster assumed 8 TWh/y by 2030 and an improvement rate of 18%.

Other energy density forecasts

Other bottom-up expert assessments of future battery energy density appear to confirm the feasibility of our energy density projection. Already today, there are lab-scale battery cells with energy densities that exceed 700 Wh/kg.[95] These technologies are on their way toward commercialization. Argonne National Labs even states a potential of 1,200 Wh/kg if some breakthroughs are made sooner than expected.[96] These batteries still have a long road to the market, but lab results show that there is ample reason to believe top-tier cell density can rise well above 600 and towards 800 Wh/kg by 2030.

New dominoes will tip

After battery car uptake took off last year, the battery domino effect is turning to new sectors. We deal with each in turn.

Stationary storage takes off

Batteries are an ideal complement to variable renewable power generation, such as wind and solar. The inherent intermittency of renewables requires backup, such as batteries, to manage variability and ensure a consistent energy supply. Analysis by the IEA shows that over a third of flexibility needed on the 2050 grid will come from batteries.[97] Hence as wind and solar continue to grow exponentially, so will the stationary storage market. Annual stationary storage additions have grown by over 45% per year since 2018, reaching 35 GWh/y in 2022 — and are expected to nearly triple in 2023 to 99 GWh/y (according to BNEF).[98] This growth is taking place at the same time as the continued, exponential growth of renewables expected over the coming decade, as discussed in a previous entry of the X-Change series on electricity.[99]

The core driver of stationary storage growth is economics. As noted by many energy analysts, solar power coupled with battery storage is the cheapest source of firm electricity generation available today.[100,101,102] In 2022, over 40% of planned solar projects globally came with on-site battery storage.[103] In California, which is a frontrunner in solar power deployment, it was over 95%.[104]

Stationary storage is not only growing on the utility side of the electricity market. An increasing number of electricity consumers are buying batteries for onsite backup power. Already in 2021, 17% of US residential solar power installations were combined with battery storage.[105] Market reports expect home storage sales to grow by 20-30% per year for the coming decade.[106]

The expected long-term market size for stationary battery storage is ~1 TWh/y in both the economic transition and net zero scenarios by BNEF, which is similar to the amount implied by the IEA's net zero scenario.[107]

The actual long-term market size for stationary battery storage is highly dependent on a wide range of variables, and we expect to adjust forecasts as technologies evolve. They include the cost of other storage technologies and the ability to incorporate the batteries of the road transport fleet into electricity storage. For example, DNV forecasts that in 2050, total storage battery deployment will be 22 TWh, backed up by 14 TWh of transport storage from 10% of the transport fleet.[108]

The EV revolution reaches trucks

The battery domino effect is about to tip the trucking sector. Rapid change is already underway. Companies already have over 300 lighter EV truck models to pick from today, and 6%-7% of lighter truck purchases (and 1%-2% of medium-to-heavy trucks) are electric today.[109] To put that in context, EV cars passed the 5% threshold only in 2020 and are at nearly 20% today.[110] Availability is improving as well: there are over 100 heavy truck models already on the market. That is double the level of just two years ago and an order of magnitude more than five years ago.[111]

Total EV truck sales in China have doubled annually from 2020 to 2022 and stand at over 6% of total truck sales in 2022. The Western world is catching up, with the EU at about 4% and the United States at about 1% today.

Truck driving ranges are rapidly improving as energy density rises. It is just a matter of time before the new generation of high-density batteries reach the market and allow competitive driving ranges — likely not much later than mid-decade.[112]

Once they do, they will likely pick up fast: at today's battery price point, battery trucks are already competitive against ICE trucks on a total cost of ownership basis in many cases.[113] Analysis by BNEF foresees EV cost parity in all trucking sectors well before 2030, and already cost parity today for lighter trucking segments.[114]

Uptake of e-trucks will further accelerate battery growth, create more scale and allow for even larger R&D budgets. This in turn will benefit all other battery technologies.

The total long-term market size for batteries in light, medium, and heavy trucks is likely to be ~5 TWh/y (see appendix for sizing details).

Knocking on the door of "hard-to-abate" sectors

Batteries' momentum shows no signs of slowing. New solutions are on the horizon, and although uncertain, there are promising signs of the integration of batteries in trains, ships and planes.

- Rail already appears closest to a tipping point. New train orders across Europe signal a shift from diesel to battery-powered rail.[115] That should come as no surprise, as analysis shows that battery trains can be competitive with diesel trains at a battery price of $100/kWh, which we are rapidly approaching.[116] Uptake is still small, but the early signs of tipping are there.

- Ships have seen first battery uptake in niche, shorter haul segments.[117] At a battery pack cost of $100/kWh (cell price of ~$75/kWh), battery ships can become competitive with fuel oil ships on routes shorter than 1,500 km. On the current cost decline trend, this will happen (well) before 2030 in both the fast and faster transition. With another halving of battery price, up to 3,000 km can become economical.[118] When such long ranges are achieved, analysis suggests some 40% of container ship traffic could electrify.[119] The first models are being tested out today. In July of this year, China-based Cosco Shipping launched its first battery electric container ship, using swappable batteries.[120]
- Aviation applications start to become possible at 500-650 Wh/kg.[121] Today's top battery density already scrapes the bottom of that range. CATL plans to start using its new 500 Wh/kg battery for aviation, expecting to launch a first model in 2027. Trial flights are already ongoing.[122] Initial e-plane models will be small, but as battery density rises, larger planes will become viable. At an energy density of 1,000 Wh/kg, most regional (~1,000 nautical miles) aviation can turn full electric.[123] Based on the current top density improvement rate trends, we may only see announcements for such batteries after 2030 though.

Batteries can also be a good complement to other low carbon fuels in shipping and aviation. For example, Heart Aerospace claims that its hybrid airplanes can be up to 50% more efficient than conventional planes.[124] Such efficiency gains will greatly help these hard-to-abate sectors to get the most benefits out of the limited and costly sustainable aviation fuel supply available to them.[125] And as history has shown, once batteries get a foothold in a niche of a new sector, they tend to grow faster than expected.

The total market size of trains will be small, but ships and planes could be up to a terawatt-hour or two per year, depending on how far energy density and cost improvements carry battery technology.[iii] Most of this uptake will only come after 2030.

Barriers are rapidly diminishing

There are several barriers to battery growth today: the need for minerals, the sustainability and equity of the supply chain, and the build-out of charging infrastructure. Efforts are under way to actively address them all.

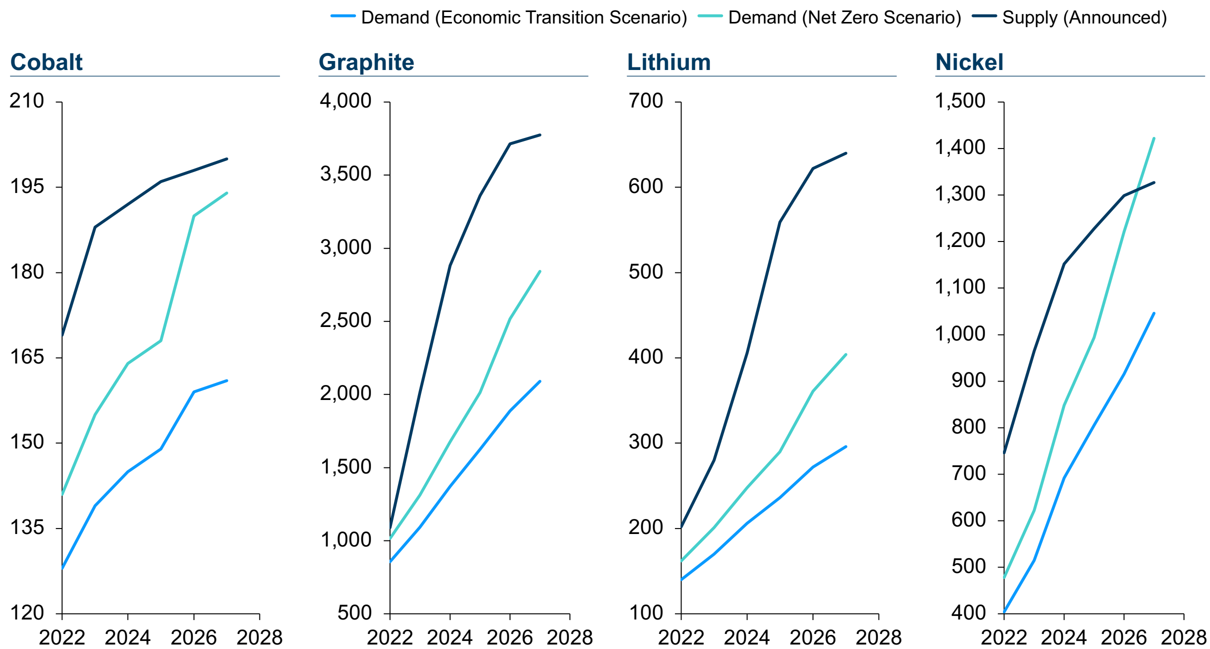
Mineral supply constraints are disappearing

Mineral supply constraints should be examined on two timescales: the short-term challenges of ramping up production, and the long-term consideration of reserve and resource limitations.

According to BNEF data in the figure below, battery mineral supply will be able to keep up with even very ambitious demand growth in the short term. This is due to ongoing acceleration of new investments in the battery mineral market. Battery mineral investments are growing by 30% per year, and as fast as 50% per year for lithium.[126] The construction of new mines and improvements in battery technology and efficiency are key factors contributing to meeting the projected demand for minerals such as lithium, graphite, cobalt and nickel. The anticipation of a short-term shortage and subsequent price hikes spurred investments that have helped alleviate market tightness, with critical mineral prices declining again over the past year.[127]

[iii] There are few good battery market sizing studies available. We can only make a high-level assumption. The Tesla master plan includes a 40 TWh shipping market. So assuming a 25-year ship lifetime means ships would be a 1.6 TWh/y market. The typical cross-Atlantic flight takes about 5 million liters of kerosene, or 500 MWh. After accounting for improved efficiency when switching from ICE to an electric motor, battery size per plane could be ~300 MWh. There are ~20,000 active planes in the world, so the total airplane market size would not exceed 6 TWh. Assuming a 20-year plane lifetime, this results in a 0.3 TWh/y market. Therefore, total market for ships and planes combined could reach up to ~2 TWh/y in demand.

Figure 18: Battery mineral supply and demand outlook, kiloton mineral per year



Source: BNEF Battery Metals Supply and Demand (as of June 1, 2023)

In the long term, analysis by the Energy Transitions Commission indicates there are more than sufficient battery mineral resources available for the entire energy transition.[128] Reaching net zero will only take one quarter of today's lithium, one-third of nickel and a quarter of known cobalt resources.

Moreover, as mineral supply has consistently been under pressure to scale, battery companies have invested heavily in innovation to help alleviate pressure on the mining sector. Innovation in higher battery energy density led to fewer minerals being needed per battery. The growth of the battery-recycling industry will alleviate demand for new mining of minerals.[129] The development of new battery chemistries such as sodium-ion, iron, lithium iron phosphate (LFP) cathodes, and silicon anodes can diversify the demand for minerals.[130]

ETC analysis shows that circularity can reduce mineral demand by up to 10% in the short term and possibly 50% in the long term, by extending battery life and recycling materials at end-of-life.[131] Driven by policies such as the EU battery pass and economic factors, battery recycling is rapidly evolving. PwC foresees a 50% cost reduction potential when pursuing recycling at scale, leading to economic viability of battery recycling in the EU by 2025.[132] As recycling scales, economics will increasingly take over from policy as the driver of battery recycling uptake.

The value chain is rapidly cleaning up

Emissions

Like all high-tech manufacturing, producing batteries comes with an emission penalty from the materials, electricity and heat used in the production process. This is currently estimated at up to 100 kg of CO_2 per kWh (but already as low as 45 kgCO_2/kWh in Sweden). However, by 2030, the battery industry is on track to dramatically reduce this footprint, targeting a reduction of over 75%. McKinsey analysis suggests that up to 80% decarbonization can be achieved with minimal additional costs, largely due to the growing role of renewable energy in electricity generation (which is in fact enabled by stationary battery storage, as discussed above).[133] Efforts by companies and policymakers are converging, with technological advancements and regulatory changes such as the EU's Carbon Border Adjustment Mechanism and the US Inflation Reduction Act driving better emission accounting standards.

As the cost-effective 80% of abatement is realized, 2030 battery production emissions will be no more than 160 MtCO2e, even in our faster transition scenario that foresees demand of 8 TWh/y by 2030. This is more than an order of magnitude less than the thousands of megatons CO2 abatement that those same batteries will enable (see Figure 24).

Social inequity

Addressing social inequity in the battery value chain, particularly in cobalt mines, has become a priority for the industry. Companies and stakeholders are actively implementing measures to ensure ethical sourcing and fair labor practices. Initiatives include stringent supplier audits to enforce labor standards, investment in technology to trace mineral origins, and partnerships with local communities to improve working conditions and livelihoods. Furthermore, significant efforts are being made to support educational and health programs in mining communities. These actions are complemented by a shift toward sourcing materials from regions with more robust regulatory frameworks, and by investing in alternative battery technologies that reduce reliance on conflict-prone minerals such as cobalt.[134] This multi-pronged approach aims to create a more equitable and sustainable battery value chain, mitigating the social impacts associated with mineral extraction.

Charging infrastructure will continue to scale

As more EVs enter the fleet, the need for charging infrastructure rises. Early uptake, particularly in EV cars, required less charging infrastructure per car: a 2018 study showed that only 5% of EV charging in the EU happened at public charging stations, as most EV owners were suburban and had space at home to charge.[135] As the EV revolution moved to urban car owners, publicly accessible charging points started to grow exponentially. Last year alone, they grew by 55% globally.[136] For comparison, EV car fleet growth has been around 62%-63% annually for the last five years.[137]

National governments are playing a pivotal role in this expansion. China is already home to the most EV charging stations globally, with over 1.8 million in 2022 — and its 14th Five Year Plan continues to promote charging station build-out, targeting 60% coverage nationally and 80% in densely populated areas by 2025.[138] The EU has approved new EV legislation that includes the construction of fast-recharging stations of at least 150kW for cars and vans every 60 km across the EU.[139] The United States is also making significant strides. Through the National Electric Vehicle Infrastructure (NEVI) Formula Program, it has allocated $5 billon of funding to support the development of over half a million chargers for a coast-to-coast highway network.[140]

The coalescence of strong government planning and proactive private sector involvement should be expected to continue the exponential trend of charging infrastructure rollout.

3 Implications of continued growth

We expect battery demand to grow by an order of magnitude and battery technology to capture all of road transport, enable renewables to clean up the power grid, and help decarbonize ships and airplanes. In doing so, batteries will put over half of global fossil fuel demand at risk and help to put the power and transport sectors on track to reach climate goals.

To concentrate on realistic near-term trends, we focus our forecasts on the period up to 2030.

Battery demand to grow by an order of magnitude

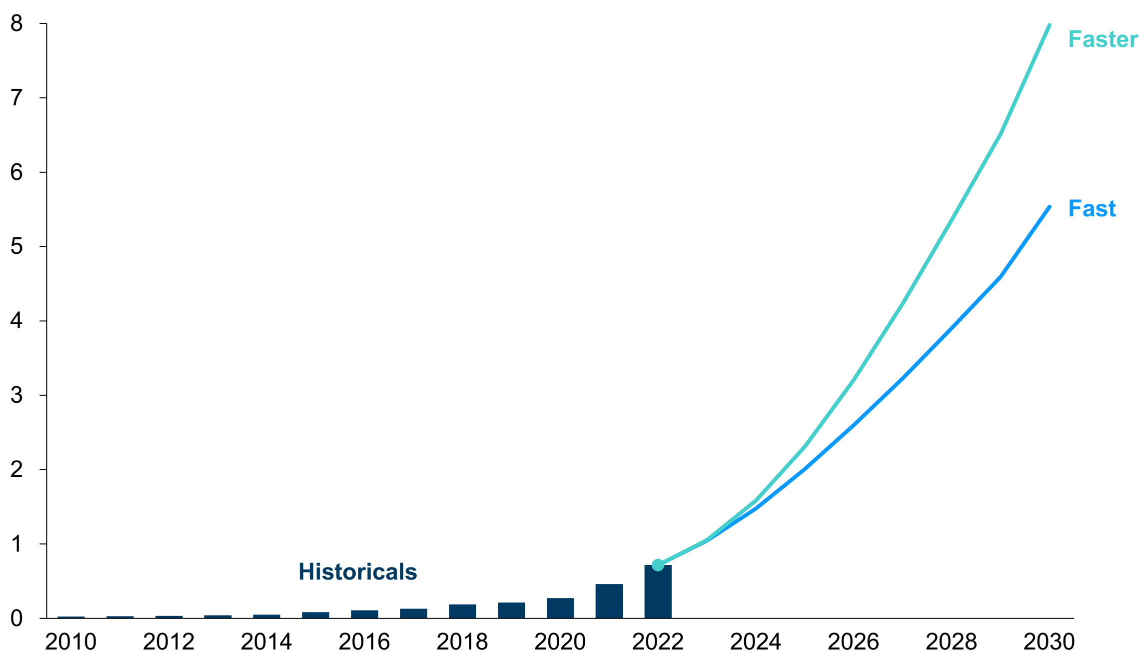
Every battery technology we have discussed so far is set to undergo exponential growth over the coming decade. EV cars (as discussed in more detail in the previous X-Change entry on cars), light trucks and heavy trucks will be the main drivers of battery demand growth over the coming decade — rising above 3,600, 500 and 600 GWh/y of demand by 2030, respectively. As renewables continue to grow (as discussed in the first X-Change entry on electricity), so stationary storage will grow above 500 GWh/y by 2030. The remaining small-demand areas of electronics, buses and two-/three-wheelers will collectively grow to at around 400 GWh/y. Battery demand from new segments in trains, ships and aviation will likely still be limited by 2030.

In total, we expect annual battery demand will grow to 5,500-8,000 GWh/y (or 5.5-8.0 TWh/y) by 2030, depending on the speed of the transition. This means that battery demand in 2030 will be 5.5 to 8 times larger than in 2023 (~1 TWh). After 2030, we expect demand will continue to grow to a terminal demand of around 13 TWh/y, or a factor of 13 larger than in 2023.

The battery industry is not unfamiliar with such growth: over the past decade, demand grew by a factor of 20 and manufacturing capacity by a factor of 30.

Battery manufacturers are already building out capacity for over 9 TWh per year of production by 2030, according to Benchmark Minerals and BNEF.[141]

Figure 19: Battery demand outlook, TWh/y



Source: BNEF,[142] RMI analysis

Batteries to become the biggest clean tech market

Such exponential growth will lead to a total global battery cell market of around $300 billion per year by 2030. To put this in perspective, the wind turbine and solar panel markets will each be below $200 billion in sales.[iv] Batteries are well on track to become the largest primary clean technology market in the world.

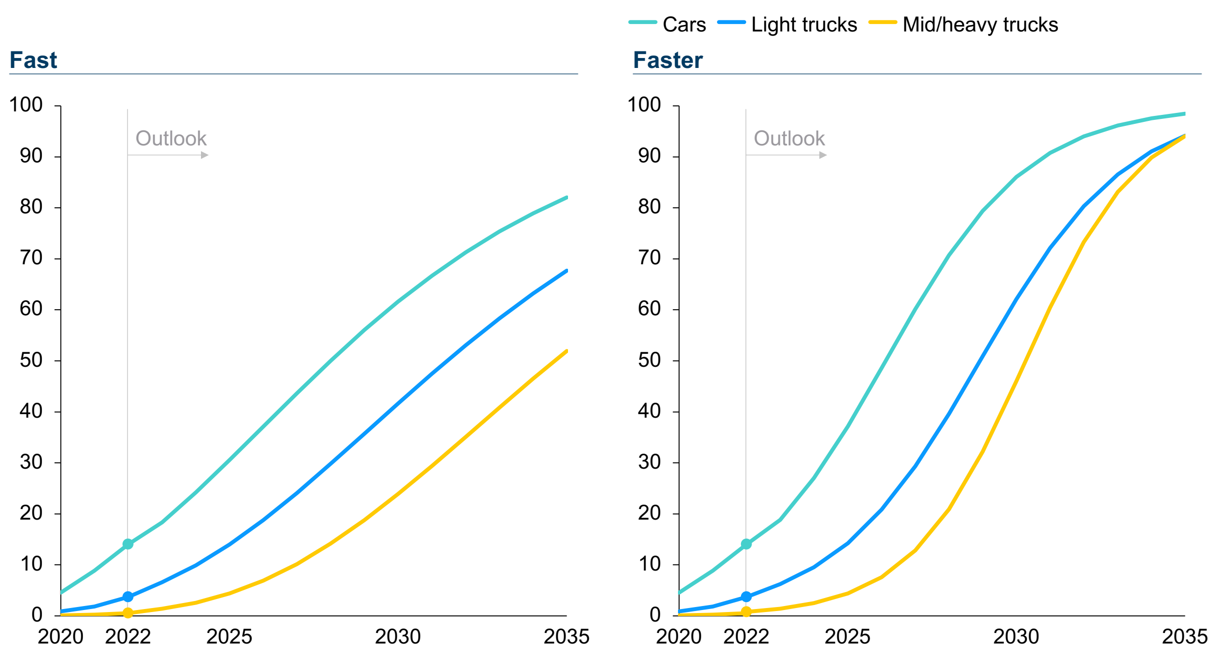
The battery domino effect will capture all of road transport

The battery domino effect will soon tip all road transport sectors. After cars, light and heavy trucks will follow.

In the fast scenario, we expect sales growth in trucks to follow a similar growth trajectory as that of cars, albeit delayed by a few years. Light commercial EVs have already passed price parity with ICE equivalents on a total cost of ownership basis and will rapidly grow to 10%-20% of sales by mid-decade. Heavy commercial vehicles will take another couple of years to reach price parity, but once this happens, they can be expected to reach 10%-20% of sales by the late 2020s. Under this scenario, we expect EV sales in 2030 to be approximately 60% in cars, 40% in light trucks and 20% in heavy trucks.

In the faster scenario, EV sales reach approximately 90%, 60% and 50% of sales across cars, light and heavy trucks, respectively, by 2030. Notably, in such a faster scenario, truck EV sales may follow a faster growth trajectory than car sales. This is in part due to the S-curve method we use: the earlier on the S-curve we are today, the wider the S-curve range between fast and faster (more on this in the appendix). But there is also good reason to believe commercial vehicle sales may move faster than cars: commercial players are more cost-driven and plan more long term. Once cost parity is reached, one may expect a faster shift in commercial segment sales than in cars.

Figure 20: EV sales in cars and commercial vehicles in fast and faster scenarios, % of sales

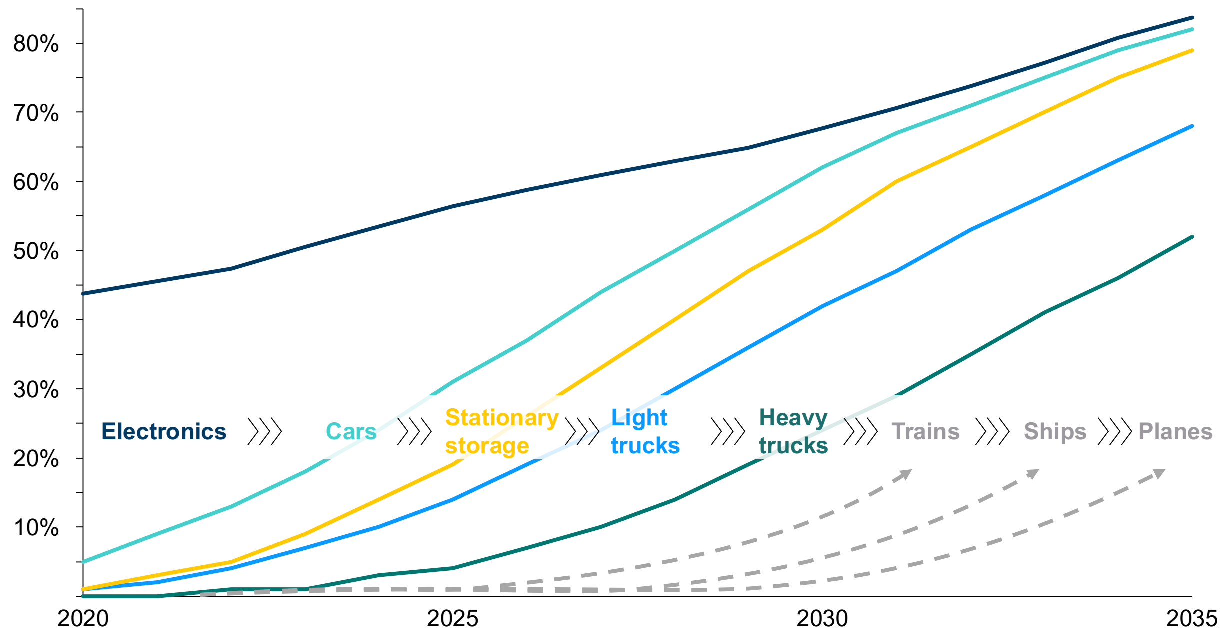


Source: BNEF,[143] RMI analysis

[iv] RMI calculation assuming 2030 volume and price estimates for wind turbines and solar panels from the previous X-Change: electricity report.

As batteries are scaled across the transport sector, trains, ships, and planes may follow. By 2030, the first percentage points of ship and airplane sales may well have shifted to battery technology as well.

Figure 21: The battery domino effect going forward, market share sales %, fast scenario



Source: RMI analysis. Note: vehicles are sale shares; stationary storage and electronics are shares of peak sales

Batteries put over half of fossil fuel demand at risk

Battery-powered technology is set to capture all of road transport, enable renewables to push fossil power generation out of electricity, and either have a direct or enabling role to play in aviation and shipping decarbonization. This means batteries put over half of global fossil fuel demand at risk: 18% from road transport, 35% from electricity and another 4% from other transport.

The end of the ICE age: batteries push out road transport oil demand

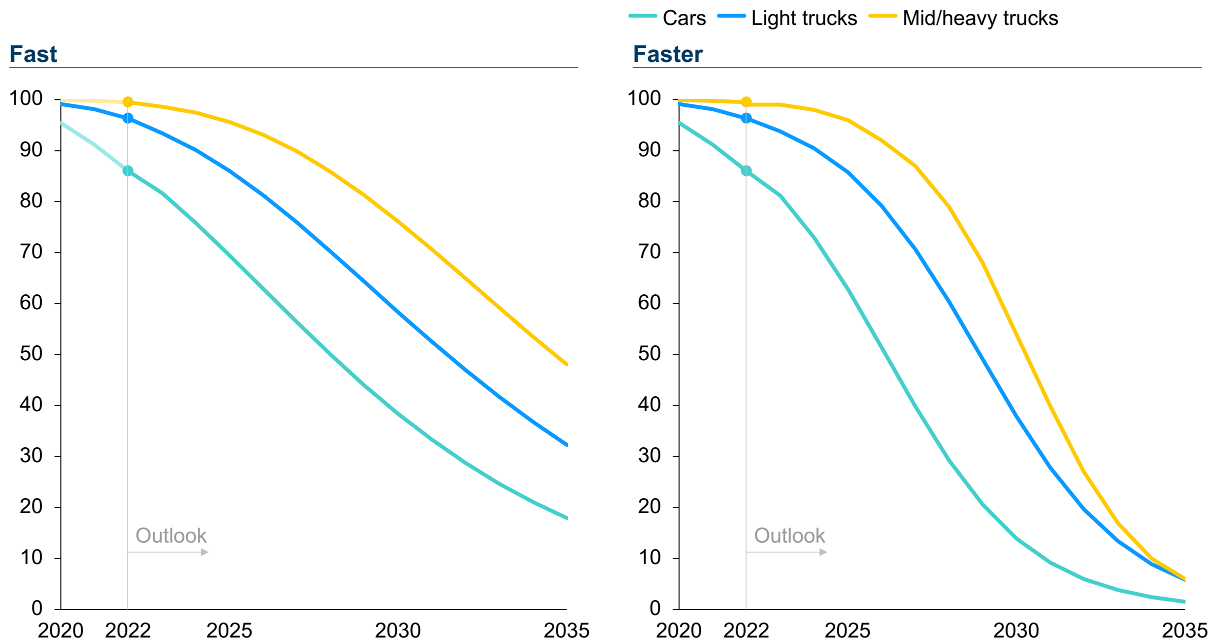
As the battery domino effect tips all of road transport, new ICE vehicle sales will be rare by 2040. In our previous X-Change entry on cars, we noted that the ICE age is rapidly coming to an end for cars. In this piece, we note that the battery domino effect is set to end the ICE age not just for cars, but for all of road transport.

Once ICE sales dry up, it will take about the average ICE lifetime of 10-15 years for the global fleet to turn over, and hence for the entire ICE fleet to effectively disappear. As lifetimes of trucks are shorter than those of cars (~10-12 years versus ~15 years), the fleet transition to EV in trucks is set to complete at around the same time as cars, even though truck sales are lagging cars by about five years.

The implication is that by 2050, virtually no ICE vehicles will be left on the road.

Well before that, ICE owners will start to experience increasing difficulty in using their vehicles as the investment market dries up. Car parts will become rare, and refueling stations will switch to EV charging, moving range anxiety from EVs to ICEs. These negative feedback loops could further accelerate the rate at which people discard their ICE and turn to an EV.

Figure 22: ICE sales by sector, % of annual sales



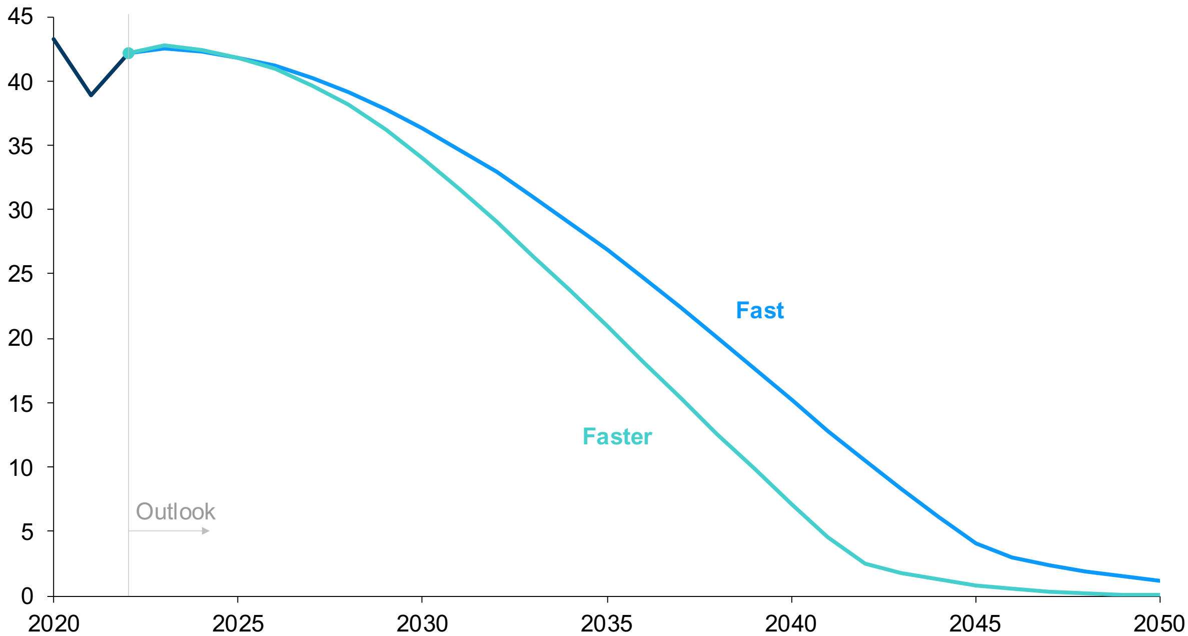
Source: BNEF,[144] RMI analysis

As ICEs are phased out, so will road transport oil demand. Road transport oil demand was 43 mbpd in 2022 according to BNEF, which was just under half of global oil demand and 18% of global fossil fuel demand. This demand will fall by 65%-85% by 2040 and almost fully vanish by 2050.

Fossil fuel savings from batteries

It is possible to calculate the fuel savings from batteries from either a top-down or a bottom-up perspective. Care must be taken to distinguish between flows and stocks. The conclusion is about the same — that each kWh of battery (weighing around 3-4 kg) over its lifetime will save around 300 kg of oil. For example, an ICE car uses around 1 ton of oil a year. If it is replaced by an EV with a 50 kWh battery, the battery will save 20 kg of oil per kWh per annum. Over a 15-year life, that is a 15 ton saving of oil demand, or 300kg per kWh of battery.

Figure 23: Road oil demand, mbpd



Source: BNEF,[145] RMI analysis

Batteries enable renewables to push out fossil power generation

As batteries enable wind and solar to continue to grow, so renewables will push out 175 EJ of fossil fuel demand for power generation, amounting to 35% of global fossil fuel demand. Renewables are likely to reduce fossil power generation by over 20% by 2030 and push out fossil fuels entirely by 2050.[146] Clearly batteries are just one among several enabling factors, but their role is nevertheless key. As noted above, the IEA states that one-third of 2050 flexibility is likely to be provided by batteries.

More dominoes will fall: trains, ships and airplanes

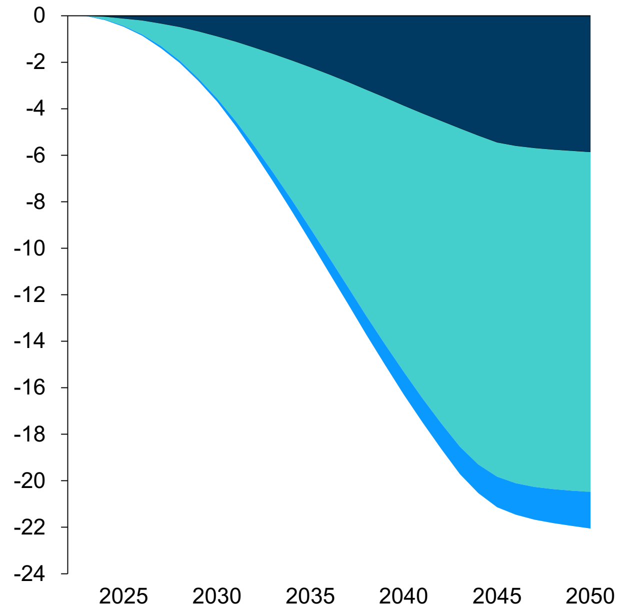
As the battery domino effect starts to tip battery uptake in trains, ships and airplanes, another 13 mbpd of oil demand is put at risk, or about 4% of global fossil fuel demand. Batteries will either serve as a sole replacement for fossil fuel technology or help ease the uptake of bio- and synthetic fuels by making fossil fuel planes and ships more efficient through hybrid battery-ICE models. Ultimately, batteries will have a role to play in the phase-out of fossil fuels in these sectors — be it as a direct replacement or as a (hybrid) enabler of another green solution.

Batteries put climate goals within reach

Batteries will help reduce over half of global energy-related CO_2 emissions

As batteries enable the phase-out of half of fossil fuel demand, they will have an outsized impact on global emissions reductions. Batteries are an essential ingredient for the decarbonization of over 22 $GtCO_2$/y: 5.9 $GtCO_2$ from the direct replacement of fossil fuel technology in road transport, 14.6 $GtCO_2$/y from enabling renewables in the electricity sector, and 1.6 $GtCO_2$/y either replaced or enabled in other transport. That is more than 60% of global CO_2 emissions, and much of the pathway to a net-zero energy system.

Figure 24: CO_2 emission abatement enabled by batteries, $GtCO_2$/y

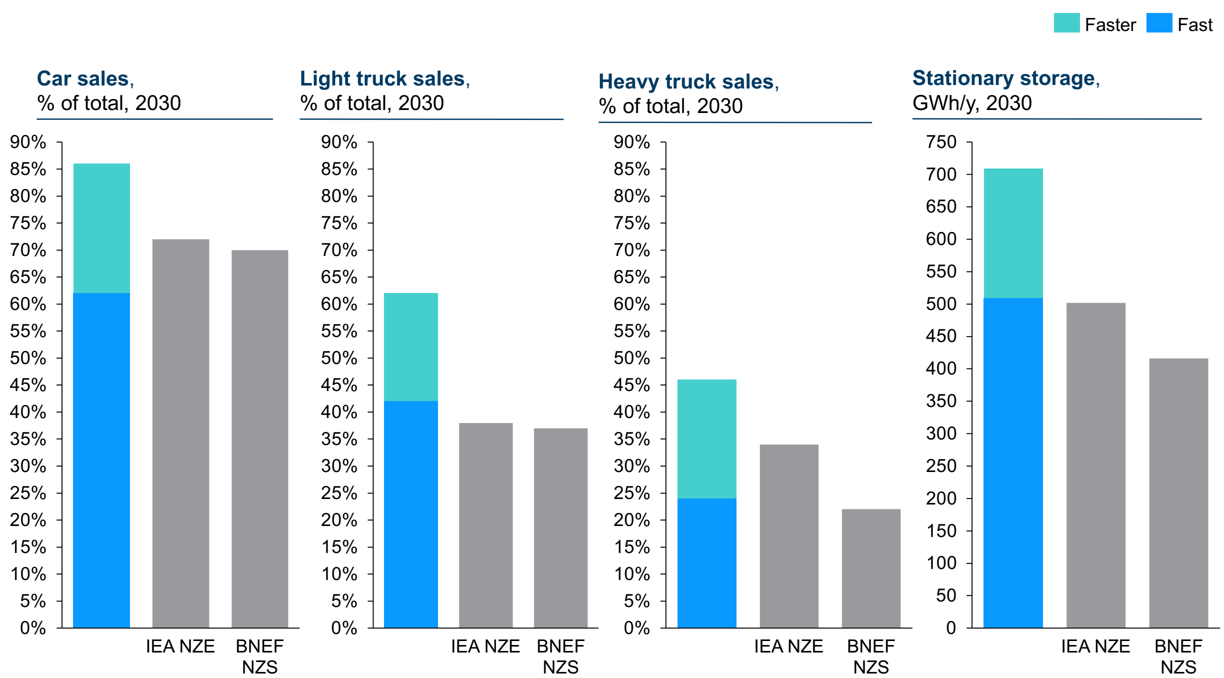


Sector	Battery technology	Comment
Road transport	EV bikes EV buses EV cars EV light trucks EV heavy trucks	Direct abatement of oil demand
Power generation	Stationary storage	Enabled abatement of power emissions by renewables
Other transport	EV trains EV/hybrid planes EV/hybrid ships	Potential abatement in other transport as domino effect continues

Source: IEA NZE scenario (other transport); RMI analysis (power and road transport)

Batteries are on track to meet this challenge. As pointed out by the IEA and detailed below, batteries are already overperforming compared to what is needed for a net-zero scenario today.[147] As battery technology continues to rise, net zero is within reach across road transport and the power sector.

Figure 25: Battery technology uptake vs. what is required in a net-zero scenario, 2030



Source: RMI analysis, IEA Net Zero Energy (NZE), BNEF Net Zero Scenario (NZS)[148]

Change will not happen by itself

As we have outlined, change is not an autonomous force, but the result of deliberate actions and concerted efforts. The exponential growth of batteries has been made possible by hundreds of thousands of people working billions of hours over recent decades to make batteries better, cheaper, and successful. The implicit assumption behind scaling laws such as Wright's and Moore's and the theory of S-curve uptake is that human ingenuity and effort will continue to be poured into technological advancement.

But this is not a given. Not all technologies make it up the S-curve. Concerted lobbying against technologies, companies not setting up sustainable value chains and underinvesting in enablers can stop technology development dead in its tracks.

Governments, companies, researchers, and climate advocates will have to unite to drive sustainable and equitable growth in the battery industry. This includes a focus on innovative R&D for sustainable technology and adaptable solutions, supported by government funding and corporate investment. Collaboration is key, with an emphasis on establishing fair supply chains and enhancing transparency, bolstered by standardized regulations to ensure safety, quality, and environmental integrity.

Simultaneously, adopting circular economy principles will be crucial. This involves designing batteries for easier recycling and longer life, promoting the reuse of materials, and supporting infrastructure for efficient recycling processes. Researchers and companies can play a pivotal role in advancing these technologies, while governments can aid by implementing supportive policies and regulations, ensuring a cohesive and sustainable approach across the industry.

To ensure fairness in the battery industry's growth, policies must equitably distribute costs and benefits, especially in mining regions. Significant investment is needed in local communities and sustainable job creation, such as emphasized by the White House's commitment to a domestic supply chain for critical minerals.[149] Moreover, a broader understanding of environmental justice impacts is crucial, beyond traditional greenhouse gas and cost analyses, to assess local socioeconomic and environmental effects fully.[150]

As batteries scale, they will continue to require lifetimes of work and generous support to develop. With ever-increasing interest in batteries from researchers, companies and policymakers, we expect this to hold true.

The road ahead for batteries is clear, but we do still need to walk it.

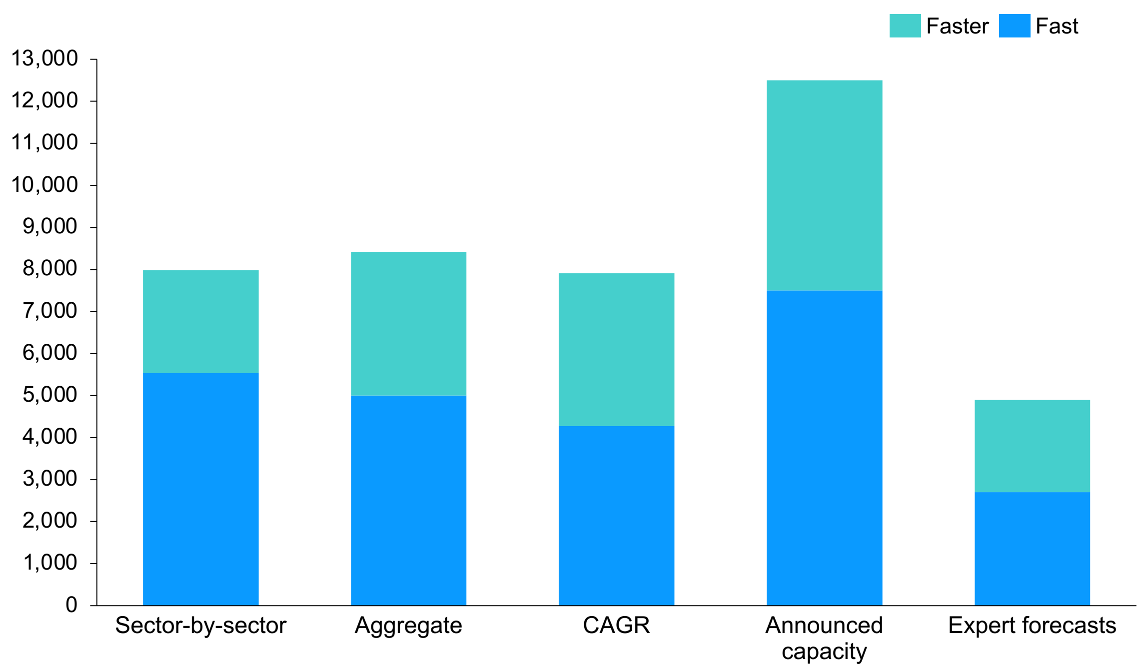
Appendix 1: Different ways to model battery sales

There are many ways to project battery sales. In this appendix, we look at five ways to forecast battery demand and summarize our conclusions below for likely battery sales in 2030.

- Sector-by-sector S-curve outlook. A range of 5.5-8.0 TWh/y based on sector-by-sector S-curves to forecast demand.
- Aggregate S-curve outlook. A range of 5.0-8.4 TWh/y using a terminal demand of ~13 TWh/y and a single S-curve for total battery demand.
- Growth rate outlook. A range of 4-8 TWh/y based on a compound annual growth rate (CAGR) of 25%-35%.
- Announced capacity outlook. From the IEA's estimated announcements of 7.5 TWh/y to Benchmark Minerals' capacity of 9 TWh/y and BNEF's of 12.5 TWh/y.
- Expert forecasts. From the E Source outlook at 2.7 TWh/y to McKinsey and Rethink Energy's 4.5-5 TWh/y.

All outlooks lead to very considerable levels of growth by 2030 versus this year's ~1 TWh/y market. Expert forecasts are the least optimistic, but conservatism has characterized expert outlooks on the battery industry for years.

Figure 26: Comparison of battery demand outlooks, GWh/y, 2030



Source: RMI analysis from charts below

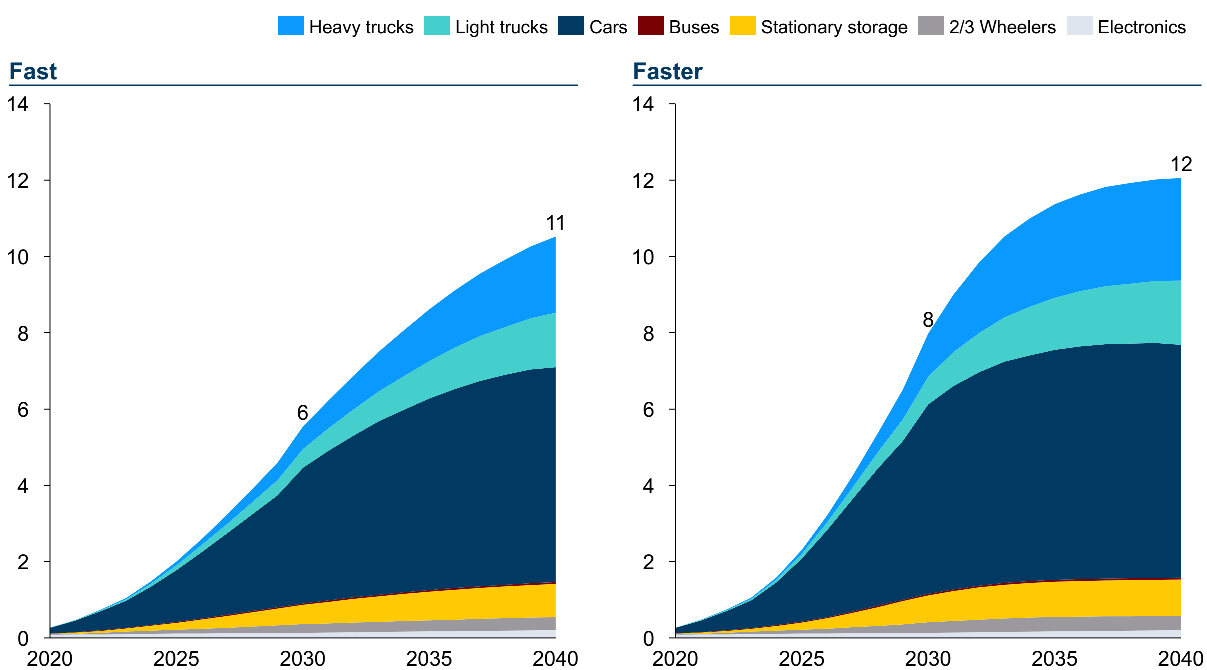
Sector-by-sector S-curve outlook

The main battery demand outlook used in this note uses a sector-by-sector S-curve approach. This approach runs as follows:

- We model each sector of battery demand independently, fitting an S-curve through the battery uptake per sector.
- We fit the S-curves based on historical data, and fit both *fast* S-curves (Gompertz curve) and *faster* S-curves (logistic curve) to the data, assuming 100% uptake in the long term. As set out in more detail in other reports in the X-change series, we have found that a Gompertz S-curve tends to have good predictive power for technologies at an early stage, while a logistics S-curve has better predictive power for later stage technologies.
- Because battery technologies are still in the early stages of their S-curve, it is hard to confidently fit S-curves to them. To remedy this, we add two years of the short-term forecasts from BNEF until 2025. This enables us to fit S-curves with a greater degree of certainty.
- The range between the two curves therefore provides a reasonable framing for future sales, as discussed in the previous X-Change note on cars.[151]
- For road transport, we take 100% uptake to be 100% of sales, which we get from BNEF.
- For stationary storage, we assume total long-term demand of 1 TWh/year, in line with the peak demand levels in BNEF. We then fit an S-curve to that total, based on historic data.
- For electronics, we take the outlook from BNEF via Avicenne.[152] This is a very minor part of end demand and is not expected to grow as fast as other sectors.

Below we provide some details on the outlooks per sector, going deeper on four key sectors of battery demand: cars, light trucks, heavy trucks and stationary storage.

Figure 27: Battery uptake by sector, TWh/y



Source: RMI analysis

Cars

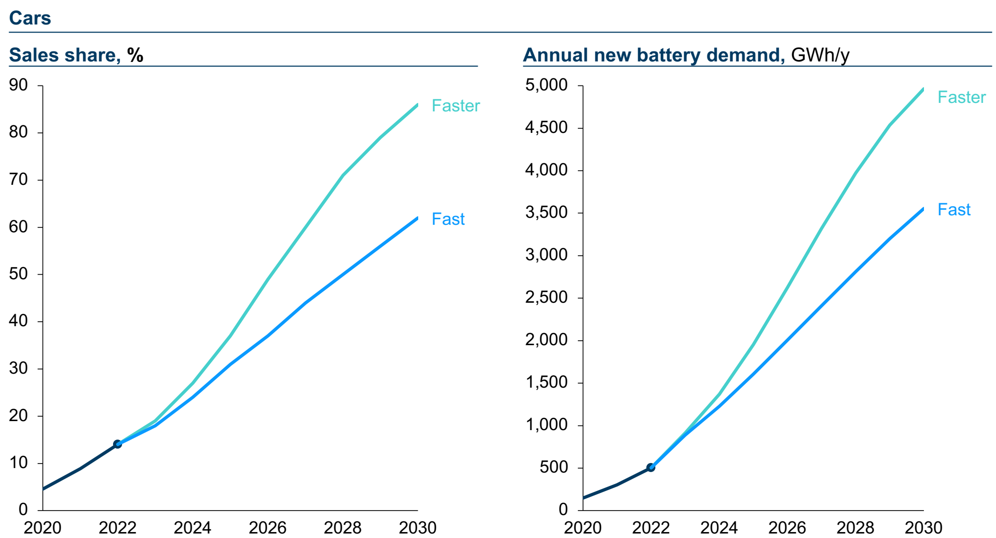
The passenger car sector is the largest piece of the battery industry.

We start by fitting two S-curves (Gompertz and logistic) on historic sales share data from 2015 to 2023, building to an end point of 100% sales share. This gives us a projection of EV market share in sales over time.

Then, for each year, we multiply the projected share by BNEF's outlooks for total car sales to get the number of EV sales. We calculate battery demand assuming a constant battery size of 61 kWh per car, which is the average battery size in BNEF's long-term outlook.

Using the methodology set out in X-Change Cars, the results of our analysis suggest that the EV sales share for cars could reach anywhere between 62% (*fast*; Gompertz) to 86% (*faster;* logistic) by 2030. This translates to battery demand of 3.5-5 TWh from the car sector in 2030.

Figure 28: Battery-powered car uptake and battery demand



Source: BNEF historical data,[153] RMI analysis

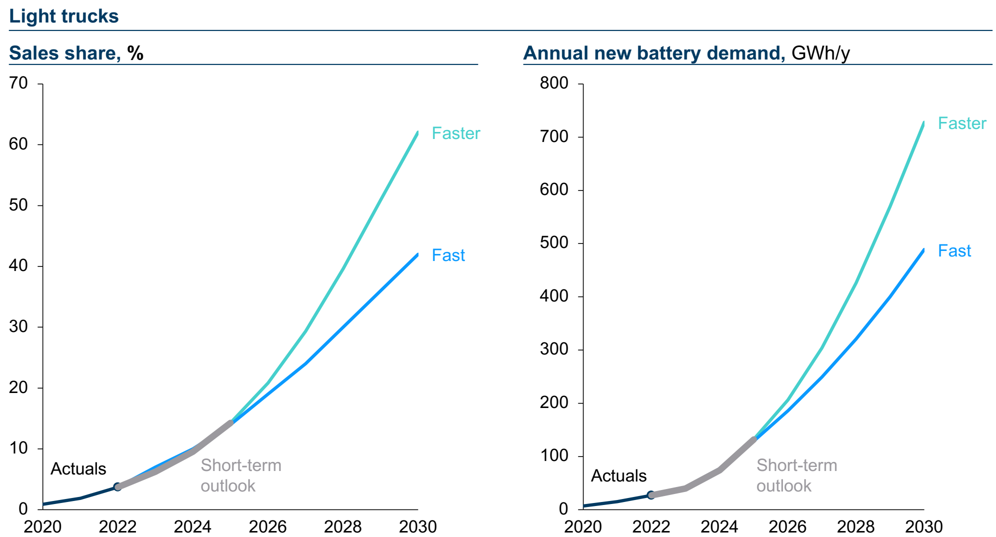
Light trucks

In the light commercial vehicles sector, we assume a similar methodology as in cars, taking the average battery size of 74 kWh per vehicle from BNEF. We take the BNEF short-term outlook for the period up to 2025 and then model an S-curve after that. The BNEF short-term outlook is mostly based on actual orders, and not projections. While such data is less firm than the historical actuals, it provides a robust glimpse into the future that we use to fit more precise S-curves (without the data up to 2025, the range between Gompertz and logistic would become almost unusably large).

The results of our analysis suggest that the EV sales share for light commercial vehicles could reach between 42% (*fast*; Gompertz) to 62% (*faster;* logistic) by 2030. This translates to annual battery demand of 0.5-0.7 TWh from the light commercial vehicles sector in 2030.

Rapid uptake in this segment is already underway with electric delivery vans and other light duty vehicles already commercially available on the market. For example, in October 2023, Amazon announced that it had 10,000 electric vans fulfilling deliveries across Europe and the United States, with plans to expand this fleet tenfold to 100,000 by 2030.[154] UPS has announced plans to purchase 10,000 electric vehicles, with a possibility of increasing this number to at least 66,000 by 2028.[155] Other delivery companies are following closely behind.[156]

Figure 29: Battery-powered light truck uptake and battery demand



Source: BNEF historical data,[157] RMI analysis

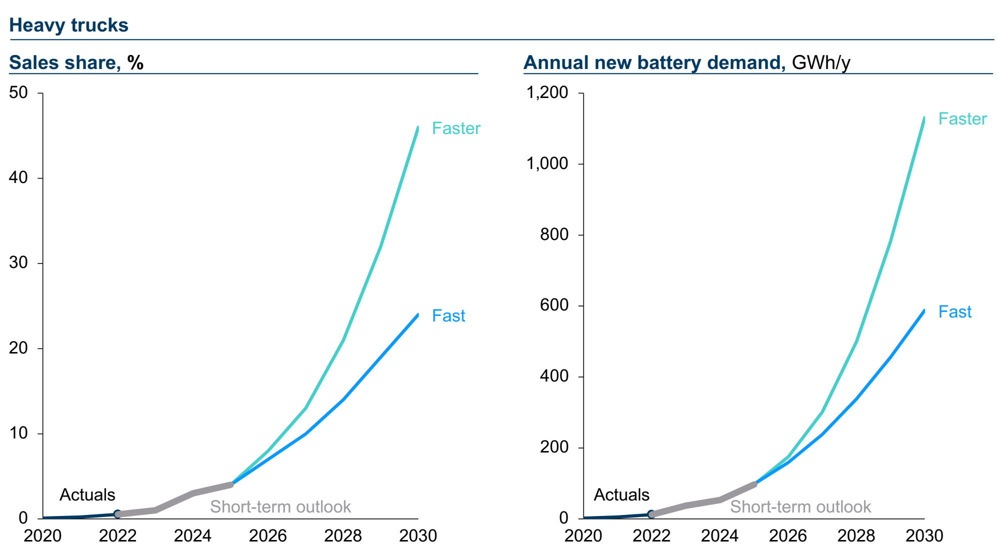
Heavy trucks

As for cars and light commercial vehicles, we assume a similar methodology for medium and heavy commercial vehicles. We use historic market share data and the BNEF short-term outlook up to 2025. We take an average battery size of 431 kWh per truck from BNEF's long-term outlook.

The results of our analysis suggest that the EV sales share for medium and heavy commercial vehicles could reach between 24% (*fast*; Gompertz) to 46% (*faster;* logistic) by 2030. This translates to battery demand of 0.6-1.1 TWh from the medium and heavy commercial vehicles sector in 2030.

We expect that heavy truck sales will pick up in the late 2020s and will transition from 10% to 80% of sales within 7-15 years.

Figure 30: Battery-powered heavy truck uptake and battery demand



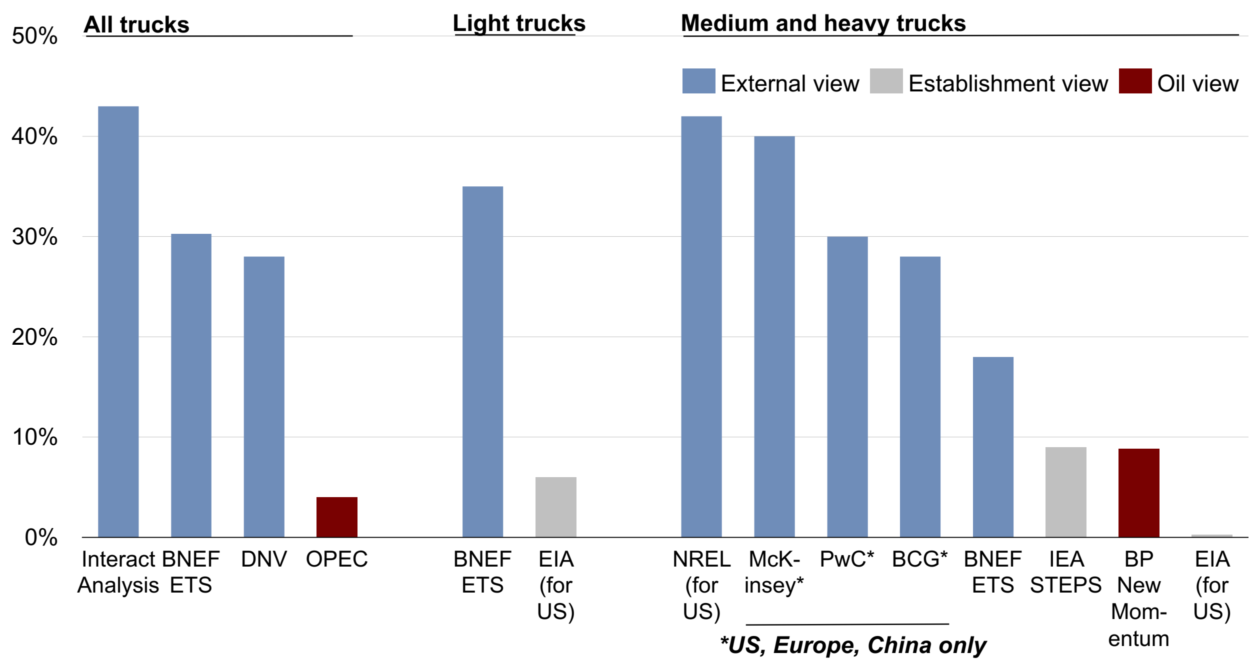
Source: BNEF historical data,[158] RMI analysis

Comparison with expert forecasts

We compare our outlook with other forecasts for truck sales. Our analyses suggest that for the light commercial vehicles segment, EV sales will make up 42%-62% of new vehicle sales in 2030. This is a bit more optimistic than the BNEF ETS scenario, which estimates light truck EV sales to be approximately 35% of new light trucks sales in 2030.

Similarly, for the medium and heavy commercial vehicles segment, we expect that EV sales will make up 24%-46% of new vehicle sales in 2030. This is somewhat higher than the global number in BNEF (18%), and in line with external organizations that focus on US, Europe, and China alone (where the proportion is likely to be higher).

Figure 31: Other forecasts for 2030 truck sales, % of sales



Source: Interact Analysis (2022),[159] BNEF Electric Vehicle Outlook (2023),[160] DNV Energy Transition Outlook (2023),[161] OPEC World Oil Outlook (2023),[162] EIA Annual Energy Outlook (2023),[163] NREL (2023),[164] McKinsey (2022),[165] PwC (2022),[166] BCG (2022),[167] IEA Global Electric Vehicle Outlook (2023),[168] BP Energy Outlook (2023)[169]

Other road segments: buses and two-/three-wheelers

There are two smaller road segments that we include in our analysis as well: both buses and two-/three-wheelers are undergoing rapid EV uptake. We assume the same approach as for the other road segments to model buses and two-/three wheelers, taking an average battery demand per vehicle of 179 and 3 kWh, respectively, from BNEF.

One innovation that has dramatically accelerated the uptake of two-/three-wheelers is battery-swapping stations. In Taiwan, for example, there are more battery-swapping stations than gas stations across major cities, with more than 1 million swappable batteries in service.[170] In Kenya, there are plans to deploy 1 million electric motorcycles supported by 3,000 battery-swapping stations by 2030.[171] Similar battery-swapping networks are quickly expanding across other countries in Asia and Africa.

Electric buses are already in commercial use in many markets and growing rapidly. For example, the European e-bus market is growing at 45% per year.[172] Ambitious policies are paving the way for fast growth in other markets as well: In New York, all 47,000 school buses in the state will be electric by 2035,[173] and Bermuda aims to have an entirely electric fleet of public buses by 2030.[174]

Despite the very large numbers of two-/three-wheelers (their current oil demand reduction benefits that are more than from EV cars for now)[175], they are a relatively small piece of 2030 battery demand, at 120-270 GWh. Likewise, we expect battery demand from buses in 2030 to be very small compared to other sectors at around 34-38 GWh.

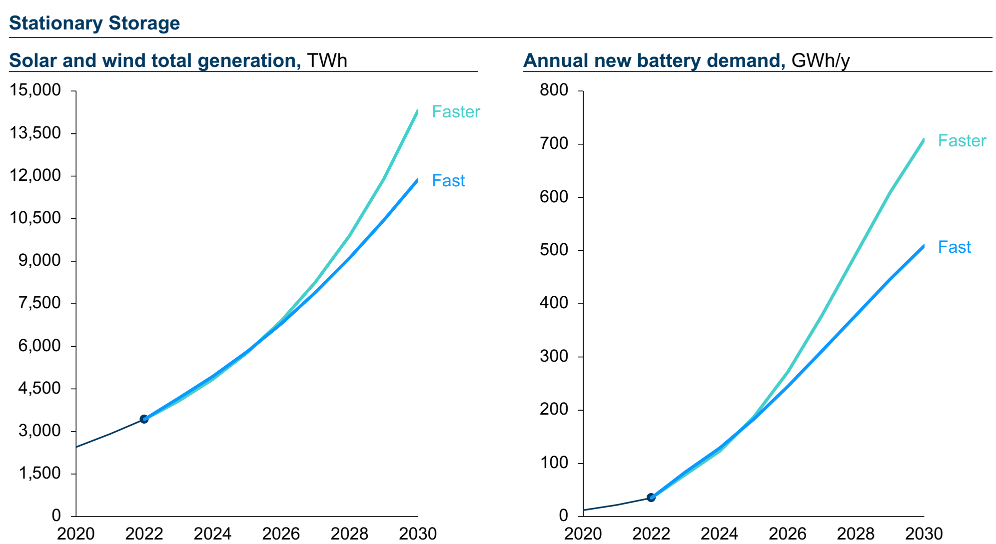
Stationary storage

We model the size of the stationary storage market in a different way. The amount of stationary storage needed is a (complex) function of the amount of variable renewable power that is deployed, which requires careful, hourly capacity expansion modelling. To account for that, we take the S-curve renewable outlook from the previous X-Change note on electricity and match it to comparable BNEF and IEA scenarios to find the required battery demand.

The BNEF NZS and IEA NZE scenarios show very comparable renewables uptake to the X-Change electricity outlook and are therefore used to analyze battery demand. We use BNEF for consistency with our historical data, taking the net zero scenario 2050 value (of 954 GWh of sales) as the endpoint and fitting the two S-curves to the historical data, plus BNEF's 2023-2025 outlook, which is based on near-term grid announcements and plans. In both scenarios, batteries are only part of the total flexibility need. For example, other solutions such as demand side flexibility, dispatchable firm capacity, interconnectors, and long duration storage solution fill in two thirds of the flexibility need in the IEA scenario.[176]

As noted above, there is much uncertainly in this terminal number of 954 GWh of sales, and there are good reasons to believe that it could be considerably higher or lower than this. If we are successful at incorporating a large share of the transport fleet to provide system flexibility, then the need for stationary storage would be lower. If batteries get cheap enough, they may supplant other flexibility solutions and demand for storage would be higher. For the purposes of this analysis, the number is not especially material because demand for batteries from the transport sector is forecast to be nearly 10 times larger than the battery storage market. As with so much in the energy transition, we will build large amounts of batteries and then optimize our use of them using the superior technologies of the future.

Figure 32: Renewables uptake and associated required battery demand



Source: BNEF historical data,[177] RMI analysis

The next dominos: trains, ships, and airplanes

The battery domino effect is heading toward three additional sectors: rail, aviation and shipping. Battery-powered technology has not yet made any significant entrance in these sectors, hence there is no data to fit an S-curve. Nevertheless, there are hopeful signs that battery technology may start picking up before the end of this decade.

Trains

Although rail — especially passenger rail — is already widely electrified, batteries can still play a crucial role by replacing diesel to operate trains on segments of rail that do not have overhead catenary lines. Studies show that the range of an average freight train in the United States (150 miles, or 241km) can be achieved with a 9-14 MWh battery. The same studies also find that battery-electric trains can achieve price parity with diesel-electric trains at current battery prices of $100/kWh.[178]

Because most diesel trains operate a diesel-electric drive, hybrid and/or battery retrofits are possible. This means that battery uptake may grow faster than in other sectors as there is no need to wait for fleet turn-over.

The first battery trains are already being rolled out. In May 2023, The Pacific Harbor Line in California unveiled its new battery electric locomotive, the EMD Joule.[179] In November 2023, Wabtec Corp. launched a 7 MWh battery electric locomotive for Australia's Roy Hill, an iron-ore mining company.[180] In Europe, Hitachi has announced plans to release in the next two years a full battery powered train that can travel up to 62 miles.[181]

Ships

As a general rule of thumb, the lighter the ship and the shorter the distance travelled, the easier it will be to electrify. Passenger ferries are a prime candidate for electrification, and there are already several models of electric ferries in operation in Scandinavia, with battery capacities ranging between 1 and 5 MWh.[182] Electric ferries also operate in places such as New Zealand, California, and New York.[183] In passenger shipping, electrification is now expanding to cruise ships, which are much bigger and longer distance: in 2023. Norwegian cruise line company Hurtigruten announced plans to deliver a battery-electric cruise ship in 2030. The ship will be powered by a 60 MWh battery and will be 443 meters long.[184]

Container shipping is also not far behind, with one study finding that over 40% of global containership traffic could be electrified cost-effectively with current technology.[185] The first battery electric container ships have already been unveiled: In 2021, Yara debuted a fully electric autonomous container ship powered by eight batteries totaling 6.8 MWh.[186] In 2023, China launched its first battery electric container ship with swappable batteries. Each swappable battery unit is housed in 20-foot containers with a capacity of 50 MWh.[187] These swappable batteries may be a game-changer for battery uptake in the shipping sector, in much the same way they were for the two-/three-wheeler sector.

Finally, it is also important to note that with some changes to current shipping practices — such as relying more on smaller ships with frequent stops instead of larger ships with one long route — batteries could power a larger portion of shipping even faster than expected. As Steve Henderson, co-founder and CEO of FleetZero (a battery cargo ship startup), points out, the current shipping system is optimized for fossil fuels — and can be re-optimized for batteries.[188]

According to Rystad, 45% of global ton mileage is to transport fossil fuels.[189] Lower fossil fuel demand will therefore tend to drive down demand for long haul shipping services in any event.

Airplanes

Though battery powered planes are unlikely to happen at scale in the next few years, there is plenty of evidence to suggest it is possible, and many actors are already working to make it a reality.

Studies have found that a typical twin-engine narrowbody aircraft with a range of 600 miles would require 800Wh/kg of specific energy from the battery pack.[190] Larger models could require around 1,000 Wh/kg.[191] Like vehicles, near-term electric planes are expected to be 60%-70% cheaper to operate than current options, such as helicopters and other short-haul aircraft.[192]

Beta Technologies recently completed a 16-stop, 1,730-mile journey across the US East Coast, using a plane that has already flown 386 miles on a single charge.[193] Meanwhile, Eviation Aircraft — an electric aircraft manufacturer — has received nearly 300 orders for the nine-seater plane "Alice", with goals for commercialization by 2027. [194]

At least 60 companies are currently working to research and develop fixed-wing electric aircraft, including major manufacturers such as Boeing and Airbus as well as airlines such as United Airlines and Virgin Atlantic.[195] Well over 100 electric aviation programs are in development around the world, in a market that has already reached $9 billion. [196]

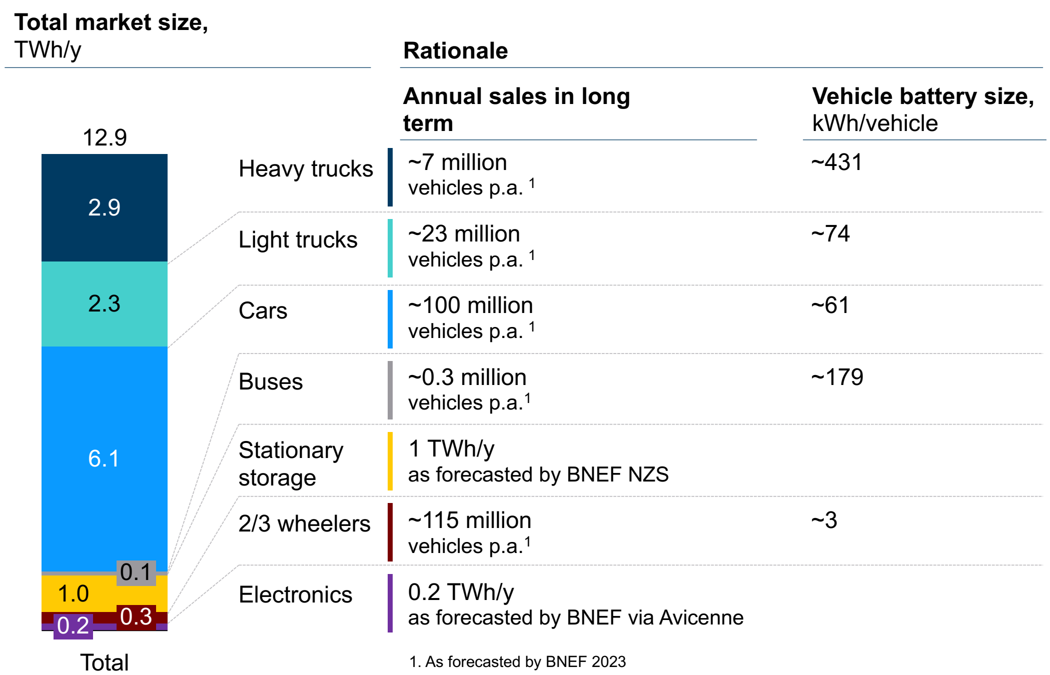
Aggregate S-curve outlook

A much simpler approach to sizing battery demand is an aggregate outlook — i.e. where we fit an S-curve through total battery demand. An aggregate outlook results in a very similar result to the detailed, sector-by-sector approach.

Sizing the total battery market

To fit an aggregate S-curve to battery uptake, one must first define the total addressable market size. If we take data from BNEF on long-term sales and average battery sizes, we get an implied addressable market of nearly 13 TWh/y in 2050.

Figure 33: Aggregate peak battery market size



Source: BNEF,[197] RMI analysis

We take historical data and near-term expectations to 2025 for total battery demand and combine it with the total potential demand (calculated above) as the end point to fit an S-curve through total battery demand. We follow the same approach as with our individual sector outlooks, fitting both a fast (Gompertz) and faster (logistics) S-curve to the data.

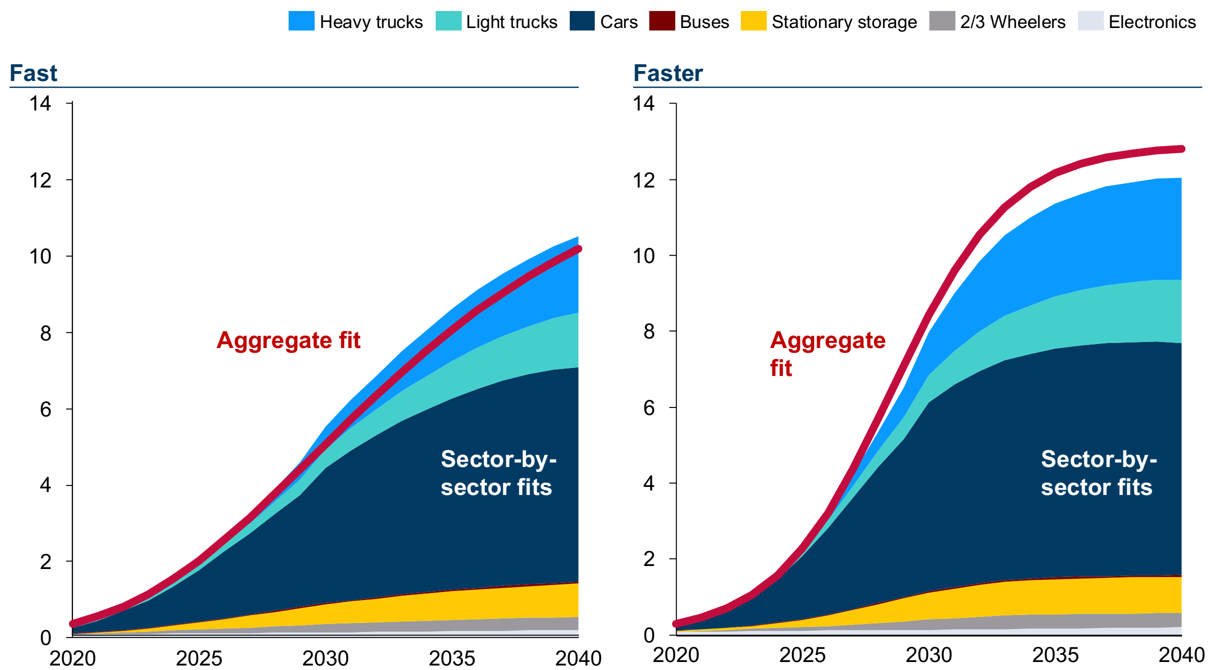
Matching sector-by-sector with the aggregate S-curve

Comparing the results of the aggregate and sector-by-sector approach reveals a striking alignment in outcome. The aggregate result matches the sector-by-sector outlook to within less than 1 TWh/y.

This finding hints at a deeper insight into S-curve growth patterns. Every global S-curve is made up of more granular S-curves by (sub-)sector or region, each with its own distinctive uptake trajectories. Like a fractal, these uptake trajectories are self-similar in shape to the whole: they also follow an S-curve. Such uniformity of uptake for cars across countries was discussed in X-Change Cars.

The consistency of the S-curve's shape at various scales provides a valuable insight — top-down S-curve analysis can yield results that can be as accurate as those from more granular analysis. This reinforces one of the leading thoughts behind this X-Change series: high-level S-curve trend assessments tend to yield equally valuable insights as more complex, granular models.

Figure 34: Sector-by-sector vs. aggregate battery market S-curve fits, TWh/y

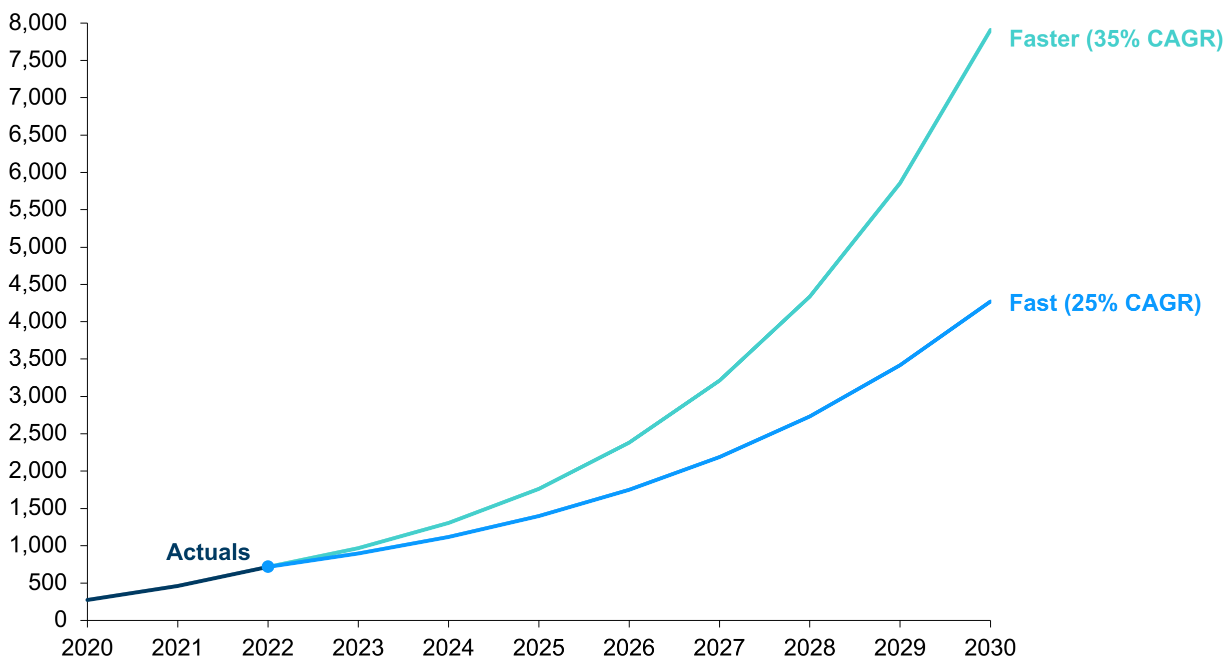


Source: BNEF,[198] RMI analysis

Growth rate outlook

We can also use a simple continued growth rate perspective to project demand. Over the past 30 years, annual sales growth rates have ranged from 20% to 60%; they have been 33% on average and over 40% in recent years. If we continue at growth rates of 25%-35% pa, total battery demand by 2030 would lie between 4 and 8 TWh.

Figure 35: Future battery sales GWh at different CAGRs, TWh/y



Source: BNEF Long-Term Vehicle Outlook 2023 (actuals),[199] RMI analysis

Announced capacity outlook

Another approach to sense-check the forecasts for battery demand growth is to look at the amount of battery capacity currently being built.

According to Benchmark Minerals, roughly 9 TWh/y of battery capacity is already planned for 2030,[200] while the IEA has an estimate of 7.5 TWh/y.[201] As of late November, BNEF's battery manufacturing announcement pipeline already includes announcements for 12.5 TWh/y of battery manufacturing capacity by 2030 — including more than 8.5 TWh/y in China alone.[202]

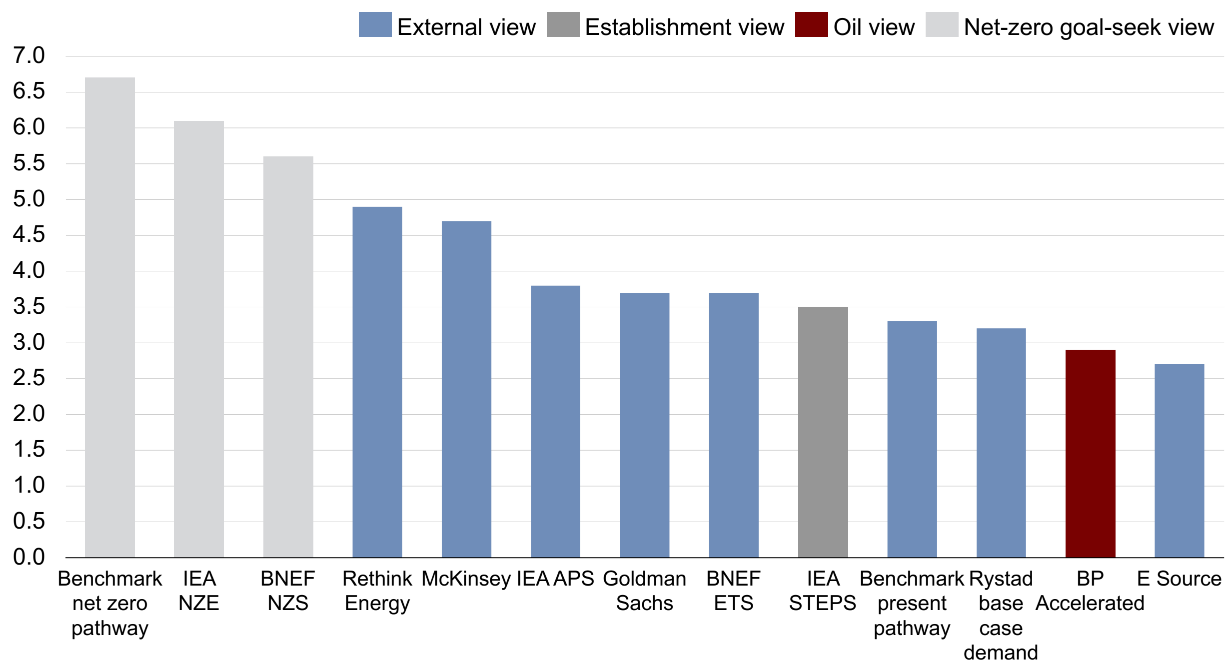
Given that we have seven years until 2030 and it takes under a year to construct a battery factory, it is fair to say that capacity plans are no constraint to the amount of demand that we foresee. Rather, it is a signal that battery production capacity will be a driver of further adoption. As production capacity comes online, battery manufacturers will create their own demand and accelerate the battery domino effect.

Expert outlooks

A final approach to forecasting battery demand is to look at expert outlooks. Expert forecasts range between 3 and 5 TWh/y of battery sales in 2030, or up to 7 TWh/y when including scenarios that do not forecast but goal-seek to reach net zero. Those at the bottom of the range assume that change will significantly decelerate from the 40% annual growth we have seen in recent years. The lowest of the range assumes a ~20% CAGR of sales to 2030, and the top end of the range implies a ~33% CAGR.

As discussed in section 1, expert forecasts have historically underestimated battery uptake. We foresee a similar trend in these forecasts: the sector-by-sector battery demand forecast we created for 2030 is 5.5-8 TWh/y, which is 40%-100% more than the expert average of about 4 TWh/y.

Figure 36: Expert forecasts of 2030 battery sales, TWh/y



Source: Benchmark Minerals (2023),[203] IEA Global Electric Vehicle Outlook (2023),[204] BNEF Long-Term Electric Vehicle Outlook (2023),[205] Rethink Energy (2023),[206] McKinsey Battery 2030 (2023),[207] Goldman Sachs (2023),[208] Rystad Battery Market Outlook (2023),[209] BP Energy Outlook (2023),[210] E Source (2023)[211]

Appendix 2: Barriers to change

In this section we consider two key barriers to change — charging infrastructure and mineral demand — in more detail to see if they can slow the battery domino effect.

Charging infrastructure

As more EVs enter traffic, the need for charging points rises. As laid out in the previous entry of this series, chargers are rising rapidly, and EV range anxiety due to a lack of charging stations will soon disappear in most of the world. The expansion of charging stations is notable in several key areas:

Rapid expansion of public charging infrastructure: The global increase in publicly accessible charging points is exponential. Last year alone, the number grew by about 55%, a testament to the accelerated deployment led by regions like China and Europe. Fast chargers grew by the same rate in the EU.[212]

Government initiatives and funding: National governments are playing a pivotal role in this expansion, as noted in section 2 of this note. According to the IEA, there are over 140 charging infrastructure-promoting policies across 35 countries, from North America to Europe, Asia and Oceania.[213]

Addressing the needs of heavy-duty vehicles: Charging a 500+ kWh battery can take a long time and requires a large grid connection. Fast charging networks are being rolled out across geographies to meet demand. Analysis by T&E on the EU market has shown that there is ample room to accommodate rapid growth of heavy trucks.[214] At the same time, innovations such as battery swapping, and electric road charging systems are emerging to cater to the unique charging needs of heavy-duty vehicles. China is leading in this area, particularly in the development and implementation of battery swapping technologies for trucks.[215]

Tackling power grid expansion: The expansion and upgrade of the power grid to connect charging points efficiently is being actively tackled. In the EU, initiatives like the Green Deal and the Alternative Fuels Infrastructure Regulation focus on grid upgrades and the integration of renewable energy sources to support EV charging infrastructure. In the United States and China, substantial government investments are being made under the Infrastructure Investment and Jobs Act and national environmental strategies, respectively, to modernize the electric grid and integrate renewable energy, ensuring it can support the growing demand from EV charging stations.

Private sector involvement: Companies are increasingly leaning in as well. Smart charging is already a $35 billion industry today and is expected to grow by 30% in the coming decade.[216] Car OEMs are also getting involved: for example, Tesla's announcement to open a portion of its US Supercharger network to non-Tesla EVs marks a significant step in increasing the availability of fast charging options. This move is particularly impactful considering that Tesla Superchargers represent 60% of the fast-charging infrastructure in the United States.[217]

These developments collectively indicate a robust global effort to expand and enhance EV charging infrastructure. The coalescence of government funding, innovative solutions, strategic planning for power grid expansion, and private sector involvement should be expected to overcome bottlenecks.

Mineral demand

Energy Transitions Commission (ETC) analysis shows that circularity can reduce mineral demand by up to 10% in the short term and possibly 50% in the long term through extending battery life and recycling materials at end-of-life.[218] Batteries that age and have reduced charge capacity can be repurposed for less energy-dense applications, such as stationary storage, effectively doubling useful lifespan.[219] Once batteries reach end-of-life, they offer a resource of richer concentrations than natural ores for key minerals such as nickel, lithium, and cobalt.

Concerns about mineral availability constraints to the battery revolution must be split into two groups: short-term ramp up constraints (can we scale up mining fast enough?) and long-term sustainability constraints (do we have enough in the long term?).

Short-term growing pains

As battery demand grows over the coming years, mining sectors need to keep up. As shown in figure 18 there is little reason to worry about undersupply in the coming years based on today's mining expansion plans. Nonetheless, annual investments keep rising by over 30% per year.[220] Promising new technology, such as direct lithium extraction (which extracts lithium by pumping up brine deposits instead of using evaporation pools or rock processing), are bringing in billions in investment from major mining companies.[221] New players are joining in as well, including Exxon, which announced a move into lithium mining with the opening of a new DLE site in Arkansas.[222]

As analysis by the ETC shows, once material efficiency and circularity are taken into account, there are hardly any high-risk areas for short-term battery mineral scale up left.[223]

This by no means implies that the race is run. Policymakers are justifiably increasing their focus on the upstream EV supply chain. National policy packages target immediate relief of the pressure on the battery minerals sectors. For example, in the United States, the Inflation Reduction Act and American Battery Materials Initiative emphasize strengthening domestic battery minerals supply, awarding billions in grants to expand critical mineral mining.[224] In the EU, the Critical Raw Materials Act proposed by the European

Commission aims to extract 10%, recycle 15%, and process 40% of the EU's annual needs for 16 strategic raw materials by 2030.[225] Meanwhile China is continuing its policy of building up mining capacity at home and abroad through FDI in JVs.[226]

In conclusion, while demand for minerals critical for battery production is scaling up rapidly, efforts to diversify and strengthen supply chains are being actively pursued by major global players. This includes significant policy initiatives and financial investments aimed at boosting domestic production capabilities and reducing dependency on specific materials.

Long-term sustainability of mineral demand

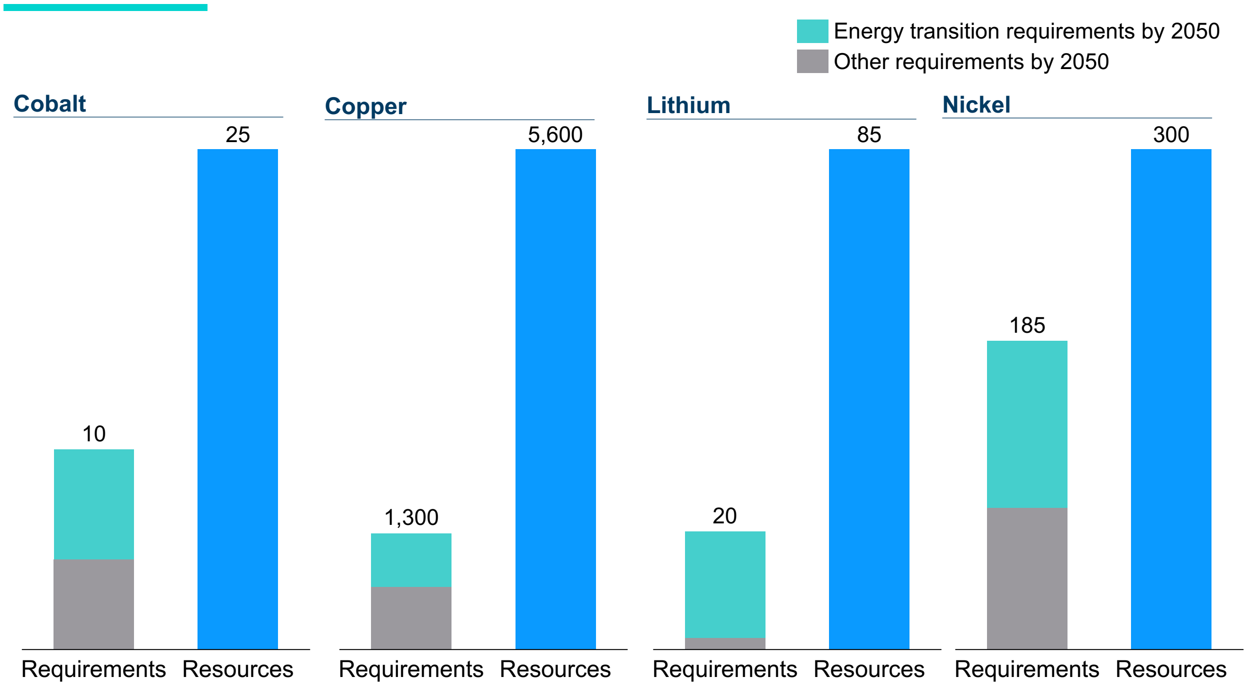
The global reserves of critical battery minerals are substantial. As described by the ETC, lithium resources are estimated at 85 million tons. Cobalt stands at 25 million tons. Nickel resources are 300 million tons, and copper at 5,600 million tons. Only a small part of this will be needed to complete the energy transition. In fact, it appears as if at least two or three energy transitions could fit within the mineral resources available to us.

And of course, as demand for minerals rises, geological exploration tends to find more resources. In 2015, the global estimate for lithium resources was still only ~40 million tons.[227] Today it stands at 85 million tons — and this total number should be expected to rise further the more we explore.

It is also worth noting that the total volume to be mined for batteries is insignificant compared to fossil fuel extraction. Total annual extraction of battery minerals would weigh less than 1% of annual coal extraction today.[228]

Hence, in the long term, mineral demand should not be an issue.

Figure 37: Critical mineral requirements vs. resources, million metric tons



Source: Energy Transitions Commission (2023)[229]

Innovation curbs demand

Smart innovation of batteries can minimize or even eliminate the use of minerals. The improvement of battery energy density has been driven by reducing material needs per kWh. As battery energy density doubled over the past decade, the amount of materials needed per battery halved.

Innovation not only reduced the need for minerals, but it also was able to fully eliminate minerals from the battery. The recent announcement of Northvolt's new battery that does not require lithium, nickel, cobalt, or graphite is an example of such innovation in materials.[230]

Circularity improves material efficiency

While mining players raise supply, innovation on circularity will help manage demand. Analysis shows that circularity can lower total battery minerals demand by up to 10% in the short term and up to 50% in the long term for some.[231]

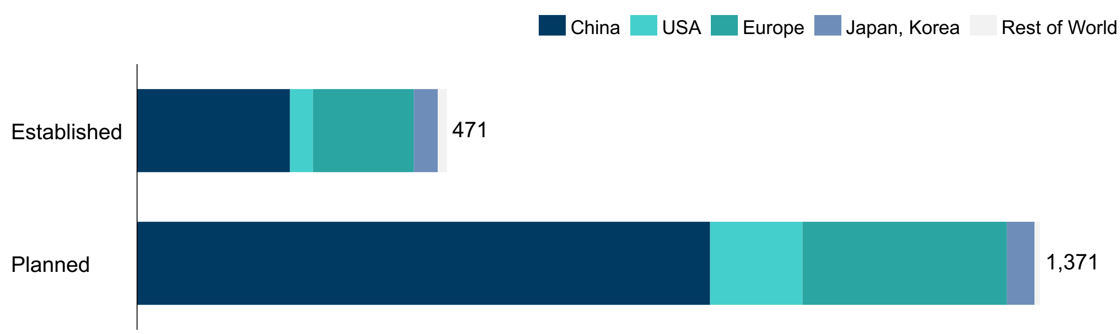
Circularity innovation follows two main strands: extending battery lifetime and recycling materials at end-of-life.

There are many ways the useful life of batteries can be extended. A battery that only has 70% of its total depth of charge left due to degradation may no longer be useful in a car (due to limited range) but can still serve well as stationary storage on the grid.[232] So batteries that are first used in the transport sector can subsequently be deployed in sectors where energy density is less important, such as grid power storage. This can significantly extend the useful lifetime of batteries.[233]

Once a battery finally reaches its end of useful life, mineral contents can be recycled. As pointed out by Amory Lovins, recycled lithium battery cells are about 17 times richer sources of nickel, 4–5 of lithium, and 10 of cobalt than their respective natural ores.[234] It only stands to reason that mineral extraction methods will find ways to supplement mining with more and more recycling.

We see battery circularity picking up rapidly. This is driven by policy, such as the EU battery pass, requiring a 65% recycling rate of lithium-ion battery materials by 2026, and 70% by 2031.[235] Economics may soon take over as a driver of recycling uptake. We are still at the start of the battery recycling scale-up tipping point. As recycling scales, costs will come down as well.[236]

Figure 38: Battery recycling plans across geographies, kilotons per year



Source: IEA Critical Minerals Market Review (2023)[237]

What is the X-Change

The X-Change is a series of reports analyzing the impact of exponential change (the X in X-Change) on the energy system. It contrasts with the orthodox view of linear change. The baseline scenario for the future of energy should assume continued exponential growth of renewable energy in the period to 2030.

Principles of the X-Change

- Identify the exponential.
- Model the exponential in a variety of ways to understand the likely future.
- Figure out if there are any insuperable barriers to change.
- Human ingenuity will continue to find ways around impediments in ways that are not foreseen today.
- Focus on the period to 2030. Costs and volumes will be very different by that point.
- Better roughly right than precisely wrong.

Conclusions of the X-Change

- Linear change is highly unlikely.
- The most likely future is on an S-curve.
- We are on a path to go fast or faster, but we must keep pushing.

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