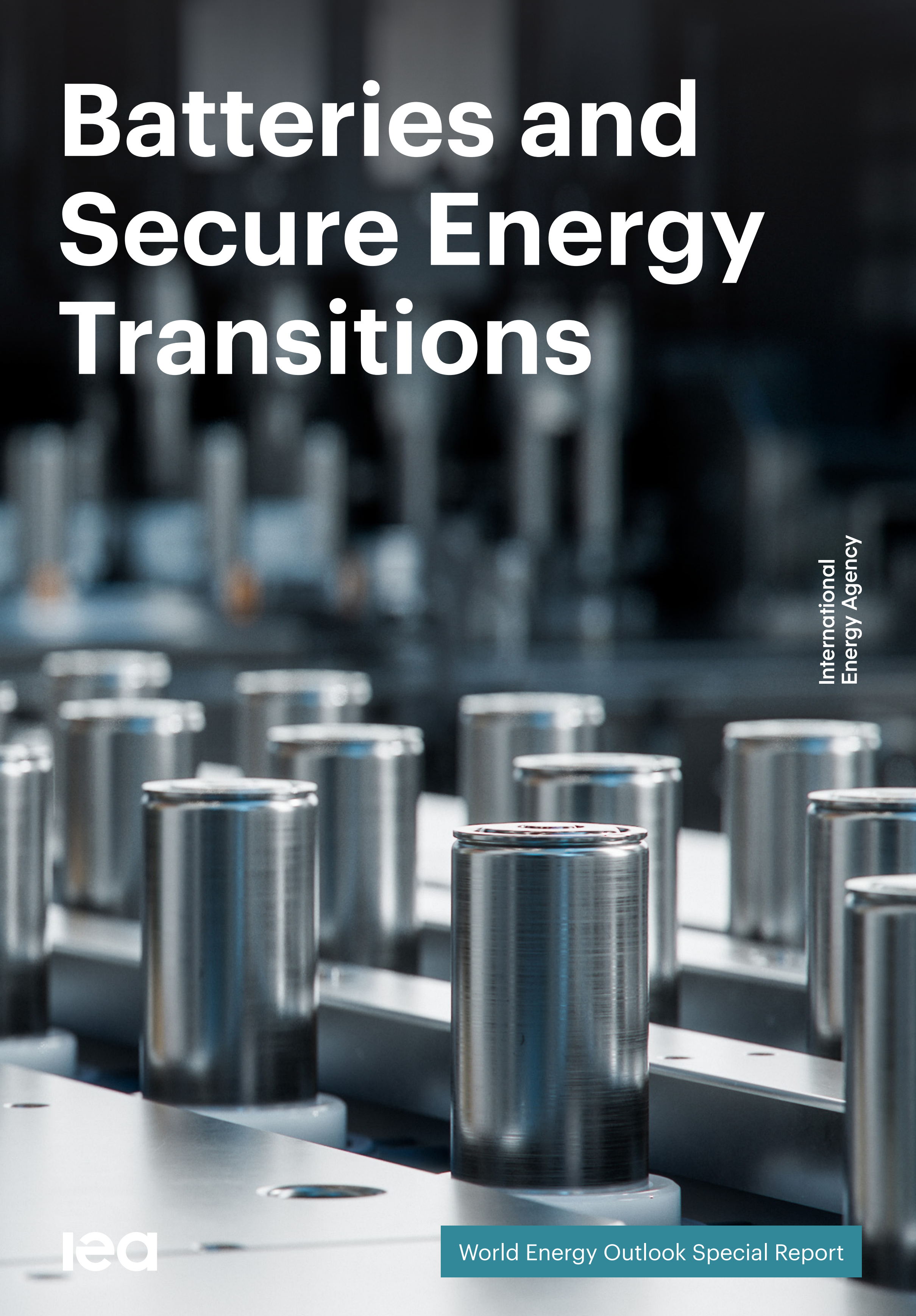
Batteries and Secure Energy Transitions



International Energy Agency

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INTERNATIONAL ENERGY AGENCY

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At the International Energy Agency (IEA), we monitor and analyse the progress of more than 500 energy technologies on a daily basis, providing valuable insights into the trajectory of the global energy sector. This process supports the development of energy policies and fosters dialogue at the highest levels of policy making.

In this new report, we provide an in-depth examination of a technology that is a linchpin in delivering clean energy transitions and protecting energy security. Batteries will be critical to achieving the energy goals agreed by nearly 200 countries at the COP28 climate change conference in Dubai, notably tripling renewable energy capacity by 2030, doubling the pace of energy efficiency improvements and transitioning away from fossil fuels.

Together with renewables and other clean energy solutions, batteries can ensure reliable and abundant supply of electricity to households and businesses throughout the world. Batteries are already the beating heart of our technology-led societies and essential to the devices, such as phones and computers, that are embedded in modern life. Now, as clean energy transitions pick up pace, the role of batteries is expanding significantly, and so too is our reliance on them. Manufacturers are producing batteries for an ever-growing range of consumer and industrial products as demand expands rapidly, from the drivetrains in electric vehicles to utility-scale power storage in our electricity systems.

Going forward, I see batteries having a profound impact on two sectors which are key pillars of the global energy transition – namely transport and power. Improvements in battery technology combined with rapidly falling costs, mean that electric vehicles in many parts of the world are increasingly competitive on price with conventional cars. In the power sector, new battery capacity globally has doubled year-on-year, with 2023 setting a new record for installations. Battery costs have declined by 90% in less than 15 years. And today, utility-scale batteries paired with solar PV are already competitive with new coal in some countries like India and, in the next few years, will be with new natural gas in the United States and new coal in China.

Reducing emissions and getting on track to meet international energy and climate targets will hinge on whether the world can scale up batteries fast enough. More than half the job that we need to do will rely, at least in some part, on battery deployment. Our analysis shows that energy storage more broadly will need to increase sixfold by 2030 to help meet the goals set at COP28, a target that will be met almost exclusively by batteries.

Yet, obstacles to progress remain. Costs must continue to come down to drive further uptake across a wide range of sectors. Battery manufacturing capacity has more than tripled in the last three years, but it remains too concentrated in only a few countries, as does the extraction and processing of the critical minerals on which it relies. However, the good news is that new chemistries for batteries will help reduce over-reliance on only a handful of key ingredients, and improving the recycling of raw materials will in time limit the need for new critical minerals supplies.

Governments have an important part to play in building out resilient local and international supply chains to ensure that securely and sustainably produced batteries come to market at a reasonable cost. Legislation such as the Inflation Reduction Act in the United States, the Net Zero Industry Act in the European Union and the Production Linked Incentive in India are good examples of how policy can affect real change in industry by backing technology manufacturing. But supportive policies are also needed to help speed up deployment by minimising barriers to market entry for developers and reducing red tape that can often stifle new projects.

I would like to thank the IEA colleagues who worked on this special report on Batteries and Secure Energy Transitions for their excellent and insightful analysis – under the leadership of Laura Cozzi, Director of Sustainability, Technology and Outlooks, and lead authors Brent Wanner and Apostolos Petropoulos. The report is the first ever comprehensive assessment of the state of play across the entire battery ecosystem. It details what needs to be done to fully leverage this technology to address the world's energy and climate challenge. If electricity is the future, batteries will charge us towards it.

Dr Fatih Birol
Executive Director
International Energy Agency

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Batteries are an essential part of the global energy system today and the fastest growing energy technology on the market

Battery storage in the power sector was the fastest growing energy technology in 2023 that was commercially available, with deployment more than doubling year-on-year. Strong growth occurred for utility-scale battery projects, behind-the-meter batteries, mini-grids and solar home systems for electricity access, adding a total of 42 GW of battery storage capacity globally. Electric vehicle (EV) battery deployment increased by 40% in 2023, with 14 million new electric cars, accounting for the vast majority of batteries used in the energy sector.

Despite the continuing use of lithium-ion batteries in billions of personal devices in the world, the energy sector now accounts for over 90% of annual lithium-ion battery demand. This is up from 50% for the energy sector in 2016, when the total lithium-ion battery market was 10-times smaller. With falling costs and improving performance, lithium-ion batteries have become a cornerstone of modern economies, underpinning the proliferation of personal electronic devices, including smart phones, as well the growth in the energy sector. In 2023, there were nearly 45 million EVs on the road – including cars, buses and trucks – and over 85 GW of battery storage in use in the power sector globally.

Lithium-ion batteries dominate battery use due to recent cost reductions and performance improvements

Lithium-ion batteries have outclassed alternatives over the last decade, thanks to 90% cost reductions since 2010, higher energy densities and longer lifetimes. Lithium-ion battery prices have declined from USD 1 400 per kilowatt-hour in 2010 to less than USD 140 per kilowatt-hour in 2023, one of the fastest cost declines of any energy technology ever, as a result of progress in research and development and economies of scale in manufacturing. They have also achieved much higher energy densities than lead acid batteries, allowing them to be stacked in much lighter and more compact battery packs.

Lithium-ion batteries dominate both EV and storage applications, and chemistries can be adapted to mineral availability and price, demonstrated by the market share for lithium iron phosphate (LFP) batteries rising to 40% of EV sales and 80% of new battery storage in 2023. Lithium-ion chemistries represent nearly all batteries in EVs and new storage applications today. For new EV sales, over half of batteries use chemistries with relatively high nickel content that gives them higher energy densities. LFP batteries account for the remaining EV market share and are a lower-cost, less-dense lithium-ion chemistry that does not contain nickel or cobalt, with even lower flammability and a longer lifetime. While energy density is of utmost importance for EV batteries, it is less critical for battery storage, leading to a significant shift towards LFP batteries.

Policy support has given a boost for batteries deployment in many markets but the supply chain for batteries is very concentrated

Strong government support for the rollout of EVs and incentives for battery storage are expanding markets for batteries around the world. China is currently the world's largest market for batteries and accounts for over half of all battery in use in the energy sector today. The European Union is the next largest market followed by the United States, with smaller markets also in the United Kingdom, Korea and Japan. Battery use is also growing in emerging market and developing economies outside China, including in Africa, where close to 400 million people gain access through decentralised solutions such as solar home systems and mini-grids with batteries in order to achieve universal access by 2030.

While the global battery supply chain is complex, every step in it – from the extraction of mineral ores to the use of high-grade chemicals for the manufacture of battery components in the final battery pack – has a high degree of geographic concentration. Battery manufacturers are dependent on a small number of countries for the raw material supply and extraction of many critical minerals. China undertakes well over half of global raw material processing for lithium and cobalt and has almost 85% of global battery cell production capacity. Europe, the United States and Korea each hold 10% or less of the supply chain for some battery metals and cells today.

Achieving COP28 targets will hinge on battery deployment increasing sevenfold by 2030

Batteries are key to the transition away from fossil fuels and accelerate the pace of energy efficiency through electrification and greater use of renewables in power. In transport, a growing fleet of EVs on the road displaces the need for 8 million barrels of oil per day by 2030 in the Net Zero Emissions by 2050 (NZE) Scenario, more than the entire oil consumption for road transport in Europe today. In the power sector, battery storage supports transitions away from unabated coal and natural gas, while increasing the efficiency of power systems by reducing losses and congestion in electricity grids. In other sectors, clean electrification enabled by batteries is critical to reduce the use of oil, natural gas and coal.

To triple global renewable energy capacity by 2030 while maintaining electricity security, energy storage needs to increase six-times. To facilitate the rapid uptake of new solar PV and wind, global energy storage capacity increases to 1 500 GW by 2030 in the NZE Scenario, which meets the Paris Agreement target of limiting global average temperature increases to 1.5 °C or less in 2100. Battery storage delivers 90% of that growth, rising 14-fold to 1 200 GW by 2030, complemented by pumped storage, compressed air and flywheels. To deliver this, battery storage deployment must continue to increase by an average of 25% per year to 2030, which will require action from policy makers and industry, taking advantage of the fact that battery storage can be built in a matter of months and in most locations.

In the NZE Scenario, about 60% of the CO_2 emissions reductions in 2030 in the energy sector are associated with batteries, making them a critical element to meeting our shared

climate goals. Close to 20% are directly linked to batteries in EVs and battery-enabled solar PV. Another 40% of emissions reductions are from electrification of end-uses and renewables that are indirectly facilitated by batteries.

Batteries bolster multiple aspects of energy security

Battery storage helps to strengthen electricity security in all markets. As the nature of electricity demand and supply changes, with more electrification and more variable generation from wind and solar PV, battery storage is well placed to provide short-term flexibility for periods of 1-8 hours continuously, and thus to help power system operators ensure there is enough supply to meet peak demands. Its fast and accurate responses to market signals, in a matter of seconds, make battery storage ideal for providing support for grid stability, and it is already being used for this purpose in many markets. Battery storage can also serve as critical back-up generators in case of grid outages or emergencies, ensuring uninterrupted power supplies to critical facilities such as hospitals, emergency response centres and infrastructure like grid substations and communication networks.

Batteries in EVs and storage installations reduce the need for imported fossil fuels, increasing self-sufficiency in many countries. EVs reduce the need for oil imports in many countries, including China, Europe, India, Japan and Korea. The need for natural gas and coal imports is reduced directly by battery-enabled renewables displacing natural gas-fired and coal-fired power, and indirectly by the electrification of industry and buildings where the use of electricity replaces fossil fuels.

Further cost declines for batteries improve their affordability in all applications and make them a cost-effective part of energy systems

Further innovation in battery chemistries and manufacturing is projected to reduce global average lithium-ion battery costs by a further 40% from 2023 to 2030 and bring sodium-ion batteries to the market. In the NZE Scenario, lithium-ion chemistries continue providing the vast majority of EV batteries to 2030. Further innovation both reduces the upfront costs of lithium-ion batteries and brings about additional improvements in their performance, notably in the form of higher energy densities and longer useful life. Sodium-ion batteries provide less than 10% of EV batteries to 2030 and make up a growing share of the batteries used for energy storage because they use less expensive materials and do not use lithium, resulting in production costs that can be 30% less than LFP batteries. Beyond 2030, battery costs are likely to decline further, and solid-state batteries are on track to be commercially available, with the potential to bring massive performance gains.

Solar PV plus batteries is competitive today with new coal-fired power in India and, in the next couple years, become competitive with new coal in China and new natural gas-fired power in the United States. Even in the Stated Policies Scenario (STEPS), which is based on today's policy settings, the total upfront costs of utility-scale battery storage projects – including the battery plus installation, other components and developer costs – are projected to decline by 40% by 2030. This makes stand-alone battery storage more competitive with natural gas peaker plants, and battery storage paired with solar PV one of the most competitive new sources of electricity.

The amount of battery storage capacity added to 2030 in the STEPS is set to be more than the total fossil fuel capacity added over the period. A significant part is behind-the-meter battery storage paired with rooftop solar PV, including many individual batteries aggregated into virtual power plants, as it becomes an increasingly attractive option for consumers in a world of broadly stable or rising retail electricity prices. For electricity access, the average electricity costs of mini-grids with solar PV and batteries halve by 2030.

Falling battery costs are set to raise the share of cost-competitive electric cars in the market from around 50% today. Currently, the least expensive EV models are available in China, with lower sticker prices than comparable gasoline or diesel cars. In advanced economies, there is still a price gap for electric cars that takes years to recover through lower fuel and maintenance costs. Battery price cuts and intense competition among car makers are set to make more types of EVs in more markets competitive. A growing number of EVs will have lower sticker prices than gasoline or diesel cars directly, and many others will cost slightly more to buy but save money for consumers over a few years**.**

Scaling up the global battery market creates new opportunities for diversifying supply chains

The global market value of batteries quadruples by 2030 on the path to net zero emissions. Currently the global value of battery packs in EVs and storage applications is USD 120 billion, rising to nearly USD 500 billion in 2030 in the NZE Scenario. Even with today's policy settings, the battery market is set to expand to a total value of USD 330 billion in 2030. Booming markets for batteries are attracting new sources of financing, including around USD 6 billion in battery start-ups from venture capital in 2023 alone.

Batteries are a "master key" that can unlock several much bigger transformations and much bigger industrial prizes. The global car market is valued at USD 4 trillion today, and leadership in it will depend on battery technology. Batteries also support more wind and solar PV, which capture USD 6 trillion in investment in the NZE Scenario from 2024 to 2030, by balancing out their variations and stabilising the grid.

Battery manufacturing is a dynamic industry and scaling it up creates opportunities to diversify battery supply chains. Battery manufacturing capacity is set to expand rapidly and, if all announced plants are built on time, would be practically sufficient to meet the battery requirements of the NZE Scenario in 2030. While China is set to expand its battery manufacturing significantly, announced plans imply that its share of the global market will decrease to about two-thirds of the global total in 2030 as other regions scale up. Both Europe and North America have announced plans to boost their domestic battery manufacturing capacity, each set to grow their market share to about 15% in 2030 and able to provide almost all their domestic demands for batteries.

There are important risks for batteries that could hinder their growth and contributions to energy transitions, energy security and affordability

Scaling up critical minerals supply in time to meet rising needs is essential to the success of batteries and requires action to address policy and regulatory barriers. In the NZE Scenario, demand for critical minerals for batteries expands rapidly by 2030, with manganese, lithium, graphite and nickel increasing at least sixfold, and cobalt more than tripling. While this requires new mining and refining, innovation on chemistries, enhanced recycling and "right-sizing" of batteries can cut demand for critical minerals by about 25% by 2030.

Failing to scale up battery storage in line with the tripling of renewables by 2030 would risk stalling clean energy transitions in the power sector. In a Low Battery Case, the uptake of solar PV in particular is slowed down, putting at risk close to 500 GW of the solar PV needed to triple renewable capacity by 2030 (20% of the gap for renewables capacity between the STEPS and NZE Scenario). If other low emission sources were not able to replace the lost solar PV, emissions reductions in the power sector would stall in the 2030s, putting the target of limiting the global average temperature rise to 1.5 °C out of reach.

The Low Battery Case would lead to prolonged use of coal and natural gas in the power sector and raise fuel import bills. Analysis indicates that import bills would be an average of USD 12.5 billion more per year from 2030 to 2050 in importing countries, with Europe and Korea as most exposed to this risk for natural gas imports and India for coal imports.

Recommendations for batteries to fulfil their roles

For batteries to scale up as necessary to support ambitious clean energy transitions, policy makers and regulators need to take action to support their deployment and minimise barriers and bottlenecks. Policy and regulatory frameworks need to ensure that batteries are able to participate in markets and are remunerated appropriately for the services they provide to the power system. The large-scale adoption of EVs calls for wider availability of affordable models and the rollout of charging infrastructure. Promoting smart charging will be vital to integrate rising numbers of EVs into power systems and reduce the need for grid reinforcements.

Policy makers and regulators need to work with national and international partners and with industry to support the development of battery supply chains that are secure, resilient and sustainable. Building supply chains requires a comprehensive approach that encompasses all stages from raw material extraction, refining and manufacturing through to end-of-life product management and recycling, minimising their carbon footprint. Battery recycling has the potential to be a significant secondary source of supply of critical minerals that is more sustainable and less geographically concentrated than primary supply. Targeted policies such as minimum recycled content requirements and tradeable recycling credits can foster its growth in the short term, especially if international standards can be established.

Status of battery demand and supply

A century of development underpinning rapid growth

SUMMARY

- Batteries are an important part of the global energy system today and are poised to play a critical role in secure and affordable clean energy transitions. In the transport sector, they are the essential component in the millions of electric vehicles (EVs) sold each year. In the power sector, they are becoming increasingly important in utility-scale and behind-the-meter applications as their costs fall and as the share of electricity generated by solar and wind rises.
- Average battery costs have fallen by 90% since 2010 due to advances in battery chemistry and manufacturing. Today lithium-ion batteries are a cornerstone of modern economies having revolutionised electronic devices and electric mobility, and are gaining traction in power systems. Yet, new battery chemistries being developed may pose a challenge to the dominance of lithium-ion batteries in the years ahead.
- The total volume of batteries used in the energy sector was over 2 400 gigawatt-hours (GWh) in 2023, a fourfold increase from 2020. In the past five years, over 2 000 GWh of lithium-ion battery capacity has been added worldwide, powering 40 million electric vehicles and thousands of battery storage projects. EVs accounted for over 90% of battery use in the energy sector, with annual volumes hitting a record of more than 750 GWh in 2023 – mostly for passenger cars.
- Battery storage capacity in the power sector is expanding rapidly. Over 40 gigawatt (GW) was added in 2023, double the previous year's increase, split between utility-scale projects (65%) and behind-the-meter systems (35%). Battery storage has many uses in power systems: it provides short-term energy shifting, delivers ancillary services, alleviates grid congestion and provides a means to expand access to electricity. Governments are boosting policy support for battery storage with more targets, financial subsidies and reforms to improve market access.
- Global investment in EV batteries has surged eightfold since 2018 and fivefold for battery storage, rising to a total of USD 150 billion in 2023. About USD 115 billion – the lion's share – was for EV batteries, with China, Europe and the United States together accounting for over 90% of the total.
- China dominates the battery supply chain with nearly 85% of global battery cell production capacity and substantial shares in cathode and anode active material production. The extraction and processing of critical minerals is also highly concentrated geographically, with China in the lead in processing the most critical minerals. Battery minerals prices have been volatile in recent years, rising steeply in 2021 and 2022 before falling sharply in 2023 and in the early months of 2024. This underlines the need for more investment and diversification as the market expands.

1.1 Introduction

Batteries have found a wide range of uses since they were first introduced over a century ago, and in recent years have become increasingly important in both the transport and power sector. Their average costs fell by 90% from 2010 to 2023, while improving their performance characteristics including higher energy densities[1] and longer cycle life.[2] As a result, batteries are now well placed to play an important part in transitioning to low-emissions energy systems.

In the power sector, energy storage in general and battery storage in particular helps to maintain electricity security by supporting grid stability, helping to meet peak load and improving integration of rising shares of variable renewables. To ensure a stable and reliable power supply, electricity demand and electricity generation need to be in equilibrium at all times. Historically, conventional sources of electricity including coal and natural gas have operated flexibly, adapting their output to match demand. Energy storage, in the form of hydropower with reservoirs, has long been a part of many power systems and supports electricity security by providing a buffer between available electricity supply from other sources and demand. Recently, batteries have emerged as another practicable way to store energy. Declining costs of batteries have made them a competitive source of flexibility in many parts of the world in stand-alone applications as well as when paired with solar photovoltaics (PV) or wind power.

In the automotive industry, a shift to electric vehicles (EVs)[3] is increasingly seen by governments and manufacturers as having an essential role to reduce air pollution and greenhouse-gas (GHG) emissions. This transition entails a transformation of the traditional automotive supply chain because EVs require fewer moving parts than cars using internal combustion engines (ICEs) and depend critically on their battery pack. As a result, industries that traditionally were not closely linked are increasingly working together. For example, many vehicle manufacturers are entering into joint ventures with battery producers and component manufacturers and securing offtake agreements with mining companies or with battery material suppliers. As well, utilities are collaborating with auto makers and battery manufacturers to identify potential synergies.

1.1.1 Batteries and secure energy transitions

Batteries are a desirable feature of the energy landscape, and they are set to play an essential role in providing stability and flexibility in power systems as variable renewables scale up. Plus, batteries are at the heart of the shift to EVs which is rapidly gaining ground. Given that the power and transport sectors currently account for over 60% of global energy-related

[1] Energy density is a measure of the amount of energy that a battery can store relative to its weight or volume.

[2] The cycle life of batteries is the number of charge and discharge cycles that it can complete before losing performance.

[3] Electric vehicle includes battery electric and plug-in electric vehicles.

carbon dioxide (CO_2) emissions, means that they have a crucial part to play in helping countries to fulfil commitments made at the 28th Conference of Parties of the United Nations Framework Convention on Climate Change in December 2023. Those pledges include tripling global renewable energy capacity by 2030, doubling the rate of energy efficiency improvements, and facilitating the transition away from fossil fuels.

Batteries have an essential role to support of the goal of tripling the installed capacity of renewables worldwide. By facilitating the integration of rising shares of solar and wind generation by providing energy storage, batteries help to reduce the use of coal and natural gas, and to promote faster electrification and increased use of electricity in heating and cooling, and in industry. They also support the transition away from fossil fuels as rising numbers of EVs reduce the demand for oil products.

Batteries also play a critical role to enhance energy security. By helping to reduce fossil fuel demand in multiple sectors, they cut fossil fuel requirements in importing countries, thus increasing their level of domestic energy independence. Batteries also support stability and resilience of electricity grids, offer a way to provide backup power for homes, businesses and services (including hospitals and other critical infrastructure). Batteries can also provide critical service in the case of emergencies caused by extreme weather or other disruptions.

Expanding electromobility brings with it a new era where the traditionally separate sectors of power and transport increasingly interact. Rising EV use increases demand for electricity, but the interactions go beyond that: advances in batteries for EVs have spill-over effects that benefit batteries used for storage applications, while the rising number of EVs offers potential for demand-side management in the power sector.

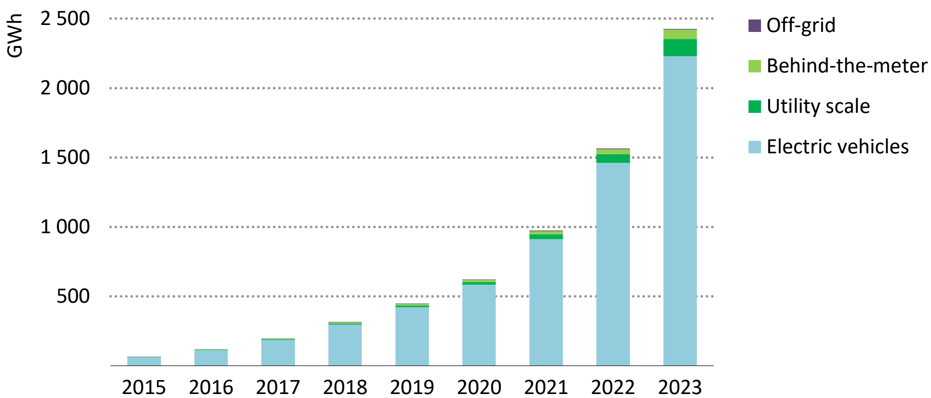
Battery use is significantly expanding across the energy sector, with new highs in EV sales and record levels of additions of battery storage in the power sector. One-in-five cars sold worldwide today is electric, and an increasing number of solar and wind power projects are paired with batteries. Announced new battery cell manufacturing facilities worldwide are many. Global scaling up of battery production offers numerous opportunities across the supply chain. However, it also brings a number of challenges, a high geographical concentration of required critical minerals, a need for recycling and re-purposing facilities, and needs to tackle regulatory and policy barriers.

This decade is crucial to scale up battery cell and material production by ensuring the availability of machinery and production equipment, as well as to establish effective regulatory and policy frameworks to ensure a sustainable and equitable transition. The shift from a fossil fuel-based energy system to one reliant on renewable energy and other low-emissions sources will boost demand for energy storage, and thus for batteries and the critical minerals required. This requires careful planning, international collaboration, diversification of critical minerals supply and the adoption of sustainable practices across the entire battery supply chain. Governments, vehicle manufacturers, battery makers, mining companies, recycling firms, utilities and grid operators all need to work collaboratively to address the challenges.

1.1.2 Battery use in the energy sector

The volume of battery use in the energy sector was over 2 400 gigawatt-hours (GWh) in 2023 – a fourfold increase since 2020. More than 2 000 GWh of lithium-ion battery volume has been added over the last five years, powering over 40 million electric vehicles and thousands of battery storage projects (Figure 1.1).

Figure 1.1 ▷ Lithium-ion battery volumes in use by type of application in the global energy sector, 2015-2023



IEA. CC BY 4.0.

Lithium-ion battery volumes in use have surged over the last three years to 2 400 GWh

Note: GWh = gigawatt-hours.

Increased demand for lithium-ion battery volumes stems from higher EV penetration, with EVs accounting for over 90% of the increase from 2015 to 2023. Strong uptake of EVs is supported by a variety of fuel economy targets, CO_2 standards, financial incentives and EV mandates. The deployment of battery storage in power systems is also accelerating, with a focus on grid stability, backup systems and the continued expansion of variable solar PV and wind generation.

The global market for battery storage doubled in 2023, reaching over 90 GWh and increasing the volume of battery storage in use to more than 190 GWh. Most growth in battery storage is from utility-scale systems, while behind-the-meter battery storage accounts for 35% of annual growth in 2023. Off-grid battery storage is currently at much lower volumes. Battery storage of all sizes is well-suited to providing short-term flexibility – shifting energy across seconds, minutes or a few hours – but can provide a broader range of services to power systems. These include ancillary and reserve services, provision of system adequacy and congestion management in transmission and distribution systems. Financial incentives, including tax credits and grants, as well as requirements to pair storage with new solar or wind projects are also driving deployment. The increase in behind-the-meter battery storage is concentrated geographically, with support measures and relatively high electricity prices driving the uptake in leading markets such as Australia, Germany, Japan and parts of the

United States. Battery storage is one of several energy storage technologies used in the power sector, with pumped hydro being the largest by far. Compressed air energy storage, flywheels and thermal storage are also gaining traction in several markets.

1.1.3 Recent developments in battery costs

The past decade can be seen as the era of the lithium-ion battery. Its fundamental advantage over older alternatives such as lead acid or nickel cadmium batteries is their much higher energy density and longer cycle life. While lead acid batteries have specific energies (energy stored per unit of weight) in the range of 35 to 40 watt-hours per kilogramme (Wh/kg), lithium-ion batteries today have a demonstrated range of specific energies around 90-300 Wh/kg at the cell level. With their higher energy density, lithium-ion batteries can be stacked into much lighter and more compact battery packs.

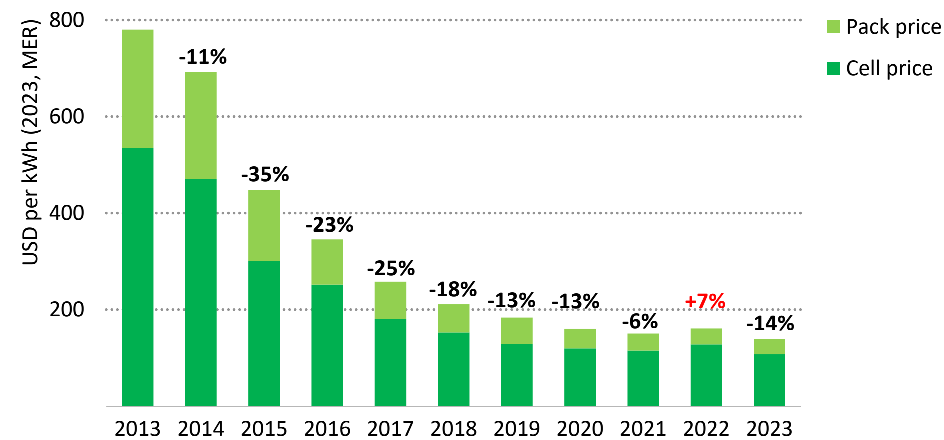
A lithium-ion cell has four main components: cathode, anode, electrolyte and separator. The cathode and anode store lithium ions, from which the technology derives its name. The primary function of separator is to prevent short circuits, while the electrolyte facilitates the movement of lithium ions from the cathode to the anode during the charging mode and vice versa during the discharging mode. Today there are several varieties of lithium-ion batteries, and they continue to evolve as the result of research and development (R&D) to improve energy densities, charging times, safety and lifetime use while also cutting costs.

Today 90% of lithium-ion batteries in use are for electrification in the transport sector. Batteries for EVs must be energy dense, small and light. Battery storage, by contrast, does not have such strict requirements for size and weight, but instead prioritises low costs and durability. Trends from the automotive industry have often transferred to the power sector, and improvements in EV batteries could significantly benefit batteries used for storage, whereas the converse may not necessarily be true. However, both sectors are looking to minimise the carbon footprint of their battery use and to maximise opportunities for battery reuse and recycling. For example, EV batteries could potentially be repurposed for second-life applications such as behind-the-meter or storage solutions.

Over a decade, lithium-ion battery prices (including cell and pack costs) have declined from around USD 800 per kilowatt-hour (kWh) to less than USD 140/kWh in 2023, thanks to continued progress in R&D, economies of scale and technological innovation. This has increased the share of raw material costs in the total cost of batteries (see section 1.5.3) and battery prices now depend in large part on the price of critical minerals, which can be volatile. For example, spikes in battery metals prices in 2022 resulted in the first ever year-on-year increase in battery prices (Figure 1.2). However, an upsurge in minerals supply and enhanced battery manufacturing capacity, coupled with lower than anticipated demand in specific regions, particularly China, resulted in a significant price decrease in 2023, with the cost of batteries falling below 2021 levels.

The battery industry continues to invest in low-cost cathode chemistry known as lithium iron phosphate (LFP) (see section 1.2.2). These packs and cells had the lowest global weighted average prices of all lithium-ion batteries in 2023, with prices falling below USD 100/kWh for the first time (BNEF, 2023a). Even in the initial months of 2024, LFP cell prices have continued their downward trajectory, and were well below USD 100/kWh in March 2024 (Benchmark Minerals, 2024). On a regional basis, lithium-ion battery prices were lowest in China and around 10-20% higher in the United States and Europe. Nevertheless, the reduction in price variance compared to the levels seen in 2022 and 2021 suggests a trend toward convergence in battery prices in different markets.

Figure 1.2 ▹ Lithium-ion battery pack and cell prices, 2013-2023



Prices for lithium-ion batteries steadily declined over the last decade with a spike in 2022, but dropping again in 2023

Notes: USD = US dollars, kWh = kilowatt-hours. Prices are weighted average across regions and chemistries.

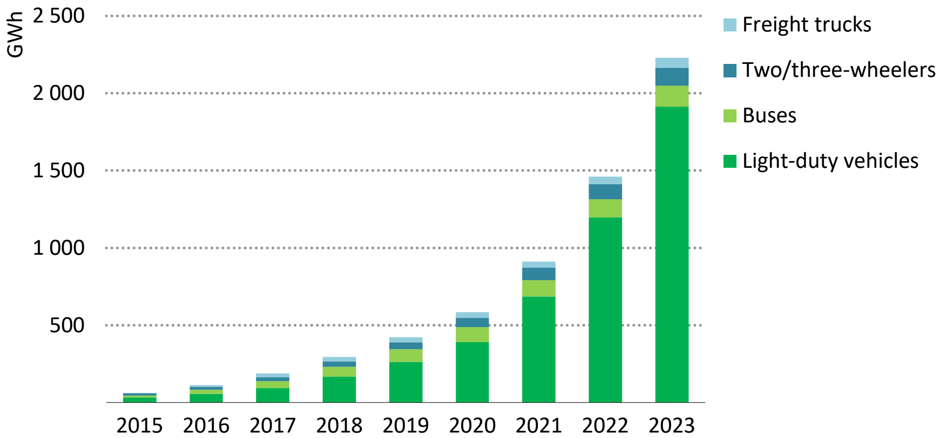
Source: IEA analysis based on BNEF (2023a).

1.2 Battery use in electric vehicles

Worldwide sales volumes of batteries for EVs rose to an all-time high of over 750 GWh in 2023 reflecting a surge in EV uptake (Figure 1.3). Today nearly one-in-five new cars sold is electric. Both bigger cars and range concerns have driven an increase in the average size of EV battery packs in recent years.

Worldwide the volume of batteries for electromobility has quadrupled over the past three years, with batteries for passenger light-duty vehicles (PLDVs) accounting for over 90% of this increase. This growth is attributed to stronger support policies compared to those available for medium freight and heavy freight trucks and buses, as well as fewer barriers associated with the larger batteries and power requirements needed for electrifying heavy-duty or long-distance transport. Electromobility is also accelerating in other modes with the electrification of two/three-wheelers and city buses moving ahead especially fast, particularly in emerging market and developing economies.

Figure 1.3 ▷ EV battery volumes in use by vehicle type, 2015-2023



EV battery volumes have quadrupled over the past three years, mostly in passenger cars

Notes: Light-duty vehicles include passenger cars and light commercial vehicles. Freight trucks include medium and heavy freight trucks.

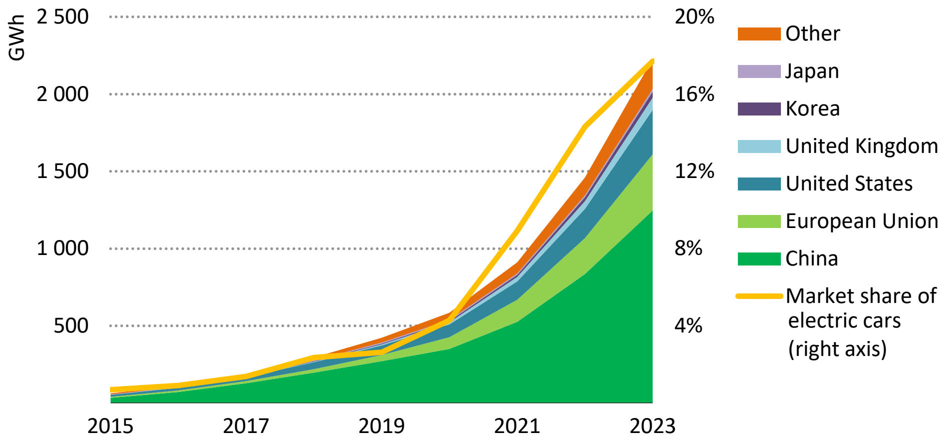
1.2.1 Leading EV markets

China dominates the global EV battery market, accounting for more than half of total EV battery volumes in 2023. The European Union and United States together accounted for 30% of total EV battery volumes in use (Figure 1.4).

EV sales are experiencing rapid growth worldwide. The market share of electric cars has increased more than sevenfold over the past five years, reaching 18% in 2023. Today, nearly 40% of all new cars sold in China are electric, while in the European Union it is over 20% of all new car sales and 10% in the United States. Batteries used in electric cars in these three regions represent 80% of the global battery volumes in use today in the energy sector. There is huge untapped electrification potential in emerging market and developing economies other than China, where electric cars currently constitute only 2% of sales, despite large year-on-year growth in countries such as India (up 70% in 2023) and Indonesia (up by over 60% in 2023), albeit from a small base.

China is seeing a gradual reduction in its dominance of the global battery market as EV sales accelerate in advanced economies and its domestic electromobility market matures. Over the last five years, China's share of battery volumes used in global EV fleets has declined from over 65% to around 55% as support mechanisms and regulations intensify in other regions. The growing preference for electric sport utility vehicles (SUVs) and EVs with longer driving ranges in advanced economies is further boosting battery demand. On average, battery electric SUVs are 15% more energy intensive than medium-size EVs, which means that they require a battery that on average is 30% larger (Box 1.1).

Figure 1.4 ▻ **Battery volumes in use in EV fleets by region and market share of electric cars in sales, 2015-2023**



China accounts for around 55% of battery volumes in use in EV fleets, but its share is gradually declining as EV sales accelerate elsewhere

The volume of EV batteries in use in various countries broadly reflect their domestic battery manufacturing capacities and the size of their automotive industries. China, Europe and the United States are currently the largest EV markets, accounting for 90% of the global EV fleet. China accounts for 83% of global battery production, Europe and the United States for another 13%, and Korea and Japan for the remaining 4%. China's leadership position in global both battery plant capacity and EV manufacturing facilities enables it to supply its own EV market, powering the world's largest electric car fleet with the most affordable batteries. Intensifying competition between battery producers trying to gain lucrative EV market share means that EV prices are dropping in some segments and regions, which is likely to further boost EV sales.

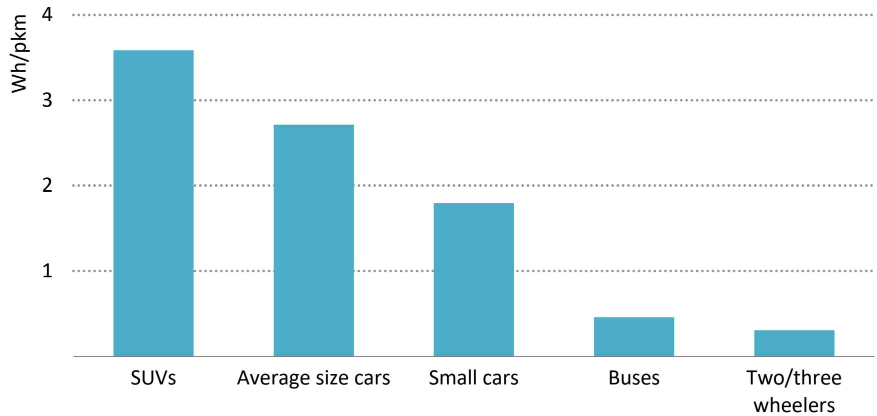
Box 1.1 ▻ **Batteries to meet passenger-kilometre demand**

Types of passenger transport have various purposes, range requirements and seating capacity, all of which influence the size of the battery requirement. When planning a sustainable and low-emissions transport sector, it is crucial to consider not only fuel economy but also the battery capacity required for operation and the relative efficiency of various modes of transport, measured in terms of passenger-kilometres. For example, battery electric buses require a lower battery capacity per passenger-kilometre than passenger cars due to higher occupancy rates.

Two/three-wheelers have the highest efficiency in terms of battery capacity needs per passenger-kilometre served, although ranges may differ for each mode. Battery powered buses offer the second most efficient performance for passenger-kilometres provided, followed by small EVs (40 kWh) and average size EVs (approximately 60 kWh). SUVs (around 80 kWh) demonstrate the least efficient performance on a passenger-kilometre basis, requiring double the battery capacity per passenger-kilometre of small EV (Figure 1.5).

1

Figure 1.5 ▻ Battery capacity per passenger-kilometre of selected electric vehicle types, 2023



An electric SUV requires twice the battery capacity as a small electric car on a passenger-kilometre basis

Notes: Wh/pkm = Watt-hour per passenger-kilometre, SUVs = sport utility vehicles. Analysis assumes average occupancy per vehicle type.

Prioritising public transport and smaller vehicles therefore makes sense in terms of optimising future battery availability and minimising demand for the critical minerals that batteries require.

1.2.2 EV battery chemistry

Lithium-ion batteries are often categorised and named by reference to the composition of elements in their cathode – one of the two electrodes in which lithium ions are stored during charging and discharging cycles. The most common chemistries are: lithium nickel manganese cobalt oxide (NMC); lithium nickel cobalt aluminium oxide (NCA); lithium iron phosphate (LFP); and lithium cobalt oxide (LCO). Differing combinations and proportions of minerals in each battery chemistry type gives rise to different characteristics. LCO is one of the most established chemistries and is primarily used in portable electronics due to its high energy density and maturity. Today, NMC, NCA and LFP chemistries dominate in the EV battery market. In recent years, alternatives to lithium-ion batteries such as solid-state and sodium-ion batteries have gained attention (Rudola et al., 2023).

Today NMC and NCA account for a large share of EV batteries because their relatively high nickel content enables batteries to be produced with higher energy densities. Nickel has gained ground at the expense of cobalt in large part because of the pressure for increased EV range, although spikes in cobalt material prices and concerns over ethical mining practices in the 2010s gave battery producers additional incentives to reduce the cobalt content in batteries over the past decade. This has led to the development of many variations of NMC chemistry, from the initial NMC 111 to variations with higher nickel content such as NMC 622 and NMC 811.[4] Even more nickel-rich chemistries such as NMC 955 have recently emerged. However, higher nickel content requires more complex and controlled production processes, and it remains challenging to remove cobalt completely because of the contribution it makes to stability. The preference for increasing the content of nickel is also a feature of the NCA chemistries that have historically been favoured by the auto maker Tesla.

LFP is a lower cost battery chemistry, over 20% cheaper today than NMC. It does not contain nickel or cobalt, and it offers a more stable chemistry than nickel-rich chemistries, with reduced flammability and a longer cycle life. However, it has a significantly lower energy density, conventionally 20-30% lower than high nickel chemistries at battery cell level. Despite its inferior energy density, the use of LFP for EV batteries has increased significantly in recent years. It has been the leading chemistry for new EVs in China since 2021, and more recently has begun to be used by European and US auto makers. The new popularity of LFP chemistry is primarily driven by its lower price and longer lifespan relative to the alternatives, by energy density improvements such as the cell-to-pack (CTP) configuration and by improved thermal stability. Its cost effectiveness and durability make LFP the preferred battery chemistry for buses and commercial vehicles.

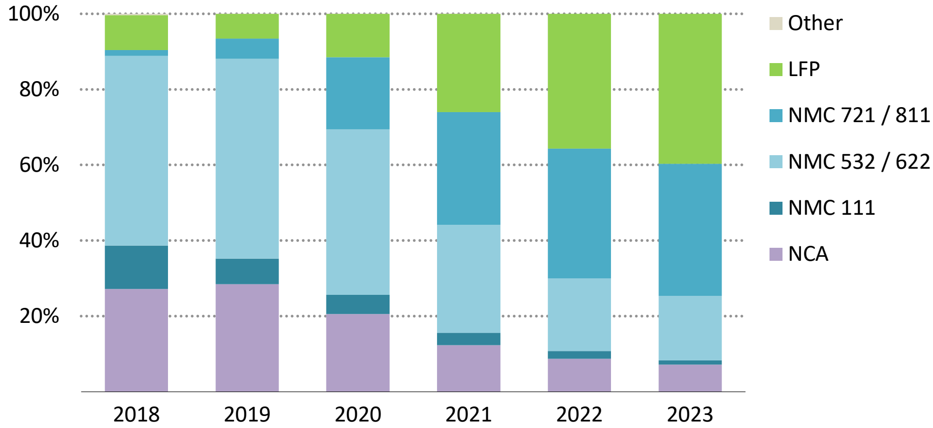
Choice of battery chemistry involves balancing performance, longevity and cost, and depends on the target market and applications. Geographical location is also important in battery chemistry selection, with LFP performing better in hot climates and NMC in colder climates. Furthermore, producing different cathode chemistries requires specialised expertise, and this is not evenly distributed globally. In 2023, NMC remained the dominant battery chemistry, accounting for over half of the passenger car market, followed by LFP with a share of around 40%, and NCA with a share of about 7% (Figure 1.6). The increasing share of LFP cathode chemistries over the past decade reflects improvements in energy density and performance. Around 95% of the LFP batteries for electric passenger cars were used in vehicles produced in China, driven by significant domestic investment, but non-Chinese manufacturers are now increasingly investing in developing their own LFP products.

Solid-state batteries (SSBs) offer higher energy density and potential safety improvements relative to traditional lithium-ion batteries, but so far it has proven challenging to demonstrate these advantages at scale and to overcome manufacturing hurdles. While SSBs

[4] The numbers after NMC denote the relative ratios of each element in the composition of the battery chemistry, i.e. NMC 111 has equal parts of nickel, manganese and cobalt.

may have limited impact in the next few years, their significance could rise substantially in the 2030s if these challenges are overcome.

Figure 1.6 ▷ Battery cathode chemistry in electric car sales, 2018-2023



NMC remains the dominant cathode chemistry for electric cars, while the share of LFP batteries is increasing and reached its highest ever level in 2023

Sodium-ion batteries use lower cost materials and need fewer critical minerals than the batteries that currently dominate the EV market and therefore are cheaper to produce. Different cathode chemistries can be employed for sodium-ion batteries, with layered oxides, typically using nickel, manganese or both, and Prussian white (made of sodium, iron, nitrogen and carbon) currently being the closest to mass commercialisation. Sodium-ion is currently the only viable battery technology that does not contain lithium. Sodium-ion batteries can also use aluminium anode current collectors whereas lithium-ion batteries require copper anode current collectors, so sodium-ion batteries also reduce copper usage. They can cost 20-30% less than LFP batteries, but their relative cost advantage is dependent on the lithium price which has been highly volatile over recent years.

Sodium-ion batteries can be manufactured using the same or similar manufacturing facilities as lithium-ion batteries. This could facilitate their wider deployment, especially in compact urban vehicles and storage applications (McKinsey & Company, 2023). However, the need to scale up supply chains, particularly for the hard carbon anode, currently is a significant constraint on production. Moreover, sodium-ion batteries currently have up to 40% lower energy density than lithium-ion batteries, which is likely to limit their use mostly to cars that are primarily used in urban areas, two/three-wheelers and storage in the power sector. Sodium-ion technology has been developed between the United States, Europe and China, but most of the planned manufacturing capacity today is set to be located in China.

Innovation in lithium-ion batteries meanwhile is bringing further improvements in their design and their chemistry. On the design front, advances such as CTP[5] and cell-to-chassis (integrating cells directly into the vehicle chassis), are helping to deliver higher energy densities and lower costs, although they raise issues in terms of battery repairability and recycling, and may also require further work to ensure safety. On the chemistry front, the addition and increase of manganese content in both nickel-based chemistries and LFP has the potential to lower the costs of nickel-based chemistries without reducing their high energy density, and to enhance the energy density of LFP batteries as the cathode moves to lithium manganese iron phosphate (LMFP). Improvements in silicon anodes may also lead to higher energy density and higher voltage batteries while reducing dependence on the highly concentrated supply chain of graphite anodes.

1.2.3 Navigating bottlenecks: Policy and infrastructure challenges

Global electric car registrations surged by 35% in 2023 compared with 2022, driving annual EV battery volumes up to more than 750 GWh. However, a number of challenges need to be tackled to maximise the future growth of EV markets.

The first challenge is affordability. Despite efforts by vehicle manufacturers to offer more affordable EVs, they still tend to cost more to buy in western markets such as the United States and Europe than their traditional gasoline and diesel counterparts. On average, consumers in Europe and the United States spend from USD 10 000 to 15 000 more to purchase a new EV model than they would spend for a comparable ICE model. Despite the upfront price difference, the payback period for a battery electric car in several markets ranges from three to eight years, with the running costs of a battery electric car on average around 35% lower than for a gasoline car.[6] However, the price tag gap remains a major barrier for many consumers. While manufacturers in the United States and Europe have tended to lean towards large and luxurious EVs, Chinese auto makers have focussed on small and lower cost models. The least expensive EV models in China are priced nearly 10% lower than their ICE equivalents (JATO, 2023). However, both Tesla and Volkswagen have announced plans to introduce electric car models priced around USD 25 000 after 2025.

The second challenge is the development of charging infrastructure, particularly outside of China, the European Union and United States. In 2023, public charging infrastructure increased by over 40%, but only 2% of the additions were located outside these regions. While advances in battery chemistries will alleviate range anxiety, the development of adequate charging infrastructure is also crucial.

A third challenge is the current lack of standardisation. Streamlining battery sizes, shapes and packaging could cut costs, facilitate battery swapping, reduce costs for reuse and

[5] Cell-to-pack design integrates cells directly into the pack structure, eliminating the need for separate assembly into modules.

[6] Assumes annual mileage of 10 000 kilometres, comparing medium-size cars and average weighting on the passenger light-duty vehicle stock per region in 2023 (IEA, 2023a).

recycling, and facilitate disposal processes. On the other hand, standardisation could hinder battery innovation and constrain manufacturers. Policy frameworks will need to balance these competing considerations.

A fourth challenge is the need for continued battery innovation. Drivers for innovation include further electrification beyond light-duty vehicles, environmental concerns, the desire for a higher degree of energy independence and raw materials supply constraints. Providing long-term planning clarity and certainty is essential. So is long-term policy support, as provided for example by the Inflation Reduction Act in the United States, the "Fit for 55" package in the European Union, the Faster Adoption and Manufacture of Hybrid and Electric Vehicles Scheme in India and New Energy Vehicle policies in China. Long-term support fosters domestic manufacturing and incentivises investment in battery-led energy transitions. The battery end-of-life management industry faces a unique challenge in the current dynamic conditions: the harmonisation of compliance mechanisms for support policies, like battery passports, would help all stakeholders to tackle the challenges involved.

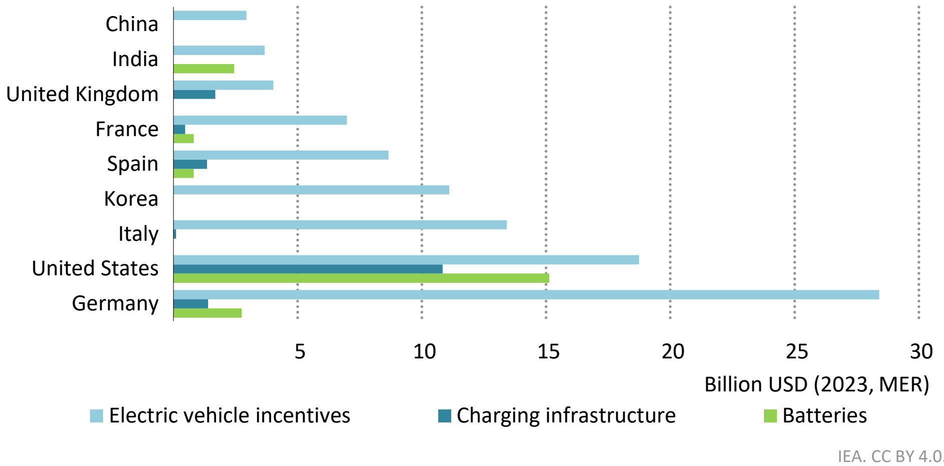
A fifth challenge concerns supply chains. As batteries play an increasingly vital role in the energy transition, there is growing need for a resilient and sustainable value chain, and for global collaboration to help achieve this. A highly concentrated market risks shortages of raw materials and components. Strategic investment could diversify supply chains, including into emerging market and developing economies outside China, and this could bring social and economic benefits for those economies, particularly if investments prioritise sustainability and ethical labour practices.

1.2.4 Policy support for EV batteries

Policy support and the relatively high cost of EVs have concentrated global EV battery demand in China, the European Union and United States, which together currently account for over 85% of the global electric car fleet. Early adoption in these regions was enabled by policies such as vehicle purchase incentives, the adoption of CO_2 emissions standards and fuel economy targets. China was also an early adopter of domestic automaking and battery manufacturing support through direct incentives, with decades of financial concessions to local firms paving the way for global EV and battery giants such as BYD and CATL. These incentives were accompanied by fiscal support for purchasers of EVs. Public support schemes for small and affordable EVs, including subsidies and incentives for both consumers and manufacturers, have been key to China's model, together with the availability of labour and access to finance.

The United States is now aiming to increase the adoption of EVs through the provision of generous subsidies under the Inflation Reduction Act of 2022 for domestically produced models that meet Clean Vehicle Tax Credit requirements, while simultaneously supporting the domestic EV industry with over USD 15 billion offered in the form of production credits for advanced manufacturing (Figure 1.7). Funding for charging infrastructure and local battery production is also part of the package of policy initiatives in the United States, with the Infrastructure Investment and Jobs Act allocating nearly USD 7 billion in grants across the battery value chain.

Figure 1.7 ▹ Government support for investment in EVs, charging and batteries in selected countries, 2020-2023



Since 2020, around USD 130 billion was provided to support electromobility and USD 25 billion for batteries

Similar efforts are being made in the European Union, where CO_2 standards are prompting European auto makers to expand EV production. National subsidies in many EU member states further support EV adoption. As battery demand rises, the EU Critical Raw Materials Act sets 2030 targets to make the battery supply chain more secure. The Net Zero Industry Act aims to ensure that 40% of the demand for certain clean energy technologies, including charging infrastructure and batteries, is met by 2030 from production sites located in the European Union. In parallel, it seeks to boost European production by fast-tracking permitting and allowing financial and regulatory support. With support provided under the EU Temporary Crisis and Transition Framework, battery producer Northvolt recently gained approval for almost USD 1 billion in grants and guarantees to build an EV battery production plant in Germany.

Similar kinds of support are also being provided elsewhere. India has allocated USD 2.5 billion through its Production-Linked Incentive scheme in a bid to develop a domestic battery manufacturing industry. Malaysia has introduced income tax breaks for domestic EV charger manufacturers. Thailand has enacted a new USD 700 million subsidy scheme that aims to lower the production cost of domestic EV batteries.

Increasing financial support from governments in recent years, provided through clean vehicle credits, tax credits and exemptions and state-backed loans, has led to a surge in global investment in EV batteries. Since 2020, nearly USD 130 billion has been spent by governments to incentivise the production and uptake of EVs, including charging infrastructure, notably through the EU Recovery and Resilience Facility and the US Inflation Reduction Act. In addition, around USD 25 billion has been provided in financial support for battery manufacturing and recycling, and in incentives for the deployment of battery storage units.

As China's EV market matures, national subsidies are decreasing, with regional targets and policies now playing a more important role. Similarly, countries such as Norway, the United Kingdom and certain EU member states are adjusting or reducing purchase incentives as their EV markets develop. Governments in such markets can achieve financially sustainable road sector electrification by redirecting support from private vehicle subsidies to charging infrastructure development, for example as in China, Australia and the United Kingdom. Other policies are likely to continue to provide support for EVs, even if that is not their primary objective. One example is low-emission zones, which are increasingly being adopted in European cities.

The question of affordability is likely to continue to concern policy makers. Corporate cars typically transition to private ownership after an average of three to four years. Therefore, electrification goals for corporate fleets could boost the second-hand EV market, making EVs more affordable for private consumers (Platform for Electromobility, 2021). Additionally, interest-free or low-interest loans for electric cars could help to make EVs more affordable and speed up decarbonisation of the road sector.

Policy makers will need to find a way to balance future EV growth policies and the desire to build domestic industries with concerns about the risks of geopolitical fragmentation. Secure and resilient supply chains will have an important role to play in this context. This is not an easy balance to strike, but the cost-effective development of innovative battery technologies, which is essential to reach global climate ambitions, ultimately depends on co-operation as well as on competition.

1.2.5 Opportunities related to the expanding battery market

Many emerging market and developing economies striving for economic growth and sustainability see opportunities in the expanding battery market, and more and more governments are looking to participate in global supply chains. Indonesia, for example, is on track to become the largest lithium-ion battery and component manufacturing hub in Southeast Asia, thanks to its abundant raw material resources. However, a wealth in raw materials is not the only entry point. Batteries require a broad range of components that vary over time as the chemistry evolves. Cell and battery component manufacturing is emerging as a lucrative market, for example, as is the recycling of metals from end-of-life batteries.

The battery market incorporates a wide span of economic activity with employment opportunities at various skill levels, ranging from battery R&D, manufacturing and integration to applications and recycling. There is scope for the global battery market to grow very significantly in the years ahead. If the world were on track with the IEA Net Zero Emissions by 2050 (NZE) Scenario, over two-thirds of the global auto manufacturing workforce would be dedicated to EVs and vehicle batteries by 2030. Manufacturing of EV batteries alone would create additional 3.5 million jobs by around 2030, equivalent to a third of the ICE vehicle manufacturing workforce today.

1.3 Battery use in the power sector

Over the course of the last decade, global installed battery storage capacity has increased exponentially, from about 1 gigawatt (GW) in 2013 to over 85 GW in 2023. Over 40 GW was added in 2023 alone, which was more than twice as much as in 2022. The strong increase in annual battery storage capacity additions recorded over the last five years has been driven almost entirely by China, the European Union and United States, which collectively accounted for nearly 90% of the capacity added in 2023.

About 65% of the capacity additions are for utility-scale systems, with behind-the-meter battery storage responsible for about 35% of the annual additions on average. Utility-scale battery storage refers to large applications connected directly to transmission or distribution networks (front-of-the-meter), typically ranging from several hundred kWh to multiple GWh in size. Behind-the-meter battery storage systems are generally installed at residential, commercial or industrial end-user locations, without a dedicated connection to the grid. They are usually, but not always, significantly smaller than utility-scale batteries.

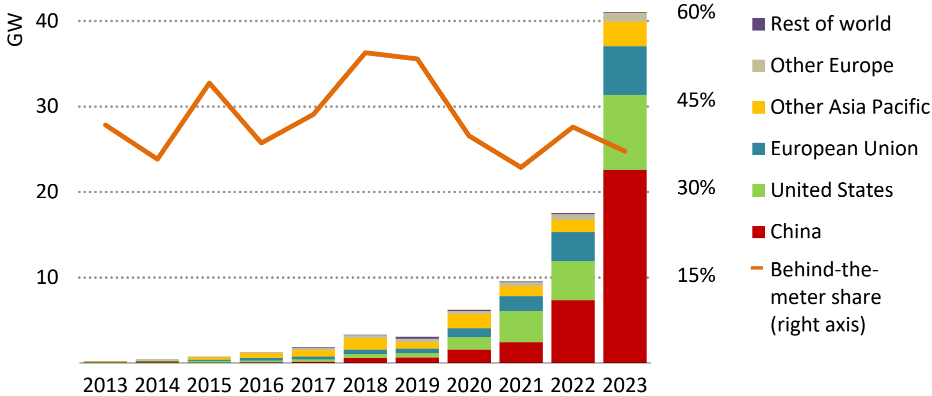
Deployment by region

China became the leading market for battery storage two years ago, with its share in annual global additions rising from around 20% in 2019 to 55% in 2023 (Figure 1.8). Capacity additions tripled in 2023 to 23 GW. About two-thirds of the additional capacity was utility scale, driven mainly by provincial level mandates to pair new solar PV or wind power projects with energy storage. Behind-the-meter storage capacity rose strongly as well, with large-scale commercial rather than residential users driving the uptake, underpinned by subsidies and increasing application of time-of-use electricity tariffs.

The **United States** is the second-largest battery storage market. Additions have roughly doubled year-on-year, rising to over 8 GW in 2023. Utility-scale projects accounted for nearly 90% of the additional capacity in 2023, with California, Texas and other states in the southwest leading deployments. Improving economics have been boosted by market reforms, falling equipment costs and an investment tax credit introduced as part of the Inflation Reduction Act. This has allowed utility-scale batteries to make inroads into ancillary service markets, where they are increasingly tapped to provide balancing services and secure capacity in states with high shares of variable renewables generation.

Installed battery storage capacity in the **European Union** increased by 70% in 2023, with annual additions rising to nearly 6 GW. Nearly 90% of the capacity growth was associated with behind-the-meter storage, mostly in Germany and Italy, where high retail electricity prices and incentives such as tax breaks and low-interest loans support the pairing of rooftop solar PV with storage. Close to 80% of the rooftop solar PV installed in Germany and Italy in 2023 came with storage. On the utility-scale storage side, additions are increasingly supported through capacity auctions. In Italy, for example, capacity auctions held in 2022 for delivery in 2024 awarded contracts totalling 1.6 GW to battery storage, with some of these systems coming online in 2023.

Figure 1.8 ▷ Battery storage capacity additions worldwide, 2013-2023



Capacity additions doubled in 2023, led by China, the United States and the European Union

Note: GW = gigawatts.

Other markets have also seen significant growth. Capacity additions in **Australia** jumped to 1.3 GW in 2023, rising more than 2.5-fold from the previous year. Utility-scale projects accounted for nearly 60%, with high price spreads on the wholesale electricity market and high ancillary service prices driving investment. Behind-the-meter capacity rose strongly as well, in part thanks to financial incentives that encourage the pairing of residential PV systems with batteries. Utility-scale battery storage capacity additions in **Japan** and **Korea** increased substantially in 2023 rising to more than 400 megawatts (MW) and 300 MW respectively. Japan has also added over 300 MW of behind-the-meter battery storage annually over the past four years. Behind-the-meter capacity additions in Korea peaked in 2018, but the market crashed following the withdrawal of subsidies and has yet to regain its 2018 level. The **United Kingdom** added over a gigawatt of battery storage in 2023, becoming Europe's largest market for utility-scale batteries. Meanwhile **Chile** added nearly 250 MW of utility-scale storage in 2023, making it the first country in Latin America to deploy battery storage at scale.

In other regions, capacity additions have so far been limited. However, in addition to further rapid acceleration in today's core markets, capacity growth is expected to broaden into new markets over the next few years. Energy storage targets and financial support mean that **India** in particular has significant potential to emerge as another large market for battery storage.

Market leaders for battery storage in the power sector

The battery storage industry is not structured in the same way as the EV industry, which is dominated by car makers and battery manufacturers. It consists of battery cell and system manufacturers like CATL, Tesla, LG, Samsung and Panasonic; system integrators, including companies like Fluence, Wartsilä, Sungrow, Saft, Nidec, NextEra and Powin; and developers, who are primarily utilities and renewable energy project developers, but sometimes, and increasingly often, large investors and oil and gas majors. There is some overlap in roles within the industry. Tesla, for example, serves as both a manufacturer and an integrator, while NextEra has roles as both an integrator and a developer.

Power companies are installing increasing volumes of battery storage, and batteries are becoming more prominent in their strategic planning. A significant number of these companies are renewable energy project developers, installing stand-alone battery storage or integrating it with onshore wind or solar PV generation developments. The market, particularly in the United States and Asia Pacific, is also shaped by investment firms that have either acquired or partnered with developers to build substantial battery storage portfolios. Notable examples include Blackrock and Australia's CEP Energy.

Half of the top-ten leading global developers of battery storage are Chinese corporations (Table 1.1), which reflects the favourable conditions and the large market in that country. Other key players predominantly are from Europe and the United States, with a recent increase in announcements of battery storage projects from the United States stemming from increased demand for storage in microgrid projects and investment support provided under the Inflation Reduction Act.

In **China**, a long-standing leader in battery manufacturing, a significant number of companies already have at least a few GW installed or at an advanced stage of development. Around 74 of the top-100 developers of battery storage globally are Chinese.

In the **United States**, the two primary players, Hecate Energy and NextEra, aim to install 10 GW of battery capacity by 2026. Among the main US players, only AES is also developing a significant pipeline in other regions, primarily in Chile and Europe.

In **Europe**, Engie has over 6 GW installed or in an advanced stage of preparation and has set itself a target of 10 GW by 2030. It is capitalising on the acquisition of US battery storage companies such as Belltown in 2022 and Broad Reach Power in 2023, both with portfolios of a few GW of projects. RWE is on track to reach 4 GW by 2027, taking account of current projects and the acquisition of Con Edison Clean Energy Businesses in the US. By 2026 Enel aims to nearly double capacity to 4 GW, primarily in Europe, Latin America and the United States.

In **Australia**, the leading player is not a power generation company but a developer, Akaysha, recently acquired by Blackrock. Akaysha is developing larger projects, for a total capacity of 2.8 GW, mainly in Queensland and New South Wales. These are set to be completed by next year.

Table 1.1 ▻ Leading investors in battery storage

	Capacity installed or in an advanced stage (GW)	Main project location
China		
CNNP Rich Energy	11.8	China
CGN Wind Energy	8.5	China
State Power Investment	6.8	China
Huadian New Energy	5.6	China
China Energy Investment	5.6	China
North America		
Hecate Energy	10.9	United States, Canada
Nextera	9.8	United States
Solar Proponent	5.5	United States (Texas)
Terra-Gen	2.4	United States (California)
AES	2.2	European Union, India, Latin America, United States
Europe		
Engie[1]	6.3	Australia, European Union, Latin America, United States
NEOEN	4.3	Australia, Canada, European Union
RWE	4.0	European Union, United States
Enel	4.0	European Union, Latin America, United States
EDF	2.0	European Union, United Kingdom
Australia		
Akaysha Energy	2.8	Australia
AGL Energy	1.5	Australia
CEP Energy	1.2	Australia

[1] Includes the assets of the US companies Broad Reach Power and Belltown which were recently acquired by Engie.

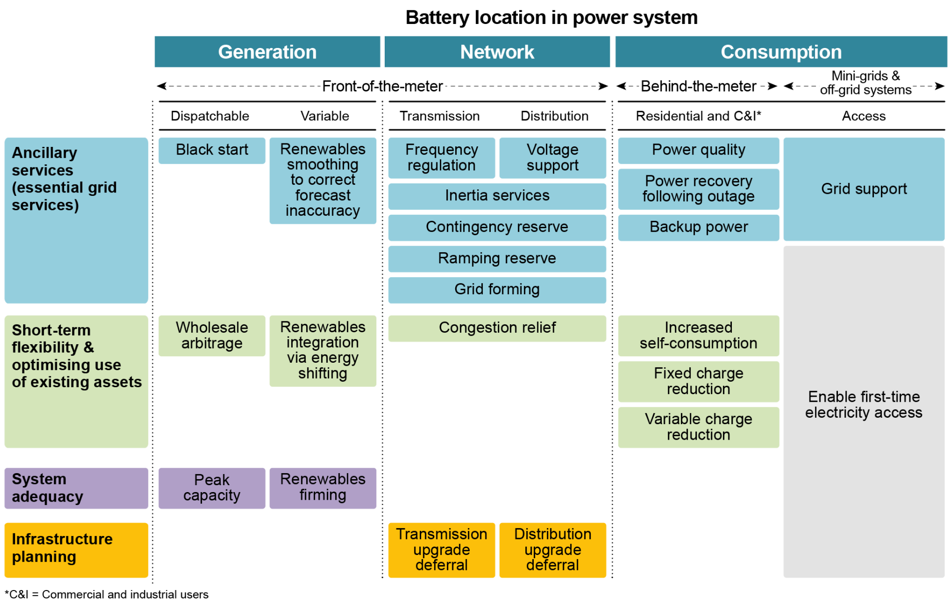
Note: Data includes installed capacity, projects under construction and projects at an advanced stage of development that are likely to be commissioned in two to three years, including stand-alone and battery systems capacity coupled with renewables projects.

Source: IEA analysis based on company reports, press releases and BNEF data.

1.3.1 Batteries have multiple roles in power systems

Batteries are highly versatile. Both utility-scale and behind-the-meter battery storage can provide a wide range of services to electricity systems (Figure 1.9). In addition to energy shifting, which helps to balance electricity supply and demand, utility-scale battery storage can contribute to maintaining grid stability and security of supply by providing ancillary services such as inertia, voltage control and frequency regulation, grid forming,[7] and delivering fast-starting reserves.[8] It can also supply capacity to ensure system adequacy and help manage congestion in electricity networks. Behind-the-meter batteries can provide backup power and help consumers lower their electricity bills by allowing them to increase the consumption of self-generated electricity, take advantage of variable electricity tariffs or reduce peak electricity consumption from the grid. If aggregated into virtual power plants (VPPs), they can also provide many of the same services as larger scale utility-scale systems.

Figure 1.9 ▻ Battery storage in power systems



Battery storage can provide a broad range of services to a power system

Note: Battery storage applications are represented along the dimensions: horizontal axis shows the location within a power system; vertical axis shows the type of services.

Source: Adapted from Schmidt and Staffell (2023).

Whether it is economical to deploy batteries depends on the individual circumstances of the particular case. The answer can vary from region to region, depending on the characteristics of the electricity system and the regulatory environment. Value stacking by providing

[7] Grid forming refers to the ability of an inverter-based source to provide voltage and frequency support to electricity networks, particularly during or after disturbances or outages, or in independent systems.

[8] Fast-starting reserves, also called fast reserves, quick start reserves or non-spinning reserves, deliver active power quickly through increased output from generation or reduced consumption from demand sources, to help control frequency changes that can arise from sudden or unpredictable changes in generation or demand.

multiple services at the same time can boost the economics of battery storage, but it also increases the complexity of the business case.

Utility-scale battery storage

Energy shifting is a key application for utility-scale batteries, especially in electricity systems with high shares of variable renewables with near-zero marginal costs. Utility-scale batteries with one to eight hours storage duration can provide peaking capacity: they can be charged in off-peak hours when the net demand is low, for example when solar PV generation peaks during the day, and discharged when net demand is high, for example in the evening when solar PV is not generating electricity. In competitive electricity markets, battery storage can monetise its energy shifting potential by engaging in energy arbitrage, taking advantage of price spreads on wholesale electricity markets by charging in hours when the price is low and discharging in hours when it is higher.

Due to their split-second responsiveness, batteries are also ideal providers of ancillary services in power grids, such as frequency regulation, voltage support and operating reserves. Furthermore, their black start capabilities can restore service after outages in place of diesel generators. In many European countries, notably Germany, France and the United Kingdom, batteries have already become key providers of frequency response and reserves, facilitated by reforms that have enabled battery storage assets to access the markets for these services. In systems with rising shares of variable renewables and declining synchronous generation as conventional thermal power plants are retired, there is increasing demand for inertia and short-circuit power, which batteries equipped with grid-forming inverters can supply. For example, the 30 MW/8 megawatt-hour (MWh) Dalrymple battery project in Australia provides frequency control plus inertia and short-circuit power: this ensures a reliable power supply in the regional network, which connects high shares of variable renewables generation but lacks synchronous generation. In the United Kingdom, 869 MW of grid forming battery storage was recently awarded contracts to provide inertia and short-circuit power to the system operator in a pathfinder scheme, with a view to procure these services via markets. Supplying ancillary services has emerged in recent years as an important revenue source for battery storage in several markets around the world, driving over 15% of new project deployments annually, particularly for batteries with one to two hours duration storage.

Providing capacity to support system adequacy is also an increasing application for battery storage. Where regulation allows, participating in capacity markets enables the owners of battery storage to lock-in long-term revenues. In the United Kingdom, where revenues from frequency regulation have been declining as markets become saturated, multi-year contracts awarded in capacity market auctions are becoming an increasingly important source of revenue for battery storage. Following the T-1 and T-4 auctions that took place in February 2024, contracted battery capacity in the capacity market is set to reach 16 GW in 2027, up from 3.9 GW today. In regions without capacity markets, the capacity of storage assets can be monetised through power purchase agreements which remunerate their availability to support power system operation. The Boulouparis battery project in New Caledonia, for instance, was awarded a 12-year contract by the local network operator which remunerates the battery owner for the services provided to the grid. The batteries will be able to deliver 50 MW of power over three hours, providing peaking capacity during evening demand peaks.

In addition, batteries can help to ease grid congestion by storing surplus power generated by renewables at times of high production thus reducing curtailment and grid integration costs. For example, with a 200 MW/800 MWh capacity the Dalian vanadium flow battery demonstration project in China is designed to alleviate peak loads on the grid and serve as an additional load point for the Dalian peninsula, enhancing grid stability. The first phase of the project was commissioned in 2022, and full deployment is expected to reduce peak loads by 8% from 2020 levels.

When used for congestion management, batteries minimise the need for transmission or distribution network investment. This is the main application of so-called grid boosters in Germany, which are utility-scale batteries deployed to alleviate bottlenecks in the transmission system and thus reduce the need for additional investment to reinforce certain lines. Under the grid booster initiative, 950 MW of storage assets were approved by the regulator as part of the network development plan, and a total of 450 MW are already under construction in the control areas of two of Germany's four transmission system operators.

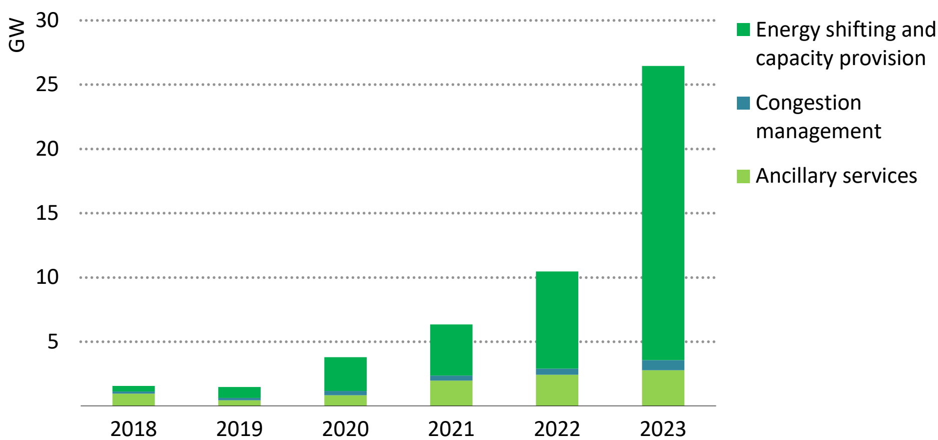
The regulatory environment and the technical characteristics of grids are the key determinants of what represents a viable use for batteries. In many jurisdictions with market-based electricity systems, including the European Union, unbundling requirements impose strict limits on the ownership and operation of storage by transmission and distribution system operators (except in the case of selected pilot projects like the grid boosters mentioned), so any congestion management services must be contracted from third parties. In the United Kingdom, recently introduced distribution flexibility markets are based on open public tenders where the costs and benefits of flexibility solutions provided by third parties are compared to the cost of grid reinforcements: in 2022-2023, batteries represented more than 30% of the contracts awarded, or nearly 600 MW of storage capacity. In France, both the transmission system operator and selected distribution system operators have recently launched local flexibility tenders which are open to battery storage assets. In California and New York, distribution system operators increasingly make use of storage assets which are co-owned or procured from third parties through power purchase agreements in order to reduce grid congestion, thereby avoiding or deferring expensive investment to reinforce their grids.

Microgrids are another application for large battery storage. In Australia and parts of the United States, for example, regulators have introduced ad-hoc measures and programmes to boost microgrid development, often based on storage solutions, in order to increase the resilience of critical facilities such as hospitals and large industrial consumers and of services for communities, in particular low-income and disadvantaged communities. Microgrids increase the resilience of the system by giving operators the possibility of disconnecting from the main grid through "adaptive islanding" in the event of major disruptions and maintaining supply despite the loss of the main energy feeder.

Certain battery technologies can also be utilised for multi-day energy storage, addressing longer peak demand periods, or compensating for episodes of low renewables generation. An example is the first-of-its-kind 100-hour long-duration iron air battery project being built in California, which will operate under the state resource adequacy programme. However, the way that power markets are currently set up means that most grid services are focussed on short duration storage. In the United States, for instance, existing market duration requirements for operating reserves (less than one hour) and capacity (four hours) have led to most installed utility-scale batteries having durations of four hours or less.

Historically, large-scale batteries have been mostly deployed for frequency regulation or energy shifting. With the increasing amounts of power generated by variable renewables and the small size of ancillary services markets, energy shifting is becoming the primary application, and it accounted for about 85% of the installed capacity in 2023 (Figure 1.10). In Germany, for instance, providing frequency control was the main driver for the deployment of utility-scale systems, but emerging new applications have opened additional revenue streams. These include the integration of variable renewables within the Innovation Tender for co-located generation and storage projects, the utilisation of storage as a transmission asset, i.e. grid boosters, and the optimisation of energy consumption at industrial sites.

Figure 1.10 ▷ Utility-scale battery storage capacity additions by application, 2018-2023



Energy shifting and the provision of peaking capacity are the primary applications of utility-scale batteries installed in recent years

Source: Adapted from BNEF (2023b).

If the regulatory framework allows, value stacking across these various applications can improve the economics of battery storage and provide a hedge against single long-term contracts. However, value stacking requires a more complex energy management system and the increased frequency of dispatch resulting from value stacking can accelerate asset degradation. Moreover, certain services may be mutually incompatible due to design choices. For example, a system optimised for high-frequency, short-duration services might not perform optimally for infrequent, longer duration ones. A reliance on value stacking also increases the complexity of the business case and makes the prediction of revenues more complex, representing a potential barrier for more risk-averse investors.

Behind-the-meter battery storage

Behind-the-meter battery storage refers to applications at the distribution level, installed at residential, commercial and industrial end-user locations. They are connected directly to the building and rooftop solar PV systems, behind the electricity meter and the building's own connection to the power grid. They form part of a suite of distributed energy resources that are increasingly important in the integration of renewables. These systems can provide benefits to both consumers and the grid by minimising costs and environmental impacts while bolstering electricity security and supporting the electrification of industries.

Behind-the-meter batteries offer consumers multiple ways to save costs. By using excess solar PV generation during the daytime to charge behind-the-meter batteries, consumers can increase the self-consumption of electricity generated by a rooftop solar PV array. By charging during hours when electricity prices are lowest, behind-the-meter battery storage allows consumers subscribing to dynamic electricity tariffs to reduce their electricity bills. The use of storage can also be timed to reduce a consumer's peak demand, allowing them to save costs by opting for a smaller peak power supply subscription. Furthermore, individual household level battery systems can be aggregated into VPPs and participate in the market (Box 1.2). In addition to cost-saving measures, behind-the-meter systems can improve electricity reliability by providing backup power during unplanned outages and by ensuring power quality: this is especially important for industry, hospitals and vulnerable customers such as those with uninterruptible power supply setups.

From a system perspective, behind-the-meter batteries can provide many of the same benefits as utility-scale batteries. If the right signals and incentives are in place, they can help to reduce overall grid demand, lower grid stress by peak shaving and provide reserve capacity. Compared to utility-scale systems however, behind-the-meter systems act at a more localised level, which can create opportunities to defer distribution grid expansion or upgrades. When aggregated into VPPs, behind-the-meter batteries can also provide ancillary services like frequency response, frequency regulation, voltage support and ramping reserves. However, the extent to which the benefits of behind-the-meter batteries are realised is highly dependent on the regulatory frameworks, most notably end-user electricity tariff structures and the rules governing market access for aggregators. It is also dependent on the deployment of smart metering.

Box 1.2 ▷ Behind-the-meter batteries and virtual power plants

Virtual power plants (VPPs) aggregate distributed energy resources, including behind-the-meter batteries, distributed renewables and flexible loads, and dispatch them as a single electricity source. To establish a VPP, each distributed energy resource is connected to a centralised control system that optimises their collective operation in response to signals from markets and grid operators. Unlike individual behind-the-meter batteries, which are limited in the extent they can interact with the grid, VPPs act like traditional power plants in terms of the services they can provide and the markets they participate in. If market rules permit, they can sell electricity on wholesale electricity markets and provide ancillary services and support electricity security through contributions to capacity adequacy. However, they differ from traditional large-scale power plants in that they have the ability to respond flexibly to constraints in local grids by adjusting the output of the individual energy resources that comprise the VPP. This makes them a potentially valuable resource in managing congestion in transmission and distribution grids.

VPPs can offer owners of behind-the-meter batteries an additional opportunity to monetise their energy storage capacity. Depending on market prices and tariff structures, participation in a VPP may be more financially advantageous than simply maximising self-consumption. VPP participants can be rewarded in multiple ways, including through direct payments for energy supplied, reduced electricity tariffs, or discounts on the upfront cost of solar PV and battery systems: the details will depend on the specifics of the VPP. Some, but not all, VPPs require a contract in which aspects such as the maximum annual utilisation of an asset by the VPP are outlined. VPPs can scale to relatively large sizes, with some integrating several thousand assets, and are able to integrate larger assets such as wind turbines, small-scale hydropower or utility-scale batteries alongside smaller ones.

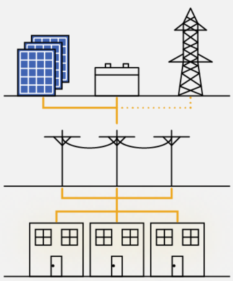
Despite the benefits they offer, VPPs face many challenges, including regulatory and policy barriers and restrictive market rules. The decision for consumers about whether to join a VPP is ultimately dependent on region specific and VPP specific factors. These include not only the capital cost of a behind-the-meter battery or solar PV system, but also how participants are rewarded for participating in the VPP, and how much local regulation and tariff structures reward self-consumption and the direct export of electricity to the grid.

VPPs are proving to be innovative in finding opportunities, and this augurs well for the future. In the United States, for example, a VPP in Vermont has aggregated behind-the-meter batteries in homes to provide grid services like frequency regulation and peak shaving, demonstrating the potential for distributed batteries to offer ancillary services. In Ontario, Canada, the system operator has enrolled 100 000 households in a VPP programme, the Save on Energy Peak Perks programme.

1.3.2 *Batteries facilitate access to electricity*

Batteries are increasingly being used in emerging market and developing economies to provide storage in mini-grids and standalone solar systems which deliver electricity to those without grid access or backup power to compensate for grid unreliability. This application of battery storage is set to rise as electrification efforts accelerate (Figure 1.11).

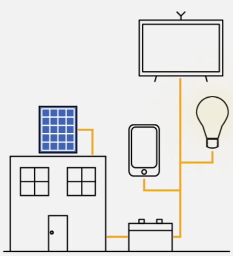
Figure 1.11 ▹ Decentralised systems for access to electricity



Mini-grid

Generation	Battery	Uptime
10 kW-1 MW	**10 kWh-1 MWh**	**Generally 90%+**

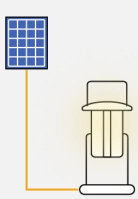
Mini-grids supply electricity to a community. They generally couple solar generation with battery storage, and may also have diesel backup generation. They may be grid connected. Battery storage in mini-grids ensure balance in supply and demand to meet peak demand in the evening, largely driven by households.



Solar home system

Generation	Battery	Uptime
10 W-1 kW	**0.2-5 kWh**	**Generally 90%+**

A solar home system can serve a household or a business. Small solar home systems support lighting, mobile phone charging and a radio. Larger systems can power more lighting and appliances such as television and/or a fan and can scale up to refrigerators and cookers. Solar home systems are increasingly being acquired by households and businesses that have inadequate grid connections and in preference to diesel backup generation.



Solar lighting and lanterns

Generation	Battery	Uptime
< 10W	**Up to 10s Wh**	**Generally a few hours per day**

Solar lighting uses small solar panels and batteries to provide the most basic, but fundamental, energy benefit: lighting after dark. These systems alone do not qualify as providing energy access, but do account for a significant number of small batteries.

Four out of five people who have yet to gain access to electricity live in remote, sparsely populated areas with low levels of existing energy demand. Extending electricity grids to these areas is often very expensive with long lead times, and off-grid systems offer a pragmatic way forward. They are already in widespread use: in 2023, 50% of new connections in Africa were delivered through off-grid systems. Cost declines in solar PV modules and battery technologies, together with modular system designs and creative financing models such as PayGo,[9] are making solar-based off-grid systems increasingly attractive, displacing alternatives such as fossil fuel generators. Batteries play a key role in these systems, turning variable renewables generation into a reliable power supply. The deployment of batteries for energy access is expected to accelerate as continued cost declines in batteries improve their affordability.

Even where grid access exists, supply reliability and quality can be a major challenge. In many large cities in sub-Saharan Africa, over half of grid customers lack access to reliable power considered as a connection that works most of the time (Gertler, Lee and Mobarak, 2017). There are similar problems in rural areas with grid access. In Nigeria, for example, more than a quarter of businesses report electricity unreliability as the main obstacle to their business, and the average household receives just under seven hours of electricity per day (Pelz et al., 2023). In this context, many households and businesses with grid access want backup generation, and the declining cost of solar PV and batteries and the rise of PayGo models are leading them to replace diesel backup generation with stand-alone solar systems. In Nigeria, it is estimated that three out of four solar home systems sold are used for grid backup (World Bank and GOGLA, 2022).

While off-grid and decentralised systems can be powered by varied sources, solar-based systems are expected to remain dominant. There are two main types, differentiated by the scale of load and number of customers: mini-grids and stand-alone off-grid solar systems. Stand-alone systems are further subdivided into solar home and solar lighting systems.

Mini-grids can power entire villages and towns, including many households and productive uses. They can be fully independent from the grid or connected to it. Batteries integrated into these systems range in scale from tens to thousands of kWh and ensure both evening and nighttime energy availability, and continual demand-supply balance. Today, solar mini-grids with an estimated combined battery volume of over 1.1 GWh supplying electricity to around 20 million people.

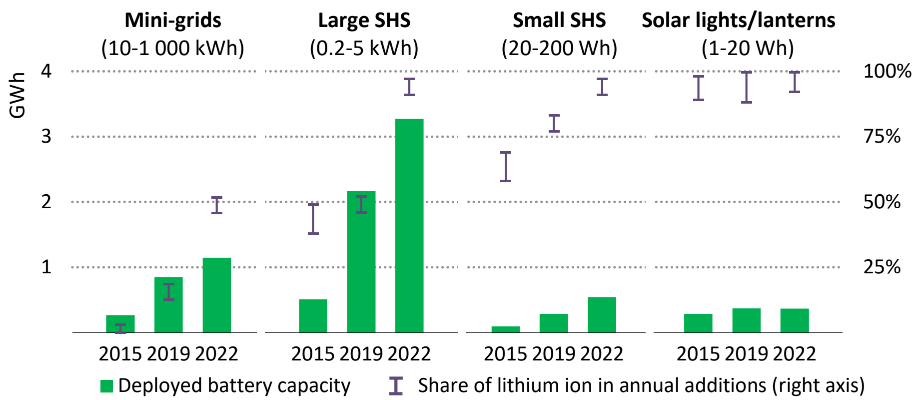
Stand-alone off-grid solar systems power individual households or businesses and range from small solar lanterns and multi-lighting systems to larger solar home systems (SHS). Solar lighting systems provide night lighting only, and do not alone qualify as delivering energy access as defined by the IEA. In 2022, these smaller systems, which include small individual smartphone scale batteries, in aggregate had a combined capacity of 0.4 GWh for around

[9] Such financing methods enable users to pay for energy through weekly instalments or other periodic payments. It eliminates the upfront cost barrier for energy access, allowing consumers to make incremental payments instead of paying for the entire system upfront.

67 million units. SHS, which incorporate battery storage ranging from 20 Wh to a few kWh, meet IEA energy access definitions and are able to power some household appliances in addition to lighting. In 2022, SHS had an estimated combined battery capacity of over 3.8 GWh and provided around 19 million households with basic or extended energy services and back-up services.[10]

Solar home systems and solar lighting are equipped with standard battery sizing options embedded in ready to sell products which are often pre-packaged with appliances. On the other hand, battery systems for mini-grids are often bespoke, with their size based on preliminary demand estimation studies. The choice of battery chemistries can vary significantly by system type and geographic location, and depends on costs, local maintenance capacity, developer experience and the nature of expected demand.

Figure 1.12 ▷ Installed battery capacity in decentralised systems by type and share of lithium-ion batteries



Battery capacity in decentralised systems reached 5.3 GWh in 2022, a fourfold rise since 2015 mainly driven by solar home systems; lithium-ion batteries dominate the market

Notes: kWh = kilowatt-hours, Wh = Watt-hours. The figure shows total installed and operational battery capacity as columns and, the share of lithium-ion in new annual sales as confidence intervals.

Sources: IEA analysis based on data from GOGLA (2023) and ESMAP (2023). Ad-hoc analysis by GOGLA based on data collected for the Global Off-Grid Solar Sales and Impact Reports from 2016 to 2022 is the basis of the lithium-ion share confidence intervals.

Thanks to their relatively low capital costs and ease of maintenance, supported by well-developed local skills, lead acid batteries have long dominated mini-grids. However, lithium-

[10] The IEA minimum level of services is defined as the "basic bundle", which includes more than one light point that provides task lighting, phone charging and a radio. The "essential bundle" category includes four light bulbs for four hours per day, a fan for three hours per day and a television for two hours per day. The IEA "extended bundle" implies a refrigerator, four hours for lighting, four hours for TV and six hours for a fan. See the IEA Guidebook for improved electricity access statistics (2023b).

ion batteries are quickly gaining ground due to their declining costs, the promise of longer lifespans and lower levelised costs (ESMAP, 2023). As a result, they now account for around half of the mini-grid market. Lithium-ion, specifically LFP, is already the predominant chemistry in smaller SHS and solar lighting systems, rising from just above 60% to nearly 100% in 2022 (Figure 1.12). Larger stand-alone systems and generators are also quickly embracing lithium-ion batteries, jumping in just 3 years between 2019-2022 from just below 50% to almost 95%.

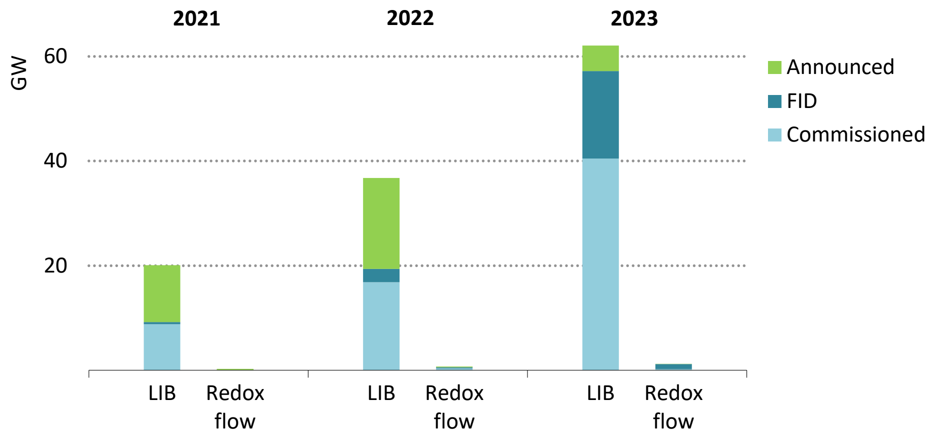
Affordability remains a challenge for energy access initiatives and batteries still account for a highly variable 10-40% of total system costs depending on loads served, location and chemistries. Future battery cost declines will not necessarily be reflected fully or quickly in the field. The expectation of future cost declines nevertheless can encourage investors and developers to delay projects in the hope of improved financial outcomes, hindering urgently needed expansion. Against this background, policy support is needed to ensure the profitability of projects. Possible support measures include the exemption of energy access batteries and cells from onerous import tariffs and the provision of support for the development of local manufacturing industries.

Component failure also remains a challenge for batteries in energy access projects. While other components have lifespans of decades, many mini-grids experience unexpected battery failures in under five years. These failures may reflect faulty, untested or low-cost components, and poor operation and maintenance. Premature battery failures can push developers to seek rapid recovery of capital costs instead of longer amortisation periods to improve affordability. They can also seriously damage entire energy access projects, drastically reduce the lifetime of products such as solar lighting devices and drive the accumulation of e-waste: an estimated 220 million products are currently faulty or in landfills. Overall, especially for newer battery chemistries, there is a need for increased battery field testing and sharing of experiences to support more informed decision making on batteries and ultimately to improve stand-alone system performance.

1.3.3 Battery chemistry for storage applications

Lithium-ion batteries dominate the battery storage market today (Figure 1.13). The chemistries available for lithium-ion batteries used in storage applications are the same as those available for the EV market (section 1.2) However, storage applications have different technical requirements and characteristics such as cost, capacity to charge/discharge frequently, safety and overall lifetime are prioritised over energy density. Lower costs, higher cycle lives and safety considerations have led to a shift towards lithium iron phosphate (LFP) batteries, which accounted for about 80% of the total battery storage market in 2023, up from about 65% in 2022. LFP batteries are currently produced almost exclusively in China, but other battery manufacturers are starting to develop them. Lithium-ion batteries are set to remain a key part of short-duration (≤ 8h) storage, but alternative chemistries are being developed either to compete with it or to complement it.

Figure 1.13 ▹ Announced, financial investment decisions and commissioned storage projects by battery chemistry in 2021, 2022 and 2023



Lithium-ion battery chemistry is predominant for storage, with minimal shares for redox flow

Note: LIB = lithium-ion battery, FID = final investment decision.

Source: IEA analysis based on BNEF data.

Sodium-ion batteries do not use lithium, are constructed from less expensive materials than lithium-ion batteries and need fewer critical materials. They attracted a lot of attention during 2023 thanks to the first sodium-ion powered EV produced by Hina, and to product launch and mass production announcements from companies like CATL, BYD and Northvolt. Sodium-ion batteries are less energy dense than lithium-ion batteries, but they could be 20% and 30% cheaper than equivalent LFP batteries if produced at similar scales. However, this cost advantage largely depends on the current price of lithium and also needs to be weighed against a potentially shorter service life than LFP batteries.

Neither lithium-ion or sodium-ion batteries are likely to be able to serve significant shares of longer duration storage (across days) because of cost and technical challenges arising from prolonged high states of charge. Other battery chemistries may be more suitable for longer storage durations (Table 1.2). An alternative battery chemistry that could provide longer (multi-day) storage is redox flow batteries, which are built in a different way from sodium- and lithium-ion batteries. They are composed of two tanks that contain the liquids in which energy is stored: when charging/discharging the battery, these fluids are pumped into a cell containing the electrodes. The physical separation of the two tanks solves the technical challenges arising from prolonged high states of charge. Energy, determined by the size of the tanks, and power, determined by how fast the liquids are pumped and the size of the surface of the membrane, can be controlled separately. This battery can use different chemistries, but vanadium is the most widely used and its supply chain is still small. Redox flow batteries based on vanadium are already relatively mature. The main challenge will be ability to scale up rapidly over the coming years. However, this is likely to happen only in response to adequate signals, for example through the emergence of longer duration storage markets.

Table 1.2 ▹ Potential applications of various battery technologies for storage applications by storage duration

	Storage duration				
	4h or less	4h to 8h	Days	Weeks	Seasonal
Lithium-ion	Suitable	Suitable	Unsuitable	Unsuitable	Unsuitable
Sodium-ion	Suitable	Suitable	Unsuitable	Unsuitable	Unsuitable
Redox flow	Marginal	Suitable	Suitable	Unsuitable	Unsuitable
Iron air	Unsuitable	Unsuitable	Marginal	Suitable	Unsuitable

● Suitable ● Marginal ● Unsuitable

Iron air and other battery technologies that potentially could enable the storage of electricity over longer durations measured in weeks, are still in their infancy. Currently it is not clear whether those technologies can be developed so as to provide what is required in a cost-efficient way. For even longer duration storage, such as seasonal storage, battery technologies are not fit for purpose, and other mechanical, e.g. pumped storage hydro, and chemical, e.g. hydrogen storage, technologies need to be deployed.

1.3.4 Policy support for battery storage

There is increasing government support for the deployment of battery storage. Countries are supporting storage deployment with targets, subsidies and reforms that remove regulatory barriers and improve access to markets (Table 1.3).

In the **United States**, the Inflation Reduction Act provides a federal tax credit of up to 50% for storage projects. Nine states have adopted storage targets, amounting to more than 50 GW of cumulative additions over the next 20 years.

In **China**, the first national target was set in 2020 to install 30 GW of additional energy storage by 2025; the target has already been exceeded. Regional 14th Five Year Plans target almost 80 GW by 2025. Qinghai municipality was the first to require wind farms to pair at least 10% of their installed capacity with energy storage. A number of provinces have followed suit and extended the policy to solar PV, with pairing rates between 5% and 30%. These requirements have become a major driver of battery storage capacity growth in China. Some provinces also provide financial support to battery storage via feed-in tariffs or direct payments, while grid tariffs and taxes are waived during charging for storage facilities that directly participate in the market.

Table 1.3 ▹ Energy and battery storage targets in selected regions/countries

	Battery storage target (GW)	Energy storage target (GW)	Target year	Note
Australia		6.3	2030	Target in state of Victoria
China		78	2025	Excludes PHS
European Union				
Greece	3.1	5.3	2030	
Hungary		1	2030	
Italy	15		2030	
Portugal	1		2030	Additional 3.9 GW PHS
Romania	0.24		2025	
Spain		22	2030	At least 0.4 GW BTM storage
India	47.24	73.93	2032	
Japan	24 (GWh)		2030	
Korea		24.51	2036	Additional 1.75 GW PHS
United States				
California	35.2	36.2	2045	
Connecticut		1	2030	
Maine		0.4	2030	
Massachusetts		1 GWh	2025	
Nevada		1	2030	
New Jersey		2	2030	
New Mexico		2	2034	
New York		6	2030	
Virginia		3.1	2035	

Note: PHS = pumped hydro storage, BTM = behind-the-meter.

In **India**, the recently released National Framework for Promoting Energy Storage Systems requires renewables projects, excluding hydropower plants, to install energy storage with a capacity equivalent to at least 5% of the renewables capacity, and inter-state transmission system charges have been waived for battery storage projects for a duration of up to 12 years. In addition, India has set up the Viability Gap Funding Mechanism to reimburse up to 40% of the capital cost of storage projects.

In the **European Union**, member states are collectively targeting deployment of around 45 GW of storage by 2030 through National Energy and Climate Plans. Several member states provide support for battery storage. Sweden, Spain, Italy and Germany have implemented reforms to eliminate the double charging of taxes and grid tariffs for storage. Greece and Italy have rolled out long-term remuneration mechanisms dedicated to storage, such as contracts for differences, that provide battery storage projects with more stable long-term revenue streams. The European Union also provides funding for selected battery storage projects through the Innovation Fund and the Recovery and Resilience Facility.

In **Japan**, the importance of battery storage is recognised in the 6th Basic Energy Strategy and the subsequent Battery Industry Strategy released in 2022. Japan aims to install around 24 GWh of behind-the-meter battery storage by 2030.

In **Korea**, the 10th Basic Plan for Long-term Electricity Supply and Demand sets a target of approximately 26 GW of energy storage by 2036.

In **Australia**, the Australian Renewable Energy Agency more than doubled its funding from AUD 81 million (USD 56 million) to AUD 176 million (USD 122 million) in 2022 to support eight grid-scale lithium-ion battery projects. Currently, the federal government is implementing the Capacity Investment Scheme, a revenue underwriting scheme that was expanded in 2023 to add a total of 32 GW of new dispatchable capacity, including battery storage, to the electricity grid. The initial stage involves six tenders for batteries and VPP projects that are to deliver 1 GW of firm capacity by 2025. In addition, the state of Victoria aims to install 6.3 GW of battery storage by 2035. The federal government is in the process of formulating its first National Battery Strategy.

Policies targeting behind-the-meter storage

Several countries are directly supporting behind-the-meter storage or have regulatory and end-user pricing frameworks in place that do so. Measures include subsidies, dynamic or time-of-use end-user electricity tariffs that incentivise energy shifting and permissive regulation that enables distributed behind-the-meter storage to access electricity markets through aggregators (Table 1.4).

Table 1.4 ▷ Behind-the-meter policy measures in selected countries

	Financial support	Dynamic and/or time-of-use tariff	Market access (through aggregators)
Australia	High	High	High
Canada	Medium	Medium	Medium
China	Medium	High	Medium
Germany	High	High	Medium
India	Low	Medium	Low
Italy	High	High	High
Japan	High	High	Medium
Korea	Low	Medium	Medium
United Kingdom	High	High	High
United States	High	High	Medium

Level of implementation High Medium Low

In **Australia**, national and state-level schemes, including tax breaks, subsidies and interest-free loans, incentivise the installation of behind-the-meter batteries. As part of its network tariff reform starting in 2017, the Australian energy regulator mandated suppliers to transition from flat to variable, cost-reflective tariffs, which increases the attractiveness of behind-the-meter storage. By 2022, 26% of residential customers across the National Electricity Market had adopted these forms of tariffs. In November 2023, energy and climate change ministers in Australia agreed to develop a National Consumer Energy Resources Roadmap. In March 2024, they agreed to a range of priority reforms under the Roadmap, including nationally consistent standards, new consumer protections and network reforms to unlock consumer benefits from behind-the-meter generation and storage.

In the **United States**, the Inflation Reduction Act includes a residential clean energy credit that provides consumers with a 30% tax credit for the installation cost of clean energy equipment, including behind-the-meter battery storage systems with capacity of at least 3 kWh. At state level, California has a support package for behind-the-meter storage that includes time-of-use tariffs, additional incentives for self-generation and a specific storage tariff. Similar measures have been adopted in Arizona, Massachusetts, Hawaii, Colorado and New York.

Several member states in the **European Union**, notably **Germany** and **Italy**, promote the adoption of behind-the-meter storage through subsidies such as grants, low-interest loans and tax rebates; although Italy recently phased out its Superbonus tax credit for home improvements, which had underpinned most of the growth in behind-the-meter storage in recent years. Across EU member states more generally, there has been a trend towards the promotion of self-consumption and away from feed-in tariffs and net metering schemes for solar PV. This has stimulated behind-the-meter storage.

The **United Kingdom** is one of the leading examples of a regulatory framework that enables participation of behind-the-meter storage in electricity markets, creating benefits for the system and opening additional revenue streams for behind-the-meter storage. Through aggregators, behind-the-meter batteries can participate in wholesale energy, capacity and local flexibility markets, while also providing grid services.

Canada introduced a 15% tax credit for investments in clean energy technologies such as solar, battery storage and wind in its 2023-2024 Budget Law. At provincial level, Ontario is introducing a pilot programme for dynamic electricity pricing for users with over 50 kW peak demand starting in 2024, and Nova Scotia has set a battery capacity target of 300-400 MW by 2030, including up to 100 MW to be connected to the distribution system or behind-the-meter.

India announced the progressive introduction of a three-rate tariff in 2023. Starting from April 2024 for small commercial and industrial consumers, it differentiates between normal hours, "solar" hours and peak hours (with prices in solar hours 10-20% lower than in normal hours), providing an incentive to deploy behind-the-meter storage.

In **Korea**, generous subsidies led to a boom in behind-the-meter storage capacity additions in 2017, but their subsequent withdrawal prompted a decline from which the market has yet to recover fully. Time-of-use tariffs predominantly are applied to high-voltage commercial and industrial customers. Korea has begun phasing in time-of-use tariffs for residential consumers in place of the previous flat tariffs. There are pilot projects for VPPs incorporating behind-the-meter storage, but so far, the use of VPPs remains limited.

In **China**, financial support for behind-the-meter storage varies from province to province and includes feed-in tariffs, subsidies and one-off investment grants. Policy support is generally focussed on industrial and commercial users (strict fire safety codes in many cities prevent the installation of batteries in residential buildings), and time-of-use pricing is becoming widespread for those users. Around 90% the provinces have policy measures in place to encourage the development of VPPs.

Japan provides subsidies for behind-the-meter batteries that reduce the upfront cost by up to USD 250/kWh. Moreover, many Japanese households equipped with rooftop solar PV are coming to the end of the ten-year feed-in tariff between 2023-2030, after which the payments they currently receive for feeding electricity into the grid will disappear or reduce significantly. This is likely to encourage self-consumption and increase the attractiveness of behind-the-meter storage.

1.3.5 Regulatory barriers to battery storage

Most countries still lack an adequate regulatory framework for battery storage, which is a key barrier to the development of viable business models. Even when short-term price signals are in place, merchant risk and uncertainty over long-term revenues may act as a brake on battery storage investment.

A common hurdle faced by storage operators in many jurisdictions is double taxation or double charging of grid tariffs. Because of its dual character as both generation and load (demand), storage may be taxed both when charging and discharging, resulting in a systemic disadvantage compared to other technologies. Even when there is no injection tariff, storage systems can be exposed to withdrawal tariffs for each of their charging cycles.

There are also restrictions on market participation and services provision by battery storage owners that limit their ability to contribute as fully as possible to energy systems. Some battery services, such as black start capability or inertia, were traditionally provided by conventional power plants at no cost, while remuneration schemes for batteries do not yet exist or are just being tested in pilot projects. In markets that are transitioning from regulated to liberalised systems, it is often still not possible for battery owners to participate in competitive procurement processes for system services or to undertake energy arbitrage on wholesale markets. In more advanced power markets, existing market products often do not enable battery storage to contribute to the provision of services as fully as they could. In addition, since system operators are generally not allowed to own and operate storage assets, transmission or distribution grid operators need to procure battery congestion management services through tenders or on local flexibility markets. Such market-based congestion management mechanisms have not yet been widely adopted.

Table 1.5 ▷ Eligibility of battery storage by type of use by country

	Type of use			
	Wholesale arbitrage	Ancillary services	Capacity	Grid congestion relief and/or grid deferral
Australia	🟢	🟢	🟡	🔴
Canada	🟡	🟡	🟡	🟡
China	🟡	🟡	🔴	🔴
Germany	🟢	🟢	🟢	🟢
India	🟢	🟡	🟢	🟡
Italy	🟢	🟡	🟢	🟡
Japan	🟢	🟢	🟢	🔴
Korea	🔴	🔴	🟢	🔴
United Kingdom	🟢	🟢	🟢	🟢
United States	🟢	🟢	🟡	🟡

Status of battery eligibility:

🟢 Legally eligible

🟡 Eligible only in some jurisdictions, or in pilot projects, or for some services only

🔴 Not eligible or type of use not available

These restrictions are widespread. For example, in the European Union the Agency for the Cooperation of Energy Regulators has identified several member states in which batteries are still not eligible to participate in short-term electricity markets and capacity mechanisms, or to provide balancing and congestion management services. Moreover, local flexibility markets are not well established in these countries, discouraging the uptake of behind-the-meter battery storage. In China, the lack of market-based outlets for storage paired with wind and solar plants is leading to utilisation rates as low as 6%, which weighs on the profitability of developers.

In many countries, and especially in emerging market and developing economies, the slow progress being made in deploying smart meters is a further barrier to the full implementation of dynamic tariffs, development of VPPs and aggregation of distributed energy resources. The absence of specific regulation regarding the operation of behind-the-meter batteries and their eligibility to participate in energy markets are major barriers to their adoption. Some net metering schemes do not encourage behind-the-meter storage: in cases where excess energy generated throughout a month is credited to the consumer account regardless of when it was produced, the effect is to discourage the storage of surplus energy for use during peak demand or low solar generation periods.

Existing market arrangements in general were designed for conventional technologies, meaning that battery storage may not receive appropriate price signals to encourage an optimal level of investment. An absence of locational signals means batteries are not incentivised to provide capacity where it is most needed, and the current arrangements for dispatch and settlement periods are often not designed to attract investment in fast-response flexible assets. Except in those cases where a carbon price is in place, current market arrangements also risk failing to incentivise storage operations to support emissions reduction targets. In China, for example, where the electricity mix is 65% reliant on fossil fuels, the average utilisation of storage paired with thermal power plants is approximately six-times higher than those of storage paired with wind and solar PV generation.

Delays in obtaining grid connections are also holding back the development and deployment of battery storage in many jurisdictions, as regulatory processes for obtaining approvals and permits can be complex and time consuming. According to the Lawrence Berkeley National Laboratory, approximately 1 030 GW of storage projects in the United States were waiting in the connection queue in 2023, up from 680 GW in 2022 (including the storage element of hybrid projects) (Lawrence Berkeley National Laboratory, 2024). Long wait times (on average nearly three years from interconnection request to an executed interconnection agreement, and five years to commercial operations) risk deterring battery storage projects. The situation is similar in many other jurisdictions. The costs of grid upgrades can also impede battery storage projects.

1.4 Investment in batteries

1.4.1 Investment by sector and location

Investment in both EV batteries and battery storage has been strongly increasing – up eightfold in EV batteries and fivefold in battery storage since 2018.[11] Total investment was USD 150 billion in 2023, of which USD 115 billion was for EV batteries and almost USD 40 billion for battery storage (Figure 1.14).

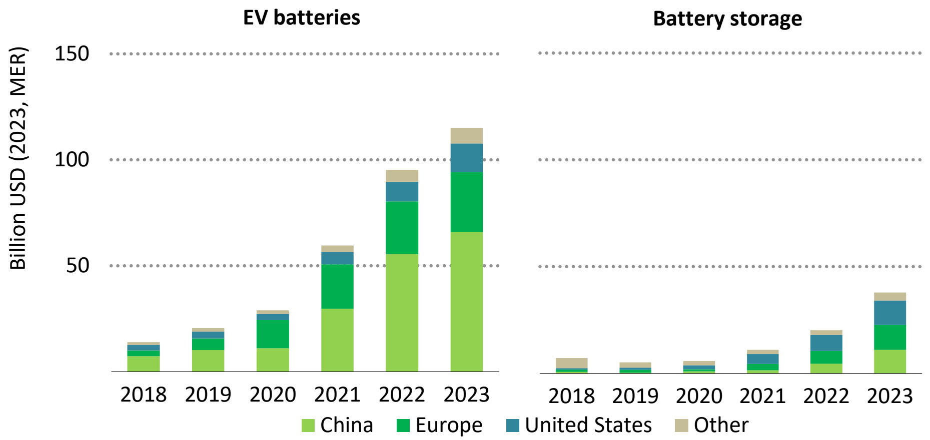
China, Europe and the United States account for more than 90% of this spending. The remainder is concentrated in other advanced economies. For every dollar invested in EV batteries and battery storage in advanced economies and China in 2023, only USD 0.02 was invested in other emerging market and developing economies.

For EV batteries, the main reason for the geographic disparity is that spending on EV batteries is closely related to sales of EVs, which in many emerging market and developing economies remain a capital-intensive investment out of reach for many consumers. Supportive policies are also a relevant factor. Sales of EVs have surged in some regions: In the United States they have increased by almost 500% since 2020, in Europe by 250% and in China by 160%. Each of these regions have implemented both demand and supply related policies to accelerate market demand and increase the availability of EVs while developing the charging infrastructure. Holistic transport policy making in emerging markets and developing

[11] The detailed methodology can be found in the World Energy Investment 2023 Methodology Annex (IEA, 2023c).

economies will be key to accelerating electric mobility – and also spending on EV batteries – together with low-cost debt financing for consumers, fiscal incentives, subsidies and increased international financial support for the electrification of public transport (IEA, 2023d).

Figure 1.14 ▻ Global investment in EV batteries and battery storage, 2018-2023



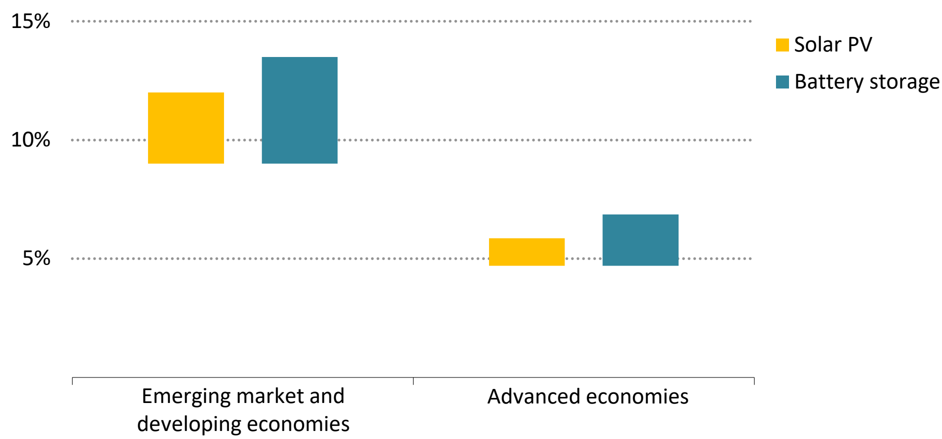
Investment in EV batteries and battery storage increased rapidly to USD 150 billion, with spending highly concentrated in China, Europe and the United States

Note: MER = market exchange rate.

For battery storage, investment has increased as more regions have adopted supportive policies and power market designs, and as higher levels of renewables penetration provide expanded opportunities for profitable battery storage operations. Battery storage projects often have to develop several revenue streams at the same time to be a profitable investment, e.g. energy arbitrage, frequency regulation, peak shaving or, if integrated with solar PV or wind power, the benefit from lowering curtailment of renewables. This especially holds for utility-scale units that can be used for renewables integration and to improve grid flexibility. While representing the majority of capacity additions, such units accounted for less than half of total battery storage investment in 2023 as utility-scale batteries are significantly cheaper per unit of capacity than smaller batteries intended for commercial or residential use. Around 85% of the spending on utility-scale battery storage was in China and the United States. In contrast, battery storage for commercial and residential applications, such as when combined with rooftop solar, has attracted most of the spending in Europe in recent years.

A major reason why capital flows to battery storage remain highly concentrated in advanced economies and China is the high cost of capital for clean energy projects in emerging market and developing economies (Figure 1.15). Survey data from the IEA Cost of Capital Observatory shows that the cost of capital for battery storage projects in emerging market and developing economies is at least twice as high as in advanced economies. While macro factors such as the rule of law and currency fluctuations are major contributors to this high cost of capital, so too are energy sector specific risks. These can include unclear or unstable regulation, lack of reliability of revenues, lack of focus on downstream policies and delays in obtaining grid connections. Increasing battery storage investment in Southeast Asia, Central and South America and India suggest that some countries are successfully addressing some of these risks, for example, through enacting policy reforms, enhancing the credit worthiness of offtakers, and issuing hybrid tenders that combine renewables with battery storage (IEA survey data shows that the cost of capital for battery storage tends to converge to that of solar PV projects in hybrid projects [IEA, 2023e]).

Figure 1.15 ▹ Cost of capital ranges for solar PV and battery storage projects with a final investment decision in 2022



Cost of capital for battery storage projects in emerging market and developing economies is at least twice as high as in advanced economies

Note: Values are expressed in nominal, post-tax and local currency. Weighted average cost of capital for solar PV projects represent responses for a 100 MW project and for utility-scale batteries a 40 MW project. Values represent average medians across countries. Advanced economies represent values in the United States and the European Union.

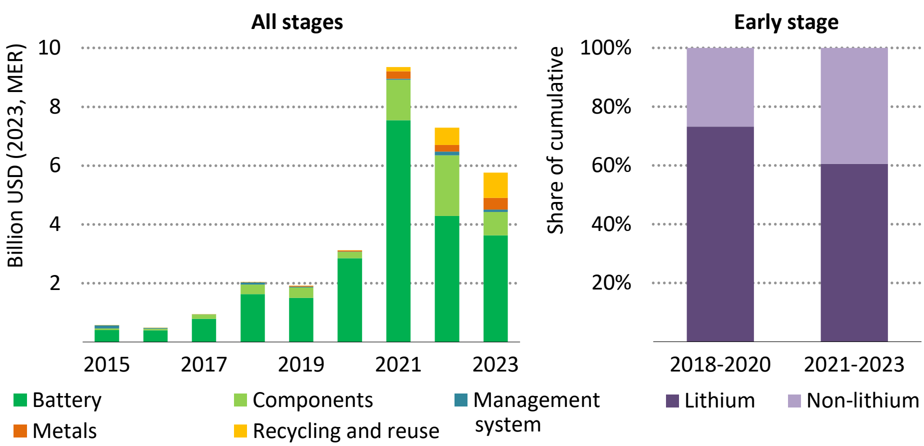
Source: Adapted from IEA (2024a).

1.4.2 Venture capital investment in battery start-ups

In the past decade, venture capital (VC) funding flowing to EV and battery start-up firms has boomed because financial investors such as banks and VC or private equity funds see a potential for future returns with high exit values. Many companies, including major incumbent auto makers, also provide funding to start-ups in order to gain a stake in the development of new technology or to acquire concepts developed by new entrants that may enhance their competitive edge.

In 2023, global VC investment in start-ups developing battery-related technologies was around USD 6 billion, which was 20% lower than the previous year (Figure 1.16). Increasing competition among EV and battery makers, geopolitical tensions, supply chain disruptions and high interest rates are all likely to have reduced the availability of high-risk capital. Nevertheless, battery VC investment remains three-times higher than the pre-pandemic levels of 2018-2019. Taken together, start-ups headquartered in China, Europe and United States accounted for 95% of all VC funding for batteries in 2023.

Figure 1.16 ▷ Global venture capital investment in battery start-ups by technology area and chemistry, 2015-2023



IEA. CC BY 4.0.

VC investment in battery start-ups boomed from 2015 to 2021, but has since slowed reflecting more challenging macroeconomic conditions

In 2023, early-stage investment[12] in battery start-up firms was around USD 400 million, while growth-stage investment [13] totalled around USD 5 billion. Novel battery chemistry and component makers accounted for 70-80% of VC investment, often for R&D and prototype projects. Over the 2021-2023 period, a higher share of early-stage VC investment than in previous years went to non-lithium battery chemistries such as metal-hydrogen, redox flow, solid-state or sodium-ion, indicating investor appetite for alternatives to lithium based technology. Another notable development was increasing funding for battery recycling and reuse, accounting for 15% of the total. Battery management systems have only attracted a fraction of the total to date. In addition to battery chemistries, just under USD 400 million was raised in 2023 by start-ups developing technologies for the extraction and refining of critical minerals like lithium, cobalt and nickel on which batteries depend.

[12] Early-stage investment includes seed and series A, referring to the first rounds of financing and the earlier stages of development.

[13] Growth-stage investment includes series B and growth equity, which refers to the later rounds of financing as start-ups increase activity.

1.5 Global battery supply chain

Today's global battery supply chain is very complex. It starts with the extraction of mineral ores, which are refined to form high purity battery-grade chemicals. Advanced materials synthesis subsequently produces cathode and anode materials (Figure 1.17). Similarly complex supply chains characterise other battery components such as electrolytes and separators. These components are eventually combined in the manufacture of battery cells which are then housed within a battery pack that is used in EVs or storage applications. In storage applications, battery units include systems for battery management, energy and thermal management, power conversion and communication: these elements are not required in EV batteries because they are embedded in the EVs.

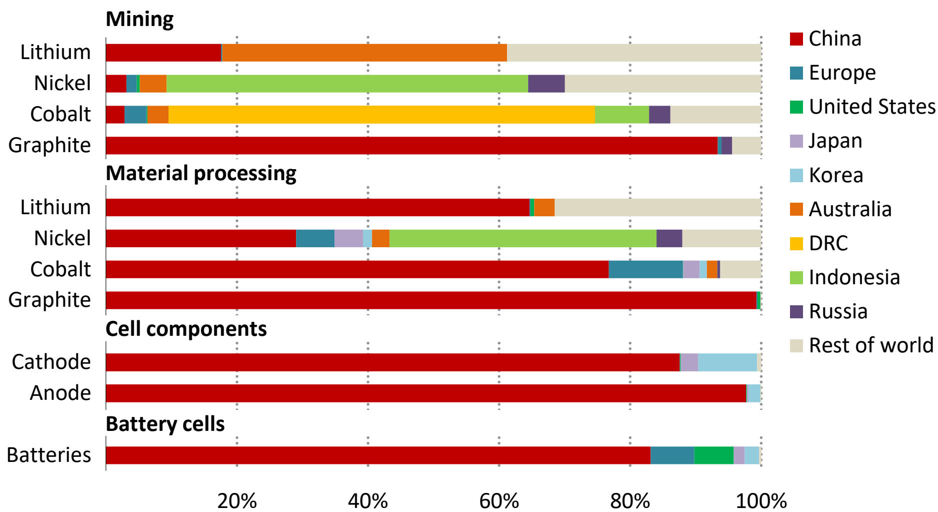
Figure 1.17 ▷ Key links in the battery supply chain

Mining	Extraction of raw ores/material required for battery materials
Raw material processing	Processing and refining of raw material into precursors for battery materials
Cell component production	Manufacture of specialised battery components: cathode and anode materials, electrolytes, separators and casings
Battery cell/packs production	Fabrication of battery cells, then integration into battery pack including electronics, sensors and battery management system
Battery storage	Battery storage enables integration of variable renewables in low-emissions power systems, ensuring reliable electricity supply
Electric vehicles	EVs are pivotal for decarbonising transport sector and reducing reliance on oil, offering substantial efficiency gains
Recycling/Reuse	Recovery of minerals, cathodes, anodes and/or reuse of used batteries in storage applications

The battery supply chain comprises multiple stages

China dominates production at every stage of the downstream battery supply chain. Over half of global raw material processing for lithium, cobalt and natural graphite occurs in China. With 90% of global graphite mining, China dominates the entire graphite anode supply chain end-to-end (Figure 1.18). It also has almost 85% of battery cell manufacturing capacity and accounts for 90% of cathode and 98% of anode active material global manufacturing capacity. Europe, which is responsible for almost 20% of EV production, holds very little of the global supply chain apart from 7% of battery cell manufacturing capacity, today mostly taking place in Poland and Hungary, and 10% of cobalt processing, which takes place mostly in Finland. The United States is responsible for 10% of EV production and 6% of battery cell manufacturing capacity. Korea has a considerable share of the battery supply chain downstream from raw material processing, particularly in cathode material production. Korea accounts for nearly 10% of global cathode active material manufacturing capacity.

Figure 1.18 ▷ Geographical distribution of the global battery supply chain



China dominates across the entire downstream battery supply chain

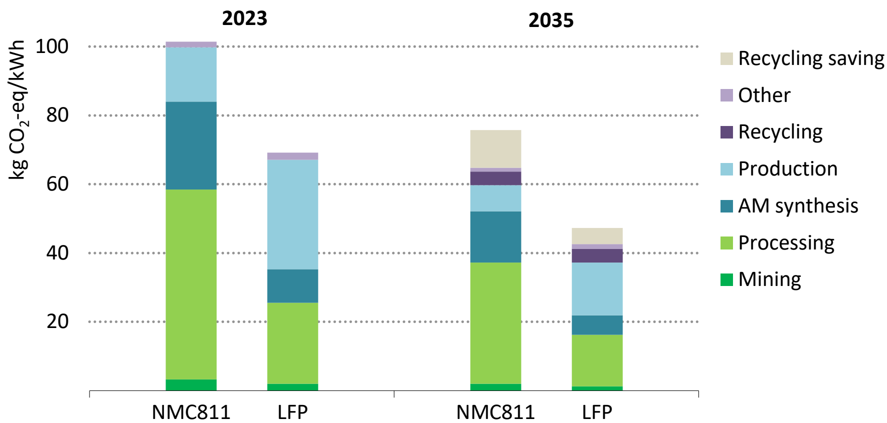
Note: DRC = Democratic Republic of the Congo. Graphite refining is only refining of natural graphite to spherical graphite. Mining and processing are based on production data. Cathode, anode and batteries are based on manufacturing capacity data.

In terms of raw material supply and extraction, battery metals are highly geographically concentrated and thus are vulnerable to supply shocks and constraints. Australia produces almost 45% of the world's lithium, while Democratic Republic of the Congo (DRC) accounts for 65% of the global cobalt production. Nickel supply is similarly concentrated, with Indonesia contributing to the largest share of production, representing 55% of total nickel supply. Much of this nickel, in the form of lateritic deposits, historically could not be economically refined into battery-grade nickel sulphate. However, over the past few years Indonesia developed the capacity to turn these nickel ores into intermediate chemicals through the use of high pressure acid leach processing. These inputs can be competitively refined into battery-grade nickel with this route currently comprising around 60% of the global supply of battery-grade sulphate.

Box 1.3 ▹ Carbon footprint of batteries

Carbon emissions related to batteries primarily arise from mineral refining, cathode and anode active material production, and manufacturing processes. Despite these emissions, the environmental benefits of batteries outweigh their drawbacks. EVs produce half the lifecycle CO_2 equivalent emissions of internal combustion engine vehicles globally, and these emissions are expected to fall as grid decarbonisation progresses.

Figure 1.19 ▹ Lifecycle emissions of NMC 811 and LFP battery packs in 2023 and in the Announced Pledges Scenario in 2035



Battery lifecycle emissions drop by more than 30% by 2035 reflecting reduced material intensity and recycling

Notes: kg CO_2-eq/kWh = kilogrammes of carbon dioxide-equivalent per kilowatt-hour; NMC 811 = $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$; LFP = lithium iron phosphate; AM synthesis = active material synthesis. Recycling saving refers to the emissions that are avoided thanks to the use of recycling materials. Other refers to emissions associated with other battery pack components like electronics and coolant. Production refers to cell and pack manufacturing. The Announced Pledges Scenario depicts a future where all countries hit their aspirational targets, including national and regional net zero emissions pledges, on time and in full. A more detailed description of the scenario is provided in Chapter 2.

Sources: IEA analysis based on data from Argonne National Laboratory (2022), EV Volumes (2024), Dai et al. (2019), Degen et al. (2023), Frith, Lacey and Ulissi (2023) and IEA (2023f).

The choice of battery chemistry is also crucial. Lifetime emissions from LFP batteries are about one-third less per kWh at the pack level than those from high nickel NMC batteries (Figure 1.19). NMC lifetime emissions come mostly from critical minerals processing, 55% of the total, but also from the production of cathode and anode active materials (25%) and battery manufacturing (15%). The equivalent figures for LFP lifetime emissions are around 35%, 15% and almost 50% (IEA, 2024b).

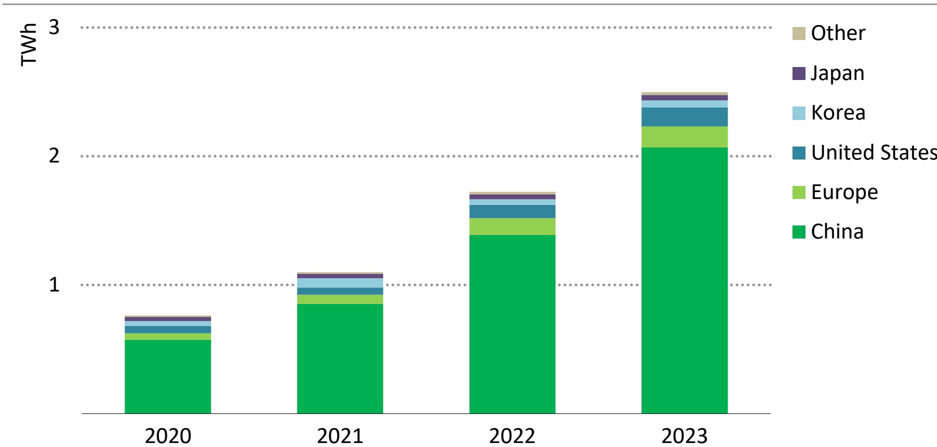
In the Announced Pledges Scenario (APS), battery lifecycle emissions decrease by 35% for both NMC and LFP through to 2035. This reduction comes mostly from a 30% increase in energy density at the battery pack level, and from 20% of the cathode active material being sourced through recycling. Both reduce material needs. The electrification of battery and battery components production is also important to reduce battery lifecycle emissions as power systems are decarbonised.

1.5.1 Lithium-ion battery manufacturing

Lithium-ion battery manufacturing capacity has more than tripled in the past four years, reaching 2.5 terawatt-hours (TWh) in 2023, with a third of this capacity added in 2023 alone. This remarkable expansion has been propelled by a rapid rise in EV sales. This trend is set to persist.

Battery manufacturing capacity is heavily concentrated in China, which accounts for 83% of current production capacity, up from 75% in 2020. Europe and the United States together account for approximately 13% of global capacity (Figure 1.20). Global manufacturing capacity is set to expand nearly fourfold by 2030 from current levels: if all announced projects are realised fully and on time, China's share is set to decline to 67% by 2030.

Figure 1.20 ▹ Lithium-ion battery manufacturing capacity by region, 2020-2023



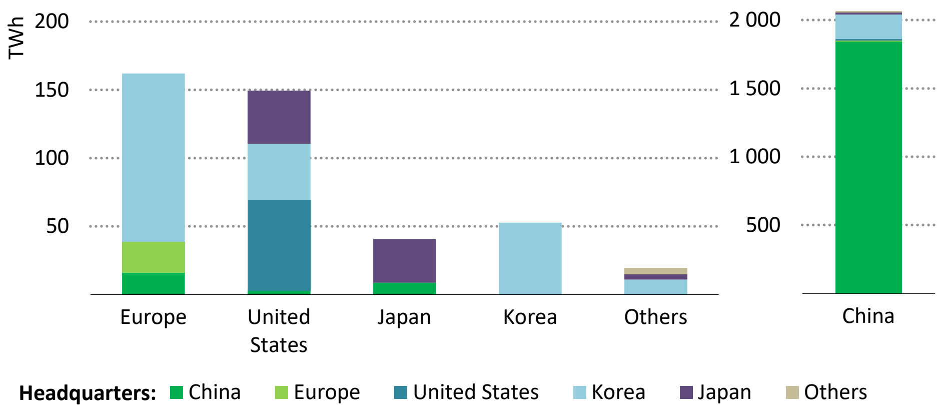
Lithium-ion battery manufacturing capacity has more than tripled since 2020, concentrated in China

Note: TWh = terawatt-hours. Battery manufacturing capacity refers to battery cells.

Source: IEA analysis based on Benchmark Minerals data.

Korean companies are emerging as pivotal international investors in battery manufacturing. They own over 350 GWh of capacity outside Korea. Japanese and Chinese companies also have battery manufacturing capacity in other countries, but the volumes are much smaller, about 55 GWh of Japanese non-domestic capacity, and less than 30 GWh of Chinese non-domestic capacity (Figure 1.21). In Europe, battery manufacturing capacity currently is dominated by Korean companies, with the LG Energy Solution plant in Poland alone accounting for half of total manufacturing capacity in Europe.

Figure 1.21 ▷ Lithium-ion battery manufacturing capacity by manufacturers' headquarter locations, 2023



Battery producers in Korea lead as primary investors in overseas markets with over 350 GWh of manufacturing capacity, followed by Japan and China

Note: TWh = terawatt-hours. Battery manufacturing capacity refers to battery cells.

Source: IEA analysis based on Benchmark Minerals data.

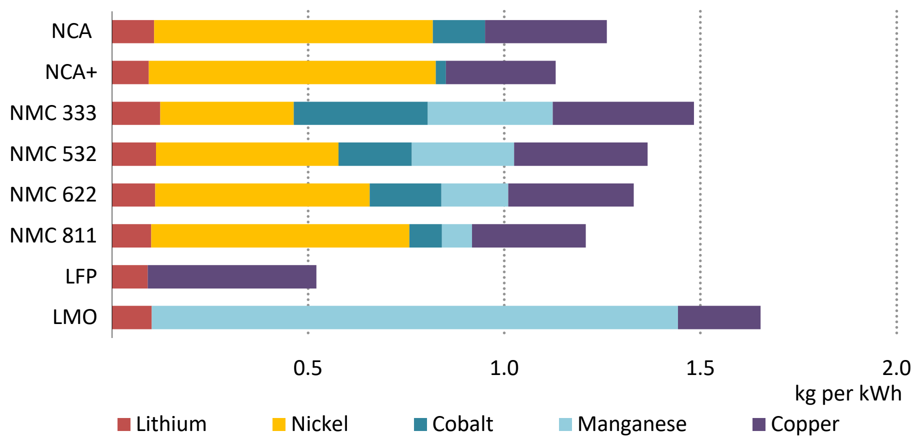
Incentives to boost the uptake of EVs or encourage the rollout of battery storage are increasingly being paired with domestic manufacturing incentives aimed at establishing or boosting domestic production of batteries and other elements of the EV value chain. In the United States, for example, the Inflation Reduction Act of 2022 makes more than USD 15 billion of production credits available for advanced manufacturing. In the European Union, the Important Projects of Common European Interest (IPCEI) initiative offers incentives to support battery manufacturing.

1.5.2 Critical minerals in batteries

As the need for batteries rises for clean energy transitions, the critical minerals that go into them are becoming increasingly important both for industry and policy makers. The major critical minerals required for lithium-ion batteries include lithium, nickel, cobalt, copper, graphite, and manganese (Figure 1.22).

In cathodes, the various chemistries, i.e. the different minerals that compose them, are what primarily determine the properties of the battery such as energy density and thermal stability. NMC batteries, the traditionally popular choice for electric cars in the last decade due to their high energy densities, require nickel, cobalt and manganese. LFP batteries, emerging as a favoured choice in both the EV and storage battery markets in recent years due to their lower costs and higher thermal stability, do not require the use of nickel, cobalt and manganese. In other chemistries such as NCA or lithium manganese oxide (LMO), nickel, cobalt or manganese are still needed. Lithium is the essential building block for all variants of lithium-ion batteries.

Figure 1.22 ▹ Mineral intensities by battery chemistry for lithium-ion battery cathodes used in EVs



Critical mineral use such as nickel, cobalt and manganese varies significantly depending on the chemistry used in the cathodes of lithium-ion batteries

In anodes, graphite is the most widely used material for lithium-ion batteries, though the use of silicon has increased in recent years. In the longer term, lithium metal anodes are expected to emerge with the advent of the all-solid-state battery. Copper is used in the anode current collector for lithium-ion batteries, as well as in the transformers that deliver power at the right voltage, and the cables and wires of electric circuits within battery packs. Aluminium is used for the cathode current collectors.

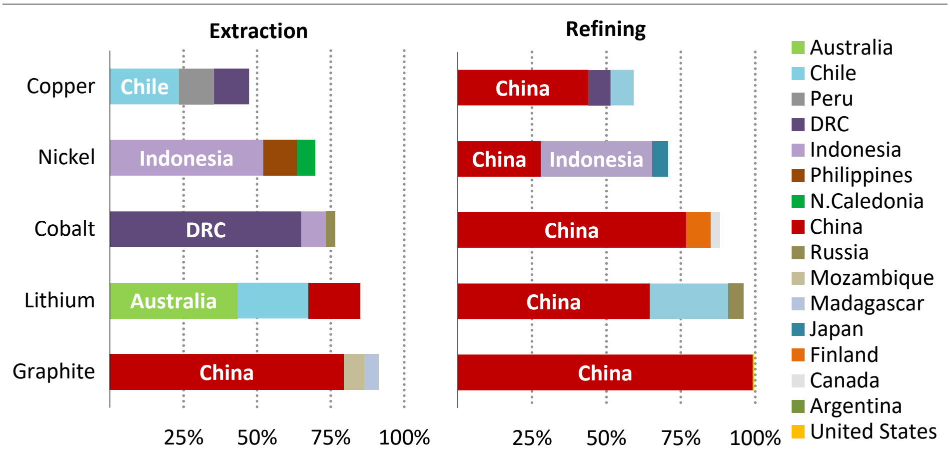
Along with the cathode and anode, the electrolyte and separator are the main components of battery cells. The electrolyte enables lithium ions to move between the cathode and the anode, which allows an electric current to pass through the external circuit and ultimately to charge and discharge the battery. The separator prevents physical contact between a cathode and an anode while ensuring the flow of lithium ions. Battery cells are then connected in series or parallel, making up a module. The stacked modules, together with cooling systems and battery management systems, make a lithium-ion battery pack that is then used in EVs or storage applications.

Efforts to reduce the demand for critical minerals are putting a spotlight on potential new chemistries. For example, sodium-ion batteries require significantly fewer critical minerals than lithium-ion batteries, and sodium is one of the most common elements on earth. Unlike lithium-ion batteries, sodium-ion batteries can also use aluminium anode current collectors, reducing the amount of copper. In redox flow batteries, which could become an alternative to lithium-ion for use in battery storage applications, vanadium is commonly used. However, scaling up its production could be challenging in light of current low levels of mining and refining as well its high cost and limited manufacturing facilities for redox flow batteries.

1.5.3 Risks in the critical minerals supply chain and price volatility

The extraction, refining and processing of the critical minerals used in the cathodes and anodes of lithium-ion batteries is highly concentrated in geographical terms, which brings considerable supply chain risks. The mining of nickel, cobalt and graphite is dominated by Indonesia, the Democratic Republic of the Congo and China respectively. The top-three producers of copper account together for around half of global production, the top-three producers of cobalt and nickel control over 70% of global production, and those of lithium and graphite well over 80%. The refining stage is even more concentrated. China dominates for nearly all minerals except for nickel, where Indonesia controls most refining (Figure 1.23). Moreover, there has been little progress on diversification in recent years. Between 2019 and 2023, the extraction of nickel and cobalt became more geographically concentrated, particularly in the case of nickel, and so did the refining.

Figure 1.23 ▷ Share of the top-three countries in extraction and refining of critical minerals for batteries in 2023

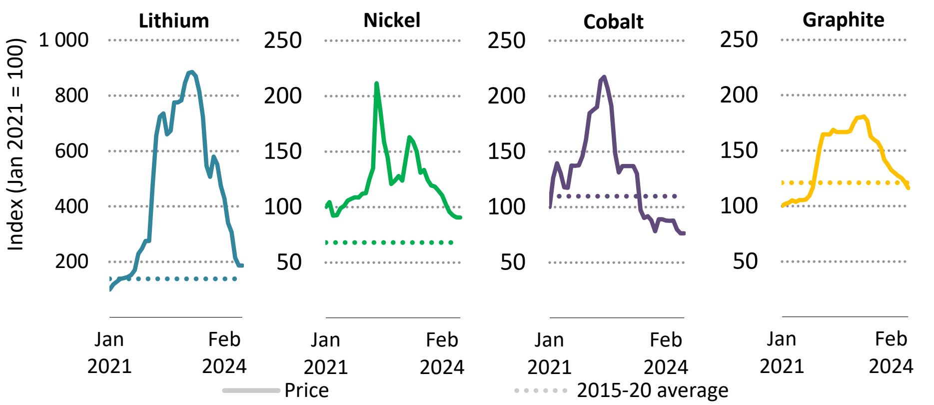


Extraction and refining of the global battery minerals supply chain are highly concentrated in geographical terms

Notes: N.Caledonia = New Caledonia, DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite.

Recent volatility in critical mineral prices has caused concern in the battery mineral market and highlighted the importance of adequate and reliable mineral supplies. Lithium prices rose as much as nine-times between January 2021 and December 2022 (Figure 1.24). They have since plummeted by nearly 80% from their 2022 peak. Other commodities also saw a price surge in 2022 and a subsequent fall. The recent fall in prices is helping to put critical mineral costs back on a declining trajectory, but there is a risk that it may at the same time discourage investors from financing future mining projects. Inadequate future investment would make it more difficult to increase and diversify supply and would increase the risk of future price volatility.

Figure 1.24 ▷ Price developments for key battery minerals



IEA. CC BY 4.0.

Lithium prices rose as much as nine times between 2021 and 2022 and prices of most battery minerals surged in 2021 and 2022 before plunging in 2023

Notes: Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices. Nominal prices.

Source: IEA analysis based on S&P Global data.

1.5.4 Direct investment in critical minerals by battery and EV producers

Battery and EV manufacturers are taking steps to ensure a stable supply of raw materials. Signing long-term binding offtake agreements for mineral supplies is a frequent strategy to ensure future supply. Many manufacturers are pursuing this option.

An increasing number of battery and EV makers are also getting directly involved in the upstream and downstream value chains, notably through investment in mines and refineries. A consortium led by CATL confirmed in June 2023 that it is providing USD 1.4 billion to build two lithium extraction plants in the Uyuni and Oruro salt flats in Bolivia (Bloomberg, 2023). CATL also announced in November 2022 a 25% stake worth USD 3.7 billion in CMOC, the second-largest cobalt producer in DRC in November 2022 (Reuters, 2022). LG Chemical, a parent company of LG Energy Solution, provided USD 75 million of equity investment for a 5.7% stake in Piedmont Lithium, a lithium miner in the United States (Piedmont Lithium, 2023). SK On, a Korean battery manufacturer, signed a 10% acquisition deal with Australian Lake Resources to supply lithium from its Kachi project in Argentina (SK, 2022).

EV makers are taking similar steps to ensure stable critical minerals procurement. In May 2023, Tesla broke ground for its in-house lithium refinery in Texas (Tesla, 2023).

The steps being taken by both battery makers and EV makers should contribute to supply chain resilience. Yet, further efforts are likely to be needed given the rapid scaling up of demand and the crucial importance of critical minerals in battery manufacturing. As of 2023, aggregated announced projects to build new battery gigafactories would be sufficient to meet the NZE Scenario demand in 2030, whereas the expected pace of growth in mineral supplies fell short. Further investment will be needed to create a diverse and resilient supply chain that is capable of meeting expanding needs in the battery industry.

Outlook for battery demand and supply

Role of batteries to achieve global energy and climate goals

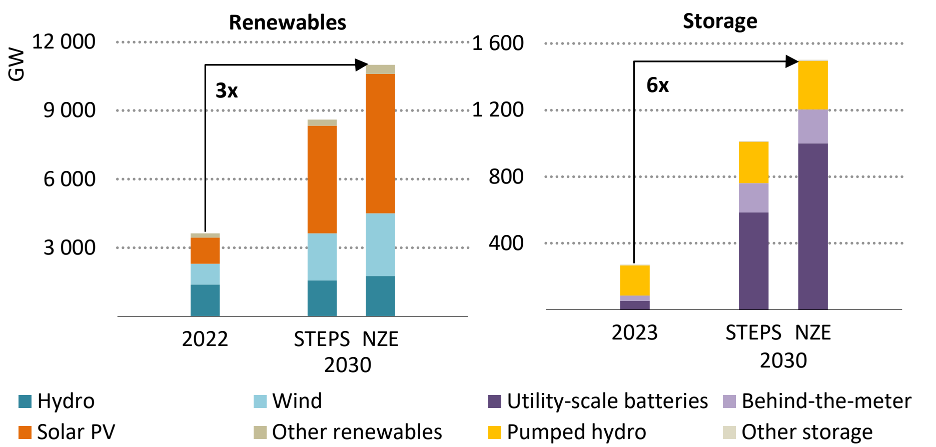
SUMMARY

- Batteries are set to play a leading role in secure energy transitions. They are critical to achieve commitments made by nearly 200 countries at COP28 in 2023. Their commitments aim to transition away from fossil fuels and by 2030 to triple global renewable energy capacity and double the pace of energy efficiency improvements.
- To facilitate the rapid deployment of new solar PV and wind power that is necessary to triple renewables, global energy storage capacity must increase sixfold to 1 500 GW by 2030. Batteries account for 90% of the increase in storage in the Net Zero Emissions by 2050 (NZE) Scenario, rising 14-fold to 1 200 GW by 2030. This includes both utility-scale and behind-the-meter battery storage. Other storage technologies include pumped hydro, compressed air, flywheels and thermal storage.
- Innovation reduces total capital costs of battery storage by up to 40% in the power sector by 2030 in the Stated Policies Scenario. This renders battery storage paired with solar PV one of the most competitive new sources of electricity, including compared with coal and natural gas. The cost cuts also make stand-alone battery storage more competitive with natural gas peaking options. Lower costs make behind-the-meter battery storage more attractive for consumers. Further it facilitates expanded opportunities to provide electricity access to the millions of people that lack it, cutting by nearly half the average electricity costs of mini-grids with solar PV coupled with batteries by 2030.
- Batteries in electric vehicles (EVs) are essential to deliver global energy efficiency gains and the transition away from fossil fuels. In the NZE Scenario, EV sales rise rapidly, with demand for EV batteries up sevenfold by 2030 and displacing the need for over 8 million barrels of oil per day. Batteries in EVs and storage applications together are directly linked to close to 20% of the CO_2 emissions reductions needed in 2030 on the path to net zero emissions.
- Investment in batteries in the NZE Scenario reaches USD 800 billion by 2030, up 400% relative to 2023. This doubles the share of batteries in total clean energy investment in seven years. Further investment is required to expand battery manufacturing capacity. Announcements for new battery manufacturing capacity, if realised, would increase the global total nearly fourfold by 2030, which would be sufficient to meet demand in the NZE Scenario. The demand for critical minerals in batteries is set to rise significantly, requiring investments in new projects, recycling and financial tools for sustainability. Battery recycling can provide a secondary source of materials, aiding production while minimising battery-related waste. Artificial intelligence may offer avenues to accelerate new battery chemistry development and to ease strain on critical minerals.

2.1 COP28 commitments and the role of batteries

In December 2023, nearly 200 governments reached agreement at the United Nations Climate Change Conference of the Parties 28th session (COP28) on new global 2030 goals. They aim to triple renewable energy capacity and double energy efficiency progress by 2030, to accelerate the transition away from fossil fuels and substantially reduce methane emissions. Collectively, these provide a clear vision for the future transformation of the energy system. Batteries are set to play a pivotal role in realising this vision.

Figure 2.1 ▷ Global installed renewable energy and energy storage capacity by scenario, 2022 and 2030



Energy storage capacity, led by battery storage, increases sixfold by 2030 in the NZE Scenario and supports the tripling of renewables capacity goal

Notes: GW = gigawatts; PV = photovoltaics; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Other renewables include bioenergy, geothermal, concentrating solar power and marine. Other storage includes compressed air energy storage, flywheel and thermal storage. Hydrogen electrolysers are not included.

Achieving the goal of tripling global renewable energy capacity by 2030 calls for rapidly scaling up battery storage in the power sector to support grid stability, security of electricity supply and integration of solar PV and wind power. In the Net Zero Emissions by 2050 (NZE) Scenario, which meets the Paris Agreement target of limiting global average temperature increases to 1.5 degrees Celsius (°C) or less in 2100, the tripling of global renewable capacity is accompanied by a sixfold increase in total energy storage from 2023 to 1 500 GW in 2030. Battery storage leads the way, with utility-scale and behind-the-meter projects combined rising to 1 200 GW by 2030, accounting for 90% of overall growth in storage. Smaller amounts of storage are provided by pumped hydro – which is the largest source of energy storage today but is projected in the NZE Scenario to be surpassed by battery storage in the mid-2020s – and by compressed air, flywheels and thermal storage (Figure 2.1). Total energy storage in the NZE Scenario is 50% higher than in the Stated Policies Scenario (STEPS), which provides an outlook based on current policies, including energy, climate and related industrial policies. Closing this gap is one of the key challenges in the power sector, along with the need to step up the pace of development in electricity grids (IEA, 2023a).

Box 2.1 ▹ World Energy Outlook Scenarios

The analyses presented in this report build on the *World Energy Outlook-2023* (*WEO-2023),* which includes three scenarios that explore different pathways for the energy sector to 2050. These scenarios include the latest energy market and cost data and build on the latest projections for economic, population and demographic trends. The scenarios consider energy and climate-related policies and industrial strategies and explore the implications of national plans, targets and Nationally Determined Contributions (NDCs) across the world. The variations between the three scenarios largely reflect the different policy choices made by governments. They are not predictions – the IEA does not have a single view on the future of the energy system.

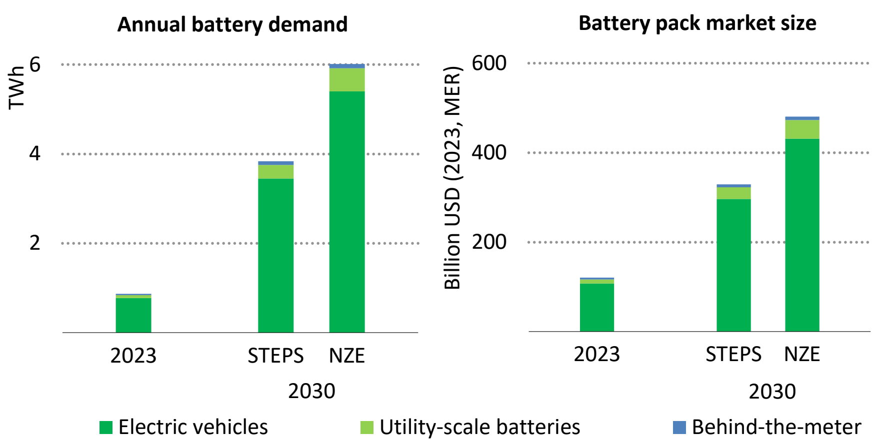
The **STEPS** is designed to provide a sense of the way in which energy systems might develop based on a detailed review of the current policy landscape. Outcomes in the STEPS reflect a detailed sector-by-sector review of the policies and measures that are in place or that have been announced; aspirational energy or climate targets are not automatically assumed to be met. It explores how energy systems might evolve under today's policy settings, taking account of industry action, including for example announced plans to increase manufacturing capacity for particular clean energy technologies.

The **NZE Scenario** describes a narrow but achievable pathway for the global energy sector to reach net zero energy-related CO_2 emissions by 2050 by deploying a wide portfolio of clean energy technologies without offsets from land-use measures. It assumes that advanced economies take the lead and reach net zero CO_2 emissions earlier than emerging market and developing economies. The NZE Scenario achieves the COP28 goals of tripling global renewable energy capacity and doubling energy efficiency progress by 2030, while achieving universal energy access consistent with the energy-related targets within the United Nations Sustainable Development Goals. The scenario is consistent with limiting the global temperature rise to 1.5 °C (with at least 50% probability).

The **Announced Pledges Scenario (APS)** assumes that governments will follow through and deliver on all announcements made, and that they will meet all commitments in full and on time, including their NDCs and longer-term net zero emissions targets. As with the STEPS, the APS is not designed to achieve a particular outcome, but instead provides a bottom-up assessment of the energy trends that seem likely to emerge if countries fulfil their energy plans and climate pledges. Countries without ambitious long-term pledges are assumed to benefit in this scenario from the accelerated cost reductions and wider availability of clean energy technologies.

Achieving the goal of doubling the rate of improvement for energy efficiency depends on accelerated electrification and increased penetration of renewables, which together deliver a third of the needed improvement In the NZE Scenario. For example, electric motors are two- to four-times more efficient than combustion alternatives and heat pumps are three- to five- times more efficient than gas boilers. Both are contingent on significant upscaling of battery deployment. In the STEPS, the market share of electric vehicles (EVs)[1] rises to around 45% by 2030; this increases to 70% in the NZE Scenario. This calls for an increase in annual EV battery volumes to reach 3.5 terawatt-hours (TWh) by 2030 in the STEPS, up from nearly 0.8 TWh today, and nearly 5.5 TWh in the NZE Scenario. This surge for EV batteries means that EVs continue to account for around 90% of battery market across the energy sector through to 2030, even with strong growth in battery storage (Figure 2.2).

Figure 2.2 ▹ Annual battery demand and battery pack market size by application and scenario, 2023 and 2030



EVs account for about 90% of battery demand to 2030, while the value of the battery pack market reaches USD 330 billion in the STEPS and nearly USD 500 billion in the NZE Scenario

Note: TWh = terawatt-hours; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario.

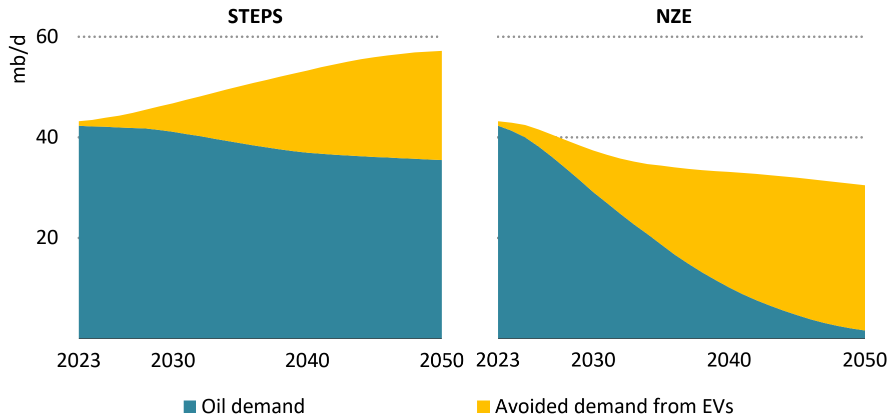
Progress on electromobility and renewable power generation through to 2030 is set to give a major boost to the battery pack market. In the STEPS, this market expands from roughly USD 120 billion today to USD 330 billion in 2030, while the NZE Scenario propels it to nearly USD 500 billion – about 1.5 times the current size of the solar PV market.

Achieving the broad COP28 goal of transitioning away from fossil fuels involves an important direct or indirect role for batteries in every sector. Their use in EVs is pivotal in the decarbonisation of transport. In the STEPS, EVs collectively avoid oil consumption of around 6 million barrels per day (mb/d) worldwide in 2030 and 22 mb/d in 2050, while faster deployment in the NZE Scenario means EVs avoid around 1.5-times more oil by both 2030 and 2050 (Figure 2.3). Currently oil accounts for 92% of fuel consumption in road transport, but this is set to decline to around 70% by 2050 in the STEPS. In the NZE Scenario, the

[1] Electric vehicles include battery electric and plug-in hybrid vehicles.

reduction is more pronounced and, by 2050, the role of oil in road transport nearly disappears, driven by robust electrification and the adoption of low-emissions fuels like biofuels. The use of batteries in the power sector similarly has important effects as batteries become essential enablers for integrating solar PV and wind power and thus move to displace fossil fuels. Currently, unabated coal-fired power is the largest source of electricity in the world, with a share of about 35%, but this is set to decline to less than 10% by 2050 in the STEPS and to zero by 2040 in the NZE Scenario, largely due to the massive expansion of solar PV and wind power. Unabated natural gas power generation with a share of 22% is the second-largest source of electricity today. It is also set to decline over time due to the rapid growth of renewables.

Figure 2.3 ▷ Oil demand in road transport and savings from EVs by scenario, 2023-2050



Battery use in EVs significantly curbs future oil demand growth from the road transport in the STEPS and avoids nearly 30 mb/d of oil use by 2050 in the NZE Scenario

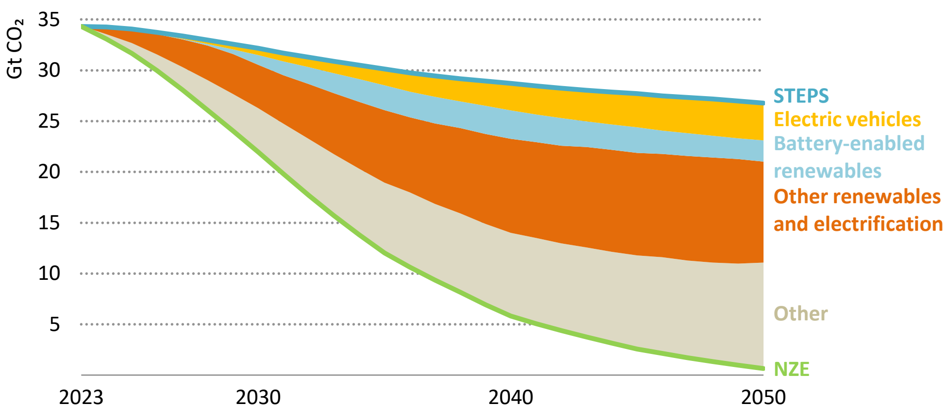
Note: mb/d = million barrels per day; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Reductions in the use of oil, natural gas and coal in other sectors are facilitated by clean electrification, supported and enabled by batteries. In industry, switching from fossil fuels to decarbonised electricity for a number of products and processes, including steel making, is an important part of clean energy transitions. In buildings, the use of decarbonised electricity for space and water heating is set to displace demand for natural gas and coal. Clean electrification also helps to reduce the current carbon footprint of batteries themselves (see Chapter 1) and contributes to the COP28 goal of reducing methane emissions.

As a cross-cutting technology, batteries are directly linked to close to 20% of the total carbon dioxide (CO_2) emissions reductions from combustion needed in 2030 to change the course of the global energy system and bridge the gap between the CO_2 emissions trajectories in the STEPS and NZE Scenario (Figure 2.4). In the NZE Scenario, EVs equipped with batteries save more than 0.6 billion tonnes of CO_2 emissions in 2030 compared with the STEPS, and

3.7 billion tonnes of CO_2 emissions in 2050. In the power sector, higher amounts of renewables enabled by battery storage in the NZE Scenario account for around 1 billion tonnes of CO_2 savings in 2030 compared with the STEPS, rising to over 2 billion tonnes by 2050. Through broader support of renewables and clean electrification, batteries are also linked to an additional 40% of the CO_2 emissions reductions needed to shift to a net zero emissions pathway. This means that in total batteries help to deliver more than 60% of all the CO_2 emissions reductions needed to bridge the gap between the STEPS and NZE Scenario. Rising demand for batteries and the needed critical minerals increase industrial activity, particularly in regions with mining and manufacturing of battery components. Widespread electrification of processes and increasing use of renewables are set to improve the carbon footprint of batteries and reduce its impact on total CO_2 emissions.

Figure 2.4 ▷ Avoided CO_2 combustion emissions linked to batteries and other technologies by scenario, 2023-2050



IEA. CC BY 4.0.

Batteries in EVs and storage applications are directly linked to close to 20% of the CO_2 emissions reductions needed in 2030 and indirectly linked to another 40%

Notes: Gt CO_2 = gigatonnes of carbon dioxide; NZE = Net Zero Emissions by 2050 Scenario. Other includes energy efficiency improvements, hydrogen and other fuel shifts, nuclear, carbon capture, utilisation and storage, activity impact and behaviour measures.

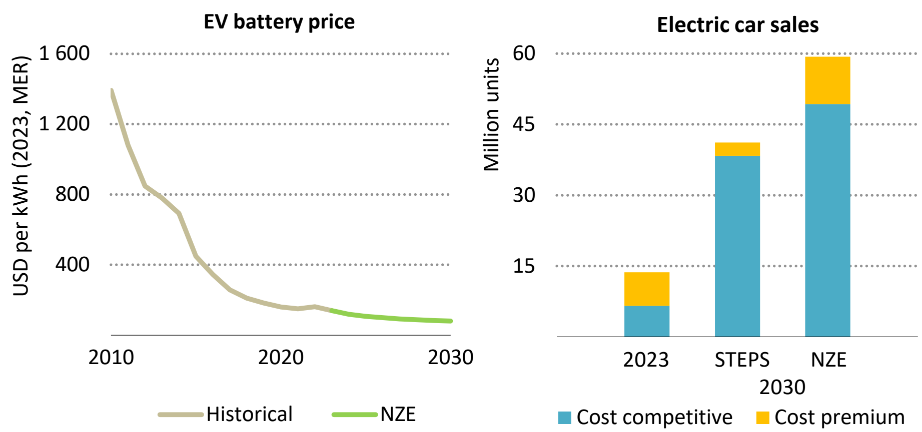
Shifting the global energy system to a net zero emissions pathway requires clear policies to support the installation of battery storage to underpin the rapid deployment of variable renewables. Current policy frameworks often hinder the integration of battery storage into the power system or lead to remuneration schemes that fail to incentivise battery storage (see Chapter 1). Effective measures and actions are also needed to support deployment of EVs and expansion of charging infrastructure, together with stringent fuel economy targets.

Battery manufacturers have unveiled ambitious capacity expansion plans which indicate that the battery market is set to expand rapidly. If fully realised, the announced pipeline of new manufacturing would be sufficient to provide the annual battery volumes needed in the NZE Scenario (section 2.5.1). Uncertainty inevitably remains about whether it will be delivered in full, but the announced plans make clear a declaration of intent. Establishing scaled-up supply chains with a low-carbon footprint presents a formidable challenge, and battery manufacturers and policy makers are increasingly focussed on how best to meet it.

2.2 Outlook for EV batteries

In 2023, annual electric car sales rose to a new high of approximately 14 million worldwide. Nearly one-out-of-five new cars sold is now electric. This increases to nearly one-out-of-two cars by 2030 and to nearly two-thirds of all new car sales by 2050 in the STEPS. In the NZE Scenario, electric car sales rise even faster: their market share surges from around two-thirds in 2030 (60 million new electric cars sold each year) to nearly 100% by 2050 (90 million new electric cars sold each year). This trend is supported by reductions in battery costs alongside commitments to decrease energy-related CO_2 emissions. With the widespread deployment of EV batteries, average battery prices are projected to decrease by another 40% relative to current prices. This, combined with the future competitiveness of auto makers, would reduce the payback period[2] for a battery electric car from 3 to 8 years today depending on the market and car segment, to nearly 3 years across all regions (Figure 2.5). The cost competitiveness of EVs, particularly electric cars, increases over time in both the STEPS and NZE Scenario. Especially in the NZE Scenario, where EV deployment is widespread across all regions, ensuring the availability of affordable EVs in all markets and making timely investment in charging infrastructure are key for putting clean energy transitions on track.

Figure 2.5 ▷ Average EV battery price and EVs competitiveness in the STEPS and NZE Scenario, 2023 and 2030

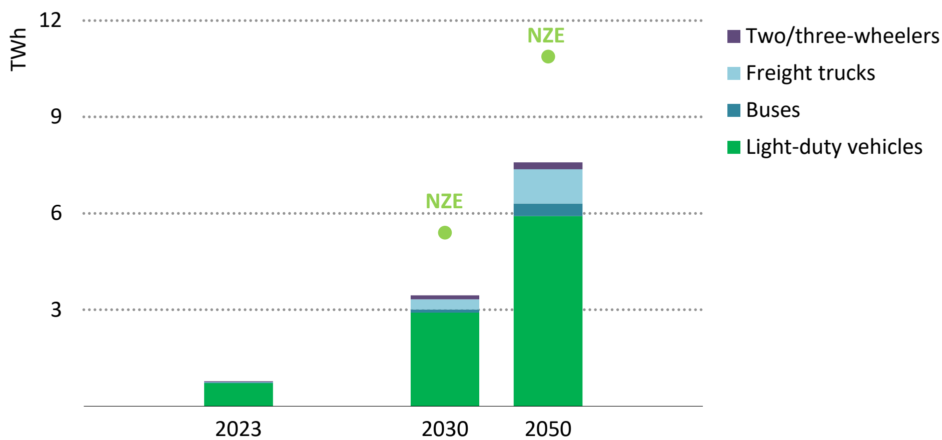


By 2030, the average battery price declines by 40% in the NZE Scenario, shortening the payback period and increasing the share of EV sales which are cost competitive

[2] The payback period is the time needed for savings in running costs (i.e. fuel and maintenance costs) to compensate for the difference in upfront costs between an electric vehicle and a conventional internal combustion engine vehicle.

As a result, annual battery volumes for EVs more than quadruple to 3 500 gigawatt-hours (GWh) by the end of this decade in the STEPS, and double again by 2050 (Figure 2.6). This leads electricity demand for EVs to grow rapidly from over 130 terawatt-hours (TWh) today to more than 1 000 TWh by 2030 and 5 000 TWh by 2050. Demand for electricity in shipping and aviation add a further 14 TWh by 2050. In the NZE Scenario, annual EV battery volumes climb to around 5 500 GWh by 2030 and a staggering 11 000 GWh by 2050, with the global EV fleet requiring over 1 700 TWh of electricity in 2030 and almost 9 700 TWh in 2050. Shipping sector electricity demand reaches 16 TWh by 2030 and over 80 TWh by 2050, with battery-powered airplanes requiring nearly 120 TWh by 2050. This underscores the urgent need for substantial advances in battery chemistries and manufacturing innovation along with significant investment and robust policy support underpinned by commitment to sustainable mining practices.

Figure 2.6 ▷ EV annual battery demand by vehicle type in the STEPS and gap to the NZE Scenario, 2023, 2030 and 2050



By 2050, annual battery volumes in the road sector increase about ten-fold in the STEPS and fourteen-fold in the NZE Scenario

Notes: TWh = terawatt-hours. Light-duty vehicles include passenger cars and light commercial vehicles. Freight trucks include medium freight and heavy freight trucks.

In the STEPS, passenger cars and light commercial vehicles account for most of the growth in EV sales over the rest of this decade. This reflects both the size of the fleet compared with heavy-duty vehicles[3] and the additional challenges involved in electrifying heavier vehicles due to their size and the long distances they tend to travel. Two/three-wheelers and urban buses also undergo rapid electrification in the STEPS, particularly in emerging market and developing economies, though two/three-wheelers use relatively small batteries and therefore account for a limited share of battery volume growth. Despite expansion of

[3] Heavy-duty vehicles include medium freight, heavy freight trucks and buses.

electrification, a number of emerging market and developing economies face challenges in developing charging infrastructure and delivering universal access to electricity.

In contrast, the NZE Scenario sees a rapid phase-out of internal combustion engines (ICE) in all regions, starting with light-duty vehicles and extending to heavier vehicles. Achieving this aim requires additional investment in public charging infrastructure compared to the STEPS other than China: over USD 35 billion in cumulative terms is needed by 2030, increasing to USD 470 billion by 2050. In the short term, light-duty vehicles account for about two-thirds of the disparity in annual battery volumes between the two scenarios. Beyond 2030, however, it is increasingly medium and heavy trucks that are responsible for the divergence between the STEPS and NZE Scenario annual battery volumes.

Table 2.1 ▷ Selected plans to phase out ICE vehicles

Region/country	Type	Description	Year
Canada	Policy	Auto manufacturers and importers must meet annual ZEV targets for LDV sales of 100% by 2035.	2023
Chile	Target	100% of sales of LDVs and public transport vehicles will be zero emissions by 2035, and by 2045 for M/HDVs.	2022
European Union	Policy	100% CO_2 emissions reduction for both new cars and vans by 2035.	2021
Israel	Target	Reduce average emissions from LDVs by 100% in 2050.	2022
Norway	Target	100% share of ZEVs in LDV sales by 2025 and in MDV sales by 2030.	2021
United Kingdom	Policy	100% of new car and van sales will be zero emissions by 2035.	2017
United States[4]	Policy	Advanced Clean Cars Rule II set a target for 100% ZEVs in LDVs by 2035.	2023
Auto maker	**Type**	**Description**	**Year**
BMW	Target	50% of sales to be EVs before 2030.	2023
Changan	Target	60% of sales to be ZEVs by 2030.	2021
Ford	Target	50% of sales to be fully electric by 2030.	2022
Geely	Target	40% of sales to be electric by 2025.	2022
Honda	Target	100% of sales to be ZEVs by 2040.	2022
Hyundai, Genesis	Target	Annual EV sales of 2 million units and BEV production share of 34% by 2030.	2023
Kia	Target	37% of sales to be EVs by 2030 reaching 1.6 million units per year.	2023
Mercedes-Benz	Target	50% of sales to be electric by 2030.	2024
Nissan	Target	55% of sales to be electric by 2030.	2023
Volkswagen	Target	50% of sales to be BEVs by 2030.	2023

Notes: ZEV = zero emissions vehicle; LDV = light-duty vehicle; MDV = medium-duty vehicle; M/HDV = medium/heavy-duty vehicle; auto maker = original equipment manufacturer of the automotive industry; BEV = battery electric vehicle. Year corresponds to the year of implementation. All auto maker targets are for the global market.

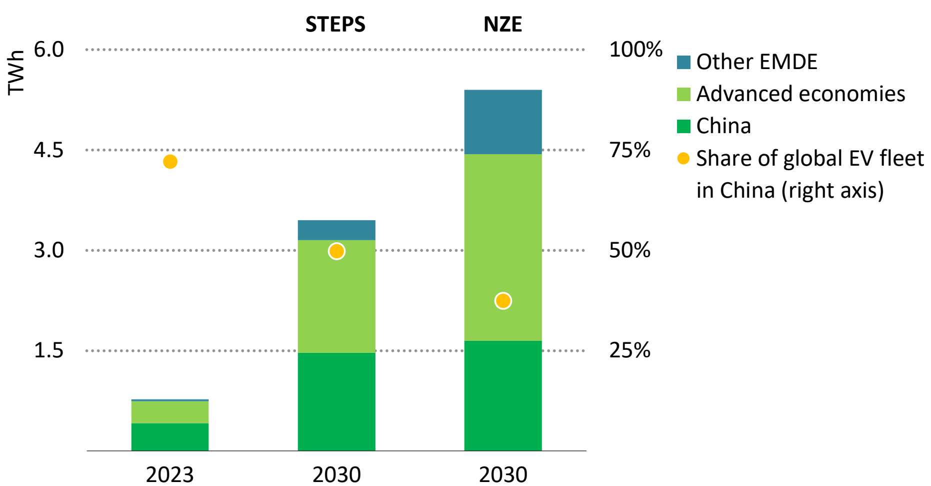
[4] Ten states and the District of Columbia adopted the target: California, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont, Virginia and Washington. Colorado, New Mexico, and Delaware have partial targets (California Air Resources Board, 2024).

The phase-out of ICE vehicles is supported by policy signals and underpinned by expanded EV production plans of car and truck makers and battery manufacturers (Table 2.1). The global discussion no longer revolves around whether EVs will enter the market, but rather how quickly their market share will increase. Though there is less clarity for the heavy vehicle segments where policy incentives are weaker, model availability is limited and progress in developing an adequate charging infrastructure is relatively slow. Policy support must be strengthened if the world is to get on track to reach net zero emissions by 2050, particularly for the electrification of long-distance transport. In parallel, well-designed policies are needed to facilitate sustainable battery supply chains from raw material production to cell assembly, together with measures for the effective tracking, recycling and reuse of battery packs after their initial use in vehicles so as to ensure environmental sustainability throughout the lifecycle of EV batteries (Box 2.2).

2.2.1 Regional outlook for EV batteries

Global annual battery volumes for EVs have risen nearly fivefold since 2020, with China leading the surge. In 2023 China accounted for over 70% of the world's EV fleet and more than half of global annual EV battery volumes. In the STEPS, China's share of the global EV fleet falls to 50% in 2030 as EV uptake spreads in other countries (Figure 2.7). In the NZE Scenario, China's share falls to less than 40% of the global EV fleet in 2030.

Figure 2.7 ▷ Global annual EV battery volumes by region and scenario, and the share of China in the global EV fleet, 2023 and 2030



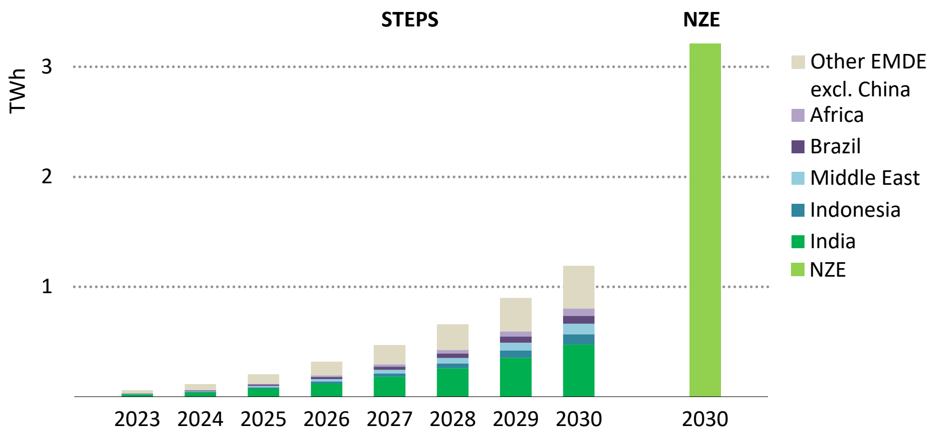
China maintains its rank with the largest EV battery volumes in 2030, though the uptake of EVs in other regions dilutes the percentage

Note: Other EMDE = emerging market and developing economies other than China.

China's outsized share of the global EV market means that it is also the largest EV battery market in the STEPS, accounting for over 40% of global annual EV battery volumes in 2030. In the NZE Scenario, annual EV battery volumes in the rest of the world, especially in other emerging market and developing economies, rises more rapidly than in the STEPS, reducing China's share in the global market to 30% by 2030. In the STEPS, the global EV battery market in 2030 is significantly larger than today, and it is much larger in the NZE Scenario, where annual EV battery volumes in 2030 are around 60% higher than in the STEPS.

The volume of batteries used in EVs in various regions in 2030 is much higher in the NZE Scenario than in the STEPS. It is approximately 10% higher in China, around 80% higher in advanced economies, and 170% higher in emerging market and developing economies outside China (Figure 2.8). This underscores the pivotal role of battery volumes to bridge the considerable gap between the two scenarios, especially in emerging market and developing economies other than China. It also emphasises the critical role of EVs to decarbonise the transport sector to achieve the goals of the Paris Agreement and COP28, and to facilitate the transition to sustainable energy pathways in all regions of the world.

Figure 2.8 ▹ Battery volumes in use in EVs in emerging market and developing economies outside China by scenario, 2023-2030

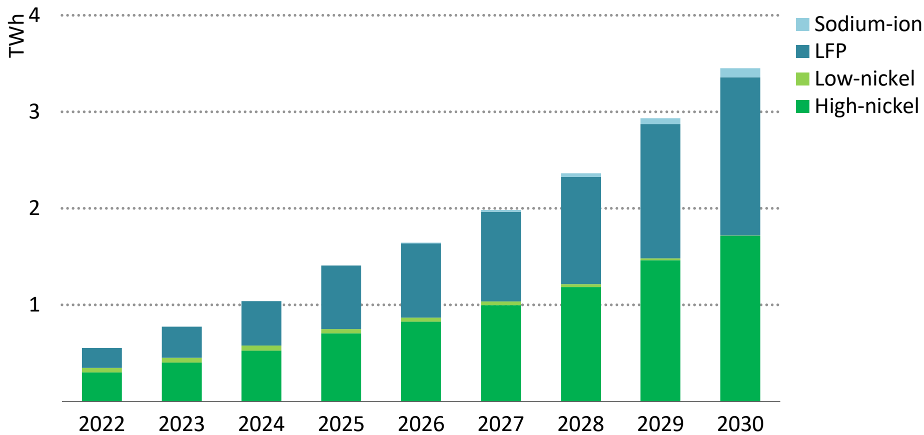


EV battery volumes in the emerging market and developing economies outside China, increase nearly twenty-fold in the STEPS and over fifty-fold in the NZE Scenario

2.2.2 What type of batteries will power future EV fleets?

Lithium-ion batteries stand out for their high energy density, efficiency, and cycle life. Today, the two primary battery chemistries in use are high nickel – mostly nickel-manganese-cobalt (NMC) – and lithium-iron phosphate (LFP). Together they are set to continue to dominate the EV market until the end of this decade. LFP and NMC battery chemistries meet EV requirements for competitive pricing, long range, fast charging and safety. Their technological maturity and established supply chain mean that lithium-ion batteries account for around 95% of annual EV battery volumes by 2030 (Figure 2.9). Moreover, rapid battery demand growth will hinder new technologies from gaining significant market share quickly at least in the short term.

Figure 2.9 ▻ Annual EV battery volumes by cathode chemistry in the STEPS, 2022-2030



Lithium-ion batteries continue to dominate the EV market, accounting for about 95% of annual volumes by 2030

Notes: LFP = lithium-iron phosphate. High-nickel = mainly lithium nickel cobalt aluminium oxide (NCA) and NMC chemistries excluding NMC111 and NMC532. Low-nickel = NMC111 and NMC532.

High-nickel batteries hold steady as a main technology to 2030, with around 50% of market share. NMC cathodes, dominant among types of high-nickel batteries, accounted for close to 50% of annual EV battery volumes in 2023, and, in the STEPS, account for less than 40% by 2030. With higher energy densities and recycle values than LFP batteries, NMC batteries have an advantage in some applications. They also have an advantage in markets with strict battery recycling requirements, such as Europe, the United States and Japan, as currently recycling of LFP batteries is not economical at scale. These regions represent a large market and by 2030, they collectively form the largest EV battery market in the world in the STEPS. However, affordability remains a key obstacle to high-nickel battery EV adoption, especially in price sensitive markets. NMC batteries also face other disadvantages relative to LFP batteries. LFP batteries have a longer lifespan, perform better at higher temperatures, have higher thermal stability and lower lifecycle emissions.

LFP batteries have experienced rapid market growth, particularly in China's EV market. LFP battery technology has been exempt from patent fees since 2022, and since is being increasingly adopted in advanced economies. Original equipment manufacturers are already making use of it. LFP battery chemistry is also gaining popularity beyond China, notably in Southeast Asia and in advanced economies, thanks to its cost effectiveness, long lifetime and enhanced safety compared to NMC batteries. In the STEPS, LFP continues to solidify its market position, with its share of annual EV battery volumes increasing from over 40% today to nearly 50% in 2030.

Both NMC and LFP battery chemistries are being continually improved, as evidenced for example in efforts to increase their manganese content, which could reduce the cost of NMC batteries while preserving their high energy density, and equally could maintain the low cost of LFP batteries while enhancing their energy density. The continuing evolution of the established battery chemistries poses a significant challenge for alternatives that seek to compete.

Innovation in battery manufacturing is equally important. Scale up and automation have been the key drivers contributing to battery prices declines over the last decade. Manufacturing batteries at scale requires high yields and great precision, typically requiring years of sustained investment. Current promising energy density innovations include new battery pack concepts, such as cell-to-pack and cell-to-chassis,[5] though the latter could make battery recycling more difficult. The optimisation of manufacturing parameters, such as through multi-layer electrodes, achieves improved battery performance and enables ultra-fast charging.

Sodium-ion batteries have begun to catch up with lithium-ion batteries. Sodium-ion batteries have similar applications to LFP batteries, although they have a lower energy density. Sodium-ion batteries are increasingly seen as appealing alternatives to LFP batteries because they may use less expensive, more abundant materials, and need fewer toxic raw materials. As with LFP batteries, China is leading the development of sodium-ion batteries, with over 90% of announced manufacturing capacity located there. Current research and development efforts for sodium-ion batteries focus on enhancing energy density, prolonging cycle life, and optimising performance at lower temperatures (see Chapter 1).

Currently, few producers are capable of rapidly scaling up the supply chain and production of sodium-ion batteries. This illustrates the challenges of introducing new battery chemistries into a large and rapidly expanding market. Nevertheless, sodium-ion batteries are set to gain traction in the late 2020s. In the STEPS, they account for around 5% of annual EV battery volumes in 2030 and are mainly used in vehicles with low energy requirements, such as city cars and two/three-wheelers. Sodium-ion batteries may be able to benefit from existing lithium-ion production facilities if demand justifies, since production requirements for the two types of chemistries are similar. However, LFP will remain a formidable competitor, and the price of lithium will play a crucial role in determining sodium-ion battery

[5] Battery packs used in EVs are typically made of a series of modules, each one containing several battery cells. In the cell-to-pack configuration, battery cells are assembled to build a pack without using modules, which reduces the need for inert materials and increases energy density. In cell-to-chassis concepts, battery cells are used as part of the EV structure without assembling them into a battery pack beforehand.

development and competitiveness. If lithium supply is not constrained in the face of rising demand, and if lithium prices continue to decline, that will help LFP in the battle for competitiveness and market share.

The current EV market is fragmented regionally due to battery export restrictions, with most batteries distributed through long-term supply contracts. Dominant battery chemistries vary by region, based on local manufacturing capacities and early adopter advantages. Automotive industry partnerships with battery manufacturers will continue to shape battery trends.

2.2.3 Innovation in battery technology beyond 2030

Innovation has the potential to reshape the battery chemistry mix in the market beyond 2030. Solid-state batteries (SSBs) employ solid or quasi-solid electrolytes instead of the conventional liquid electrolytes, which increases cell energy density and safety with reduced flammability. Nevertheless, uncertainties surround the widespread adoption of SSB technology in the mass market, primarily owing to integration challenges at the battery pack level, i.e. applying high stack pressures, which today are about one order of magnitude higher in SSBs than in lithium-ion batteries. These challenges may offset the higher energy density at the cell level and result in higher costs, ultimately limiting the role of SSBs in the market especially by 2030. Nonetheless, supporting the development of advanced SSBs remains worthwhile, particularly for applications requiring long-range driving, such as electric medium freight and heavy freight trucks, and especially in markets where the establishment of widespread charging infrastructure or battery swapping is likely to face difficulties.

Lithium sulphur batteries also have the potential to make a mark in the EV battery market beyond 2030. Lithium sulphur batteries offer high energy density, cost effectiveness and the use of cathodes based on abundant and inexpensive sulphur. They can potentially make use of both liquid and solid electrolytes: liquid electrolytes have been undergoing R&D since the 1960s. Challenges remain, such as the tendency of polysulfide shuttling to lead to low cycle life, but efforts to overcome these challenges and develop solid-state lithium sulphur batteries are continuing.

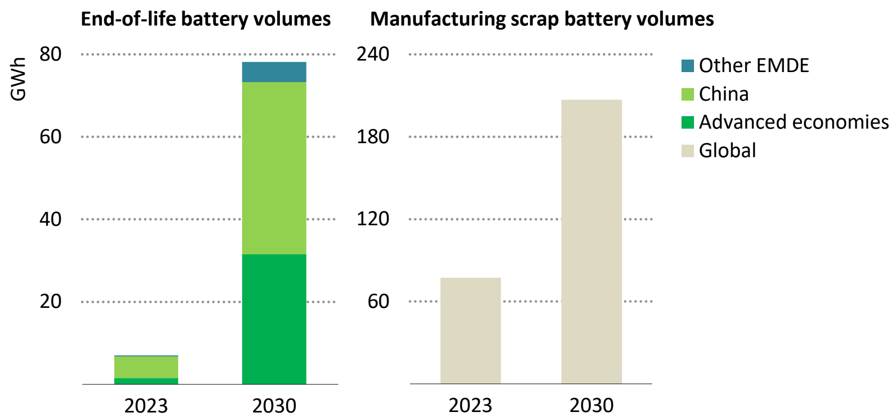
Box 2.2 ▹ EV battery recycling and reuse

The lithium-ion battery recycling process aims to reclaim valuable metals such as lithium, nickel, cobalt, copper and aluminium. Pyrometallurgy involves high-temperature smelting to recover cathode metals, while hydrometallurgy uses chemical leaching for metal separation. These two methods are often used together with poorly sorted feedstock. Direct recycling is an emerging method of recycling that preserves cathode structure, reducing the need for raw material synthesis. It suits cathodes with fewer valuable metals, such as lithium-iron phosphate, but requires customisation to each chemistry, limiting production to the same battery type (IEA, 2023b).

Battery recycling capacity worldwide currently is about 2 million tonnes per year, of which almost 85% is in China. A number of countries have plans to expand recycling capacity, though China is set to remain dominant. Manufacturing scrap, comprising around 10% of current battery cell components production, is the main recycling source (IEA, 2024a). Policy mandates like extended producer responsibility foster collaboration. Automotive industry, battery manufacturers, and mining and refining companies are gradually working more closely with independent recyclers.

Recycling rates are strongly influenced by policy, regulation and support for innovation. This provides policy makers a clear opportunity to enhance the lifetime sustainability of batteries. Battery passports and standardised tracking can streamline end-of-life collection, ensuring a stable flow for recyclers. Onsite recycling aids supply, while traceability enhances safety and high collection rates. Ambitious targets and R&D support cost decreases and prepare recyclers for handling diverse battery chemistries, fostering sustainability. As recycling is an expensive and energy-intensive process, operations may require support or incentives to help recyclers manage the impact of initiatives like the European Union Battery Regulation, which mandates a 70% recycling efficiency rate for lithium-ion batteries by 2030, including the less valuable LFP batteries that are expected to account for nearly half of global EV battery market share by 2030.

Figure 2.10 ⊳ EV annual battery volumes with potential for recycling by region in the STEPS, 2023 and 2030



Although limited today, almost 80 GWh of end-of-life and 210 GWh of manufacturing scrap-based EV battery volumes become available for recycling in the STEPS in 2030

Notes: GWh = gigawatt-hours; Other EMDE = emerging market and developing economies excluding China. Analysis assumes that EV batteries reach their end-of-life in the country in which they were originally sold.

Clear regulatory frameworks and standards are needed globally before 2030 to manage recycling and reuse of the rising number of EV batteries that come to the end of their life in vehicles. EV batteries could retain up to 70-80% of their capacity after their first use, therefore offer opportunities for second-hand EV markets and second-life applications. Second-life battery applications, like behind-the-meter and utility-scale storage, fast chargers and uninterruptible power supplies, enhance the environmental profile of batteries. However, the challenges involved in collection, dismantling and repackaging hinder the development. Second-life batteries currently offer limited cost savings compared to new batteries, potentially making their use outside of second-hand EV markets less appealing.

In the STEPS, nearly 80 GWh of EV battery volumes reach the end of their first life in 2030, with China accounting for more than half of volumes. Nonetheless, EV battery manufacturing scraps remains the main source of battery materials for recycling plants, with almost 210 GWh in 2030 (Figure 2.1). Scrap materials remain in nearly pristine state, making them easier and cheaper to recycle and feed back into the manufacturing plant. Efficient recycling is vital if minerals are to be recovered after full utilisation of EV batteries, with market prices guiding cost-effective routes, and policies and regulations underpinning support and ensuring sustainability.

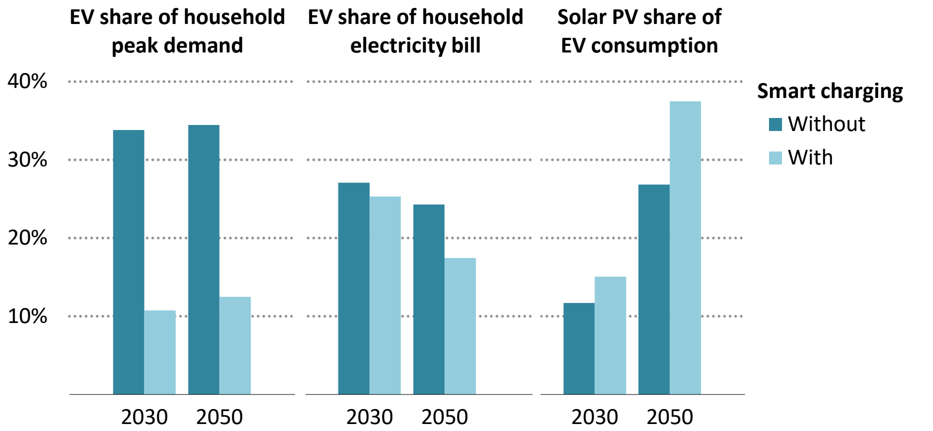
2.2.4 Evolving relationship between EVs and electricity networks

Batteries for EVs and storage are linked in several ways. First, there are synergies in manufacturing batteries for EVs and storage applications: production processes and manufacturing know-how from one industry can inform the other. Second, end-of-life EV batteries can acquire a "second life" by being repurposed to be used in storage applications. Third, EV batteries can supplement grid flexibility through programmable battery recharging schedules when plugged into home, work or public charging units – this is termed "smart charging". Fourth, EV batteries can offer bi-directional charging, allowing EVs to supply electricity either within a building (vehicle-to-building (V2B)), or directly into the grid (vehicle-to-grid (V2G)). While smart charging is a promising solution with a relatively straightforward implementation pathway, bi-directional charging faces some uncertainties related to the vehicle technical capability to offer the service, remuneration arrangements, potential enhanced degradation of the battery and warranty voidance.

Potential for smart charging

By optimising EV charging operations, smart charging can provide flexibility to power systems, reduce the need for grid reinforcements and public charging infrastructure, and help accommodate additional electricity demand. By reducing overall capacity and infrastructure requirements, it can also lower the demand for critical minerals such as copper. When paired with onsite renewables or a decarbonised grid, it can significantly reduce energy-related CO_2 emissions. When linked with smart tariffs, it can help consumers to cut their electricity bills.

Figure 2.11 ⊳ Smart charging benefits for an EV household, 2030 and 2050



Smart charging offers many benefits to an EV household, e.g. significant peak demand reduction, reduced utility bills and increased use of electricity generated onsite

Notes: Consumer response to dynamic tariffs via mono-directional charging is assumed in this analysis. The solar PV share in electricity consumption depends strongly on charging patterns of the home system.

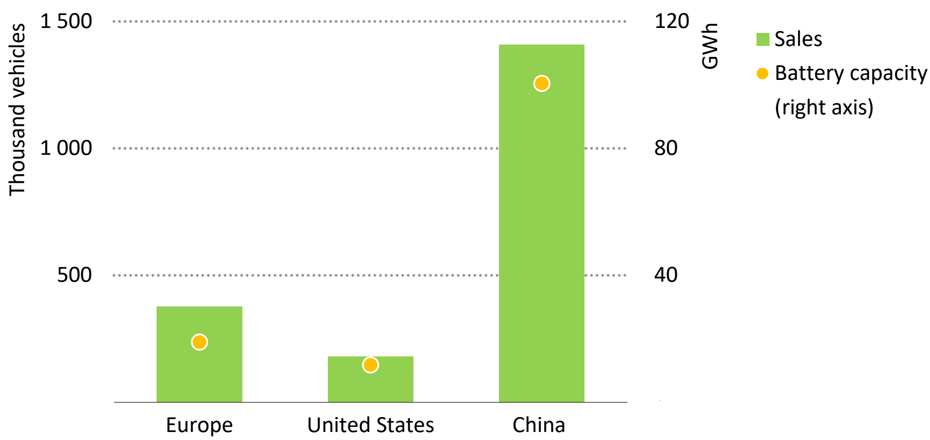
By 2030, smart charging could cut the contribution that EVs make to peak demand by more than two-thirds and reduce the average electricity bill of EV owners by nearly 10 percentage points (Figure 2.11). When paired with rooftop solar PV and smart charging, it could also increase an EV-owning household use of self-generated electricity by over 10 percentage points in 2050. A combination of batteries and smart charging could also reduce curtailment, thus improving overall system efficiency.

Vehicle-to-building and vehicle-to-grid connectivity

Given the size of the EV market, V2B/V2G, if rolled out at scale, could reduce demand for battery storage in the power sector. But there are technical, commercial and regulatory obstacles that reduce the likelihood of broad deployment of such approaches in the near term. EV batteries are typically designed for fewer number of cycles than batteries for storage applications, and additional charging and discharging may lead to faster degradation of the EV battery. Furthermore, V2B/V2G operations are usually not covered by EV battery warranties, further reducing their attractiveness to consumers. V2G is also facing many of the same regulatory hurdles with respect to access to potential markets and sources of revenue that other types of demand response and behind-the-meter battery storage solutions are facing (see Chapter 1).

A typical behind-the-meter battery storage system is approximately 10 kilowatt-hours (kWh) in size, while the average battery size of an electric car is 40-60 kWh. To provide several hours of supply to a household during peak times, an electric car battery would thus only need to discharge around 15-25% of its total capacity. This shallow depth of discharge could limit the impact on lifetime of the battery. At the same time, limited use of EV battery capacity for V2B/V2G applications results in lower economic benefits for the end-use consumer. The need to co-ordinate mobility and storage needs makes corporate fleets a more promising V2B/V2G market than individual households: fleets offer the combined advantages of battery application predictability and larger aggregated flexibility services. EVs equipped with LFP and sodium-ion batteries could be more suitable for V2B applications than NMC and lithium nickel cobalt aluminium oxide (NCA) batteries because of their lower cost and higher cycle life, though it remains to be seen whether sodium-ion batteries can develop a competitive advantage over LFP batteries.

Figure 2.12 ▹ V2G-capable light-duty vehicle sales by region, 2023



China leads with over 1.4 million V2G-capable LDV sales in 2023, which could make 100 GWh of new battery storage capacity available for V2G integration

Note: V2G = vehicle-to-grid; LDV = light-duty vehicle.

Today there are more than ten electric light-duty vehicle models with bi-directional charging capability. China leads for such models with over 1.4 million vehicles sold in 2023, which together could potentially make 100 GWh of battery capacity over time available for V2G integration (Figure 2.12). In Europe, fewer than 400 000 V2G-capable electric cars were sold in 2023, though this was about twice the sales in the United States. Taken together electric LDV sales in China, Europe and the United States represent around 130 GWh of V2G-capable battery capacity – an amount comparable to more than two-thirds the current global battery storage capacity.

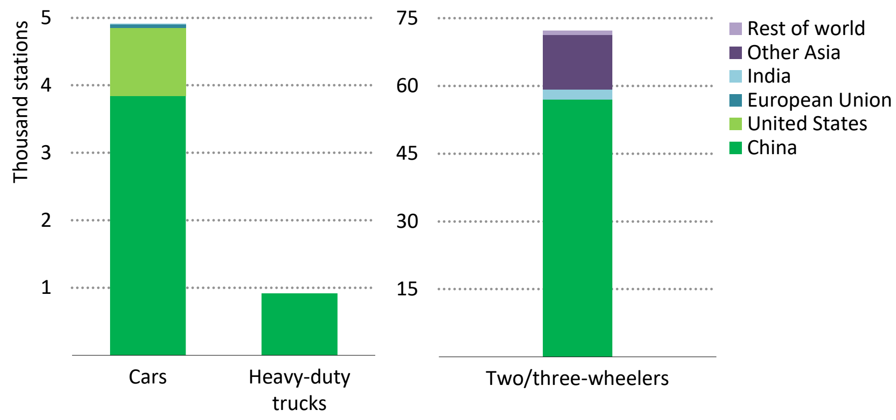
Box 2.3 ⊳ Battery swapping for deferred grid enhancement

Battery swapping is the process of replacing a depleted vehicle battery with a fully charged one at a battery swapping station. This approach offers recharge times that are twice as fast as ultra-fast charging. BSS operators lease batteries to consumers, significantly reducing upfront EV costs. Swap-capable EVs can be designed with a small battery for short trips to lower battery leasing costs or a larger battery for long journeys, or multiple small batteries for use as necessary. This model significantly enhances EV affordability (GF Securities, 2020).

High upfront costs of a battery swapping station requires high utilisation levels relative to an EV charging station to be competitive. They can yield a higher internal rate of return than plug-in stations once past the break-even point (Founder Securities, 2021).

Battery swapping offers potential benefits. It optimises battery usage by reducing grid impact and leveraging renewable electricity and it requires less land per vehicle than plug-in charging stations. The main drawbacks of battery swapping include the high capital investment needed and a reliance on standardisation of EV models. For such reasons, so far, some battery swapping businesses have not proven to be viable.

Figure 2.13 ⊳ Battery swapping stations by vehicle type and country/region, 2023



Today, China has the vast majority of battery swapping stations for cars and trucks and other Asia is notable for the two/three-wheeler market

Note: Heavy-duty trucks include medium freight and heavy freight trucks.

EVs equipped for battery swapping so far have been largely limited to China where they enjoy significant policy support (Figure 2.13). In 2022, only 2% of new EVs worldwide were swap-capable. In China they accounted for 4% of the EV market (Forbes, 2022). Progress has been particularly strong for trucks in China, where half of all electric heavy-duty trucks sold in 2023 were swap-capable (BNEF, 2024). China also hosts 80% of the world's battery swapping stations, with combined energy storage capacity of around 5 GWh – equivalent to the combined battery storage capacity of Japan, Korea and the United Kingdom (Fastmarkets, 2023). Battery swapping for two/three-wheelers is gaining traction in India and other Asian markets, especially where the vehicles are used for commercial purposes and cover long distances each day.

In addition to their benefits for busy drivers, battery swapping services have the ability to reduce the peak load of a grid, improve grid flexibility by operating like power storage stations and supports the grid with bi-directional charging. NIO and Aulton, an auto maker and a smart energy service platform provider, already employ peak load shifting in China. NIO's battery swapping station used over 2.3 GWh of clean electricity between 2021 and 2022. Operating in this way reduces the need for grid enhancements. In the STEPS, over 40% of two/three-wheeler sales in emerging market and developing economies outside China are electric by 2030, creating scope for those countries to benefit significantly from battery swapping technology.

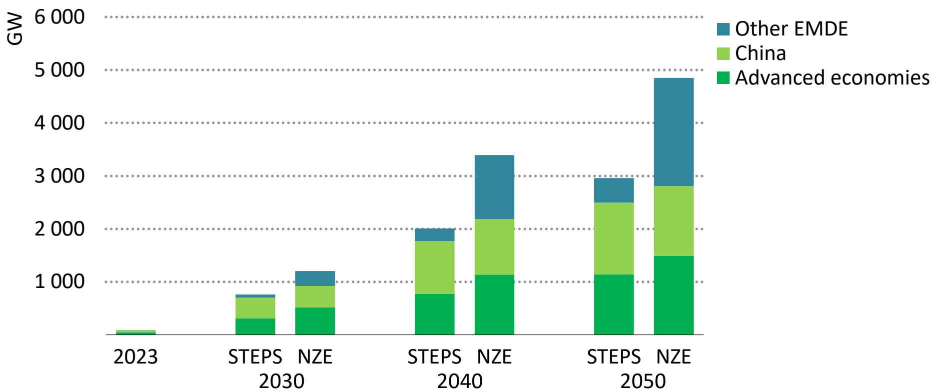
Battery swapping also provides benefits for the second-life battery market. The batteries of swap-capable vehicles can be extracted less expensively than others, creating a stronger economic foundation for reuse. Moreover, battery swapping stations constantly assess battery health using a centralised monitoring system. This provides an opportunity for battery tracking standardisation – one of the key barriers for the establishment of a second-life battery market.

2.3 Outlook for battery storage in the power sector

Global deployment of battery storage is projected to increase rapidly in the years ahead. Growing shares of variable renewables in power systems are increasing the utility of storage. At the same time, the cost of battery storage is falling and government support in many regions is rising. Total global installed battery storage capacity increases ninefold by 2030 from 86 GW in 2023 to over 760 GW in the STEPS (Figure 2.14). In the NZE Scenario, which sees a tripling of global renewable electricity generation capacity over the same period, total global installed battery capacity rises 14-fold to 1 200 GW by 2030.

Up until today, more than 95% of capacity growth has taken place in advanced economies, most notably the United States and European Union, and in China. These economies are projected to continue to lead the deployment of battery storage. In the STEPS, advanced economies account for roughly 40% of the global installed battery storage capacity in 2030, down from about 55% in 2023. Around 50% of the installed capacity is in China. Other emerging market and developing economies, especially India, are projected to see capacity growth accelerate over the period to 2030, with their share in global installed capacity rising to nearly 10% in 2030. In the NZE Scenario, the speed and breadth of the global roll-out of battery storage is greater than in the STEPS, with emerging markets and developing economies outside China seeing the largest relative increase in the growth of battery capacity: they account in 2030 for nearly 25% of global battery storage capacity, China for 35% and advanced economies for the remainder.

Figure 2.14 ▷ Global installed battery storage capacity by scenario, 2023-2050



Total installed battery storage capacity rises significantly in both scenarios, with strong growth in emerging market and developing economies outside China in the NZE Scenario

Note: GW = gigawatts; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; Other EMDE = Emerging market and developing economies other than China.

Strong growth is set to continue after 2030 as batteries become vital sources of short-term flexibility and secure capacity in power systems characterised by high shares of variable renewables. By 2050, global installed battery storage capacity rises to close to 3 TW in the STEPS and nearly 5 TW in the NZE Scenario.

As battery storage investment costs continue to fall and rising power system flexibility needs increase the utility of bulk energy shifting, the share of battery storage systems with durations between four and eight hours increases considerably relative to shorter duration systems in both scenarios, especially in regions with high shares of solar PV in the electricity mix. In the STEPS, the average duration of the global battery storage fleet increases from around two hours today to 2.7 hours in 2030 and 3.4 hours by 2050.

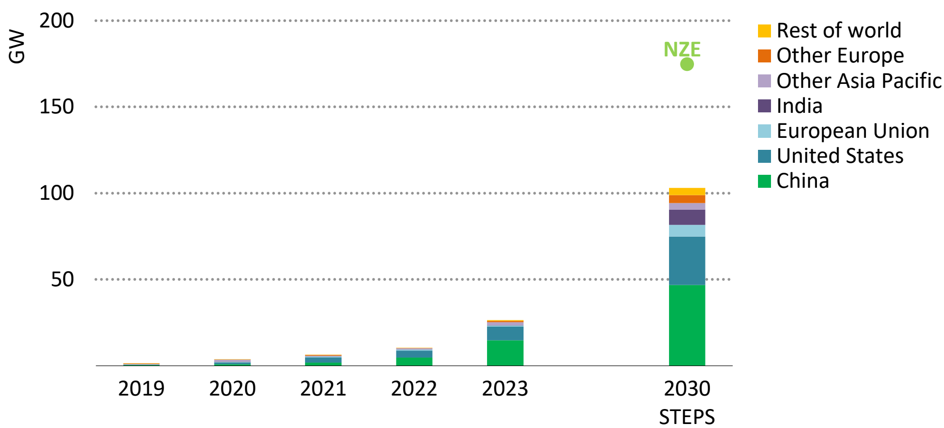
2.3.1 Regional outlook for battery storage

Strongly rising demand for battery storage means that annual battery storage capacity additions will continue to increase rapidly in the coming years. Annual additions of utility-scale battery storage capacity rise from 26 GW in 2023 to over 100 GW in 2030 in the STEPS and 175 GW in the NZE Scenario. Behind-the-meter storage continues to increase as well, with global annual additions rising from 15 GW in 2023 to 29 GW in 2030 in the STEPS and over 35 GW in the NZE Scenario.

Utility-scale battery storage

In the STEPS, annual utility-scale battery capacity additions in **China** increase by nearly 20% per year between 2023 and 2030 to over 45 GW (Figure 2.15). Much of this growth is driven by province-level regulation that requires the pairing of wind and solar PV projects with energy storage, and more generally by the rising flexibility needs associated with the increasing share of variable renewables in its power system (the combined share of wind and solar PV in China's electricity mix is projected to rise from about 15% today to over 35% in 2030). Market reforms designed to establish and open electricity and ancillary service markets are another factor driving battery capacity growth.

Figure 2.15 ▷ Global utility-scale battery storage capacity additions, 2019-2023, and by scenario in 2030



Utility-scale battery storage capacity additions expand significantly by 2030, mainly in China and the United States

The **United States** remains the second-biggest market for utility-scale batteries, with annual additions rising from close to 8 GW in 2023 to 28 GW in 2030 in the STEPS. State-level energy storage targets and the Inflation Reduction Act storage tax credit are expected to drive and support this growth, with many utilities looking to battery storage to help achieve renewable energy targets, reduce the emissions intensity of their electricity mix, and increase the reliability of power supply.

Capacity additions in **India** are projected to accelerate considerably over the next seven years, rising to nearly 9 GW in the STEPS, and making India the world's third-largest market for utility-scale batteries in 2030. Strong growth in PV capacity will drive up short-term flexibility needs and increase the utility of energy storage. India has issued regulations requiring wind and solar PV projects to pair at least 5% of their installed capacity with storage.

Utility-scale battery capacity additions in the **European Union** rise from less than 1 GW in 2023 to around 7 GW in 2030 in the STEPS. Several EU member states have already set energy storage targets, and the EU's electricity market reforms will require all member states to establish energy storage targets as part of their National Energy and Climate Plans. The rising share of wind and solar PV, paired with onsite storage in some countries, is expected to support this growth, as is rising demand for secure capacity.

In the **United Kingdom**, annual capacity additions increase in the STEPS from under 1 GW today to 3 GW in 2030, much of it contracted through the capacity market.

Australia, **Japan** and **Korea** remain the largest markets for utility-scale storage in the Asia Pacific outside China and India, with combined additions rising to 3 GW by 2030. Australia supports the roll-out of utility-scale battery storage through its Capacity Investment Scheme, which seeks to facilitate the integration of rising shares of variable renewables and fill the gap left by the planned retirement of significant amounts of coal-fired capacity over the coming years. Near-term growth in Japan is underpinned by subsidies, and upcoming capacity auctions for low-carbon capacity will provide a potential additional revenue stream for utility-scale battery storage.

Annual utility-scale battery storage capacity growth in **Central and South America**, the **Middle East** and **Africa** starts to accelerate around 2030 in the STEPS as capital costs continue to decline and as rising shares of variable renewables increase power system flexibility needs.

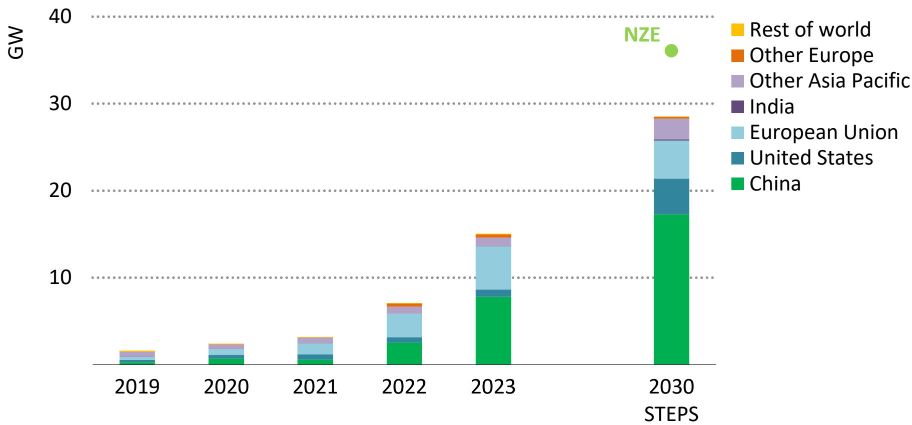
The NZE Scenario sees stronger and more broad-based growth in battery storage capacity. By 2030, global utility-scale battery storage capacity additions are 1.7-times their level in the STEPS. Batteries play a crucial role to support an accelerated roll-out of renewables. They also provide much-needed dispatchable capacity as the rapid electrification of end-uses increases peak demand and as coal power plant fleets are phased out around the world.

Behind-the-meter battery storage

Global behind-the-meter battery storage capacity continues to increase steadily in the STEPS, and total annual capacity additions nearly double from their 2023 level by 2030. Growth occurs mainly in regions that are already seeing the bulk of the additions of behind-the-meter storage today, encouraged by subsidies, high end-user electricity prices or the proliferation of time-of-use pricing. The conditions that support the adoption of behind-the-meter battery storage are discussed in more detail in section 2.3.5 .

China remains the leading market for behind-the-meter battery storage, with annual capacity additions rising in the STEPS from nearly 8 GW in 2023 to 17 GW in 2030 (Figure 2.16). China differs from most other regions in that many of its behind-the-meter systems are relatively large installations by commercial and industrial consumers seeking to benefit from time-of-use pricing and are close to utility-scale systems in terms of size and cost. Some provinces have mandated the pairing of solar PV installed by commercial and industrial consumers with energy storage. Both factors are expected to continue to drive additions in capacity.

Figure 2.16 ⊳ Global behind-the-meter battery storage capacity additions, 2019-2023, and by scenario in 2030



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Behind-the-meter battery storage additions nearly double by 2030, with the biggest markets in China, the United States and European Union

With annual growth of around 5 GW per year to 2030 in the STEPS, behind-the-meter battery storage capacity additions remain broadly stable in the **European Union**. Germany and Italy have been responsible for most of the growth so far. In Germany, rooftop solar PV is commonly paired with battery storage and attachment rates currently approach 80%. Capacity growth is set to decline in Italy as subsidies expire, but additions are projected to continue to increase in Germany, where high domestic electricity prices and declining equipment costs are expected to more than offset a gradual phase down of subsides.

The **United States** becomes the third-largest market for behind-the-meter storage in the STEPS. Annual capacity additions increase from slightly less than a gigawatt in 2023 to nearly 4 GW in 2030. California, where residential rooftop solar PV is frequently paired with battery storage, has been leading the way and will continue to play an outsized role through to 2030, followed by Florida and Texas. Falling costs, lower feed-in tariffs for solar and the proliferation of time-of-use tariffs all contribute to the attractiveness of behind-the-meter battery storage to consumers.

Australia and **Japan** are the second- and third-most important markets for behind-the-meter storage in the Asia Pacific region. Government subsidies mean that investing in behind-the-meter storage will remain financially attractive to consumers in both countries, in particular when paired with rooftop solar PV.

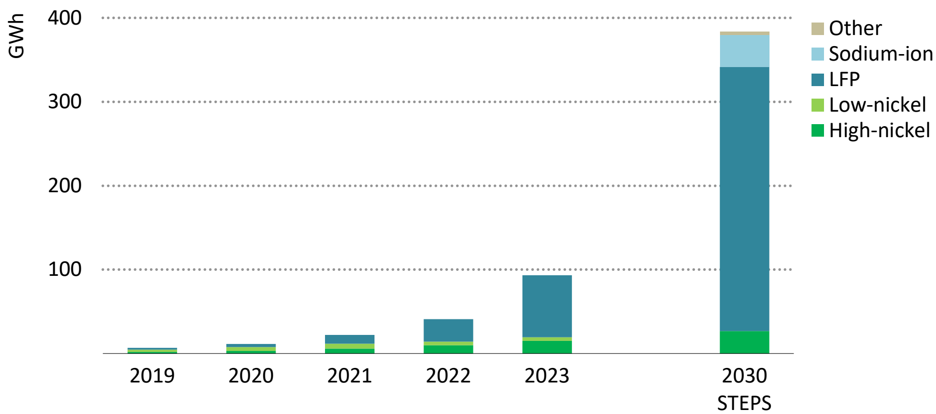
In **other regions**, conditions for behind-the-meter battery storage are less favourable. While the number of installations is expected to increase in places with frequent outages and low reliability power supplies, such as South Africa, their contribution to total global capacity growth is likely to remain marginal.

In the NZE Scenario, behind-the-meter battery storage capacity additions increase more rapidly. By 2030, they are about 25% higher than in the STEPS, thanks to stronger growth in rooftop solar PV, a faster decline in costs, and high end-user electricity prices, all of which increase the attractiveness of behind-the-meter storage to consumers.

2.3.2 The evolution of the chemistry mix

Lower costs, higher cycle lives and improved safety due to greater thermal stability mean that LFP batteries – although less energy dense than nickel-based lithium-ion batteries – have become the technology of choice for battery storage in recent years, with their share in annual battery storage capacity additions rising from about a third in 2020 to 80% in 2023. These characteristics seem likely to mean that LFP remains the dominant chemistry through to 2030, accounting for the vast majority of the additional battery storage capacity coming online between 2023 and 2030 (Figure 2.17).

Figure 2.17 ▷ Battery storage capacity additions in GWh by cathode chemistry, 2019-2023, and 2030 in the STEPS



LFP is set to continue to dominate the battery storage market, with sodium-ion starting to make inroads towards 2030

Note: LFP = lithium-iron phosphate.

In recent years, sodium-ion batteries have attracted considerable interest from battery manufacturers because they do not require relatively expensive critical minerals like lithium and could potentially be produced at a lower cost than LFP batteries. Although slightly less energy dense, they share many of the characteristics of LFP batteries, including greater thermal stability and higher cycle lives than other types of battery, and this makes them potentially well suited for stationary storage applications. However, the cost advantage of sodium-ion batteries will only be realised once manufacturing is scaled up to levels comparable to lithium-ion batteries, and even then it very largely depends on the price of lithium, which has recently declined, but could rise again as demand grows: competing on cost will be challenging if lithium prices remain low. There is considerable announced manufacturing capacity, most of it located in China. As a result, we expect sodium-ion to start making inroads into the battery storage market towards 2030 in all scenarios, with its share in annual capacity additions rising to about 10% by 2030 and growing further beyond.

Alternative battery chemistries like redox flow or iron air could come into play after 2030, in particular for longer-duration (greater than eight hours) storage. However, many technical challenges remain to be solved. While redox flow batteries based on vanadium are already relatively mature, vanadium is currently very costly, and the main challenge will be to substantially scale up its production. Solid state batteries, although potentially promising for high energy density applications like EVs, are unlikely to be a competitive choice for battery storage in the power sector, where energy density is a less important consideration.

2.3.3 Role of battery storage

Battery storage can provide a broad suite of services to the electricity system, ranging from energy shifting through to the provision of ancillary services and secure capacity, and the management of bottlenecks in transmission and distribution systems.

The fast-rising share of variable wind and solar PV in power systems around the world, coupled with an increase in the volume and variability of demand due to the electrification of additional end-uses, such as EVs, air conditioning and electric heating, is driving a substantial increase in the need for power system flexibility, in particular over shorter timescales ranging from minutes to days. At the same time, the phase-out of coal in many regions and rising peak demand are increasing the need for additional dispatchable capacity to ensure adequacy of supply.

Battery storage is well placed to provide both short-term flexibility and secure capacity in power systems with rising shares of variable renewables, especially with a shift towards longer duration (four to eight hour) battery storage. In all scenarios, battery storage becomes a key provider of short-term power system flexibility, in particular after 2030. Together with smart charging EVs, they provide over half of the global short-term flexibility required in 2050. They also become a vital source of secure capacity in hours with high electricity demand and low output from renewables.

Beyond energy shifting, batteries are expected to make further inroads in ancillary service markets in regions where they have not done so already, though the share of battery storage targeting this application is set to decline as these markets become saturated and as the global battery fleet expands considerably.

Further growth is also expected in the number of battery storage systems whose primary role is congestion management and transmission/distribution investment deferral, in particular in regions where the expansion of power grids lags behind the growth in the share of variable renewables and the pace of end-use electrification. In emerging market and developing economies with weaker electricity grids, batteries are likely to be increasingly tapped to provide essential services beyond energy shifting and to help increase the reliability of power supplies, with an eye to functionalities such as black start capability, islanding and grid stabilisation at the local level. Batteries providing these services however are likely to account for a small share of global battery capacity compared to those that provide flexibility and secure capacity through bulk energy shifting.

Although batteries will play a crucial role in providing flexibility, stability and secure capacity to power systems characterised by high shares of variable renewables, it is important to recognise that they are part of a suite of options that includes demand response, other types of storage such as pumped storage hydro, thermal or compressed air energy storage, and flexible hydro and thermal power plants. All these options will be needed to provide flexibility and capacity to ensure secure, decarbonised and affordable electricity supply at all times. For example, pumped hydro capacity is targeted to reach 120 GW in China by 2030 and 27 GW in India by 2032. Digitalisation, which improves real-time information flows and facilitates more advanced data analytics, has an essential part to play here as an enabler for power system transformations relying on distributed assets like renewables and batteries.

Should battery storage grow more slowly than expected, there would be significant risks for clean energy transitions (see Chapter 3), and energy systems would need a significant push towards alternative solutions for the provision of short-term flexibility and for meeting peak demand in a secure manner. Relying on unabated fossil fuel capacities to compensate for the lack of batteries would lead to an increase in CO_2 emissions and make reaching emissions reduction targets more difficult and more expensive.

Provision of flexibility

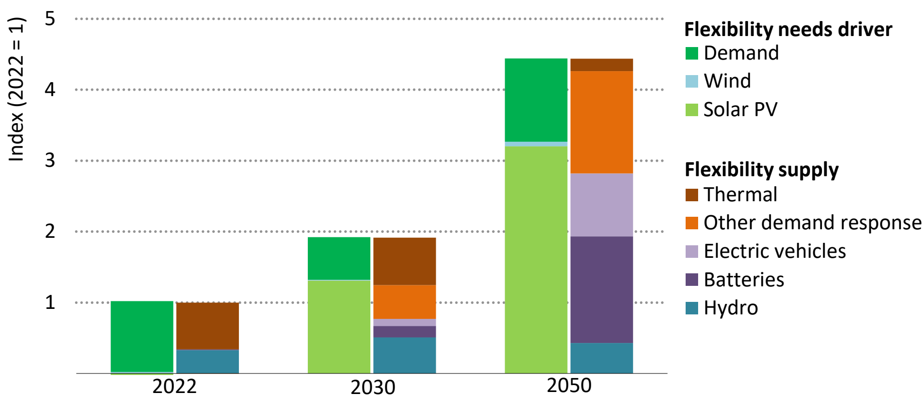
Battery storage is set to become an important source of short-term flexibility in power systems around the globe.

Power system flexibility needs are driven primarily by the rising share of variable wind and solar PV in electricity generation and by changes in electricity demand profiles. Flexibility needs are defined over specific timeframes, ranging from milliseconds (to ensure grid stability) to short-term flexibility (hourly balancing) and seasonal flexibility needs (seasonal balancing). The share of wind and solar in the global electricity mix rises from 12% today to 30% in 2030 and 54% in 2050 in the STEPS. In the NZE Scenario, which sees a tripling of the installed renewable energy capacity by 2030, it increases to 40% in 2030 and 71% in 2050. In the APS, which assumes that governments around the world meet their energy and climate pledges in full and on time, the share of wind and solar reaches 35% in 2030 and 64% in 2050.

Rising shares of wind and solar PV increase the variability of the net load – the load that remains after removing wind, solar and run-of-river hydro generation from electricity demand – while the electrification of additional end-uses, e.g. electric heating, road transport or industrial processes, raises peaks and increases the variability of electricity demand. Together they drive up power system flexibility needs. While these needs increase across all timescales from hours to days and across seasons, it is short-term flexibility needs, which measure the variability of the net load from one hour to the next, that see the sharpest increase overall.

Most of the projected increase in short-term flexibility needs worldwide is driven by the growth of solar PV, which, with its pronounced daily cycle, increases the hourly variability of the net load. The increase in the variation of demand is the second-biggest driver: wind is less variable than solar over short periods of time and thus does not contribute as much to the overall increase in short-term flexibility needs. In the APS, for example, average global short-term flexibility needs double by 2030, driven largely by a tripling of global solar PV capacity and a 26% increase in annual electricity demand. These flexibility needs subsequently increase 4.5-fold by 2050 from their current level. (Figure 2.18).

Figure 2.18 ▻ Global average short-term power system flexibility needs and supply in the APS, 2022-2050

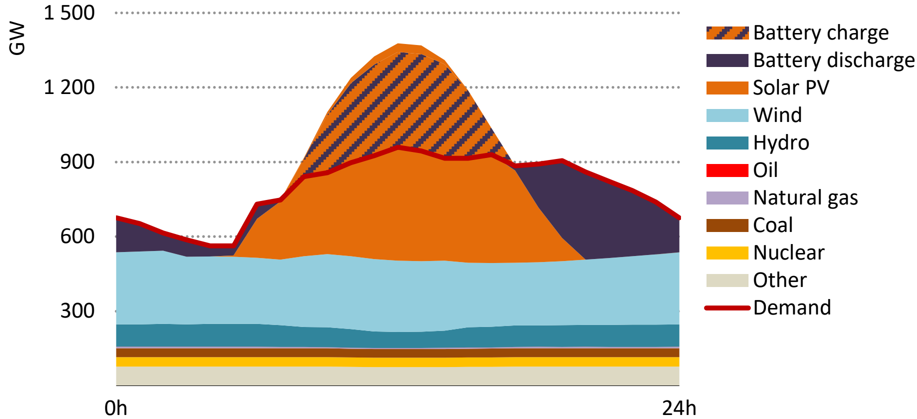


Battery storage and directed charging of EVs provide the bulk of the short-term flexibility needs that rise 4.5-fold by 2050

Notes: Other demand response includes the flexible operation of electrolysers, and flexible thermal storage for water and space heating/cooling in buildings, and other appliances. The figure represents the global average and therefore does not include the contribution of imports or exports.

Today, short-term power system flexibility needs are met mostly by hydro and dispatchable thermal power plants capable of rapidly responding to variations in the net load. However, battery storage is set to become an important source of short-term flexibility in many power systems by 2030 as renewables are scaled up and traditional providers of flexibility such as coal-fired power plants are retired. The flexibility provided by batteries lies in their ability to shift electricity generation from periods with surpluses to periods in which the net load is high. Since batteries are primarily for short duration storage, they are well suited to smooth the daily cycle of solar PV-based electricity generation. This is illustrated in Figure 2.19, which shows how batteries charge during the hours when solar PV is producing and discharge afterwards. In competitive electricity markets, utility-scale battery storage responds to market price signals, optimising its charging and discharging cycles to maximise its revenue.

Figure 2.19 ▷ Hourly electricity supply mix for a sample day in India in the APS, 2050



Battery storage takes advantage of surplus solar generation to charge during the day and discharge during evening peak load

The batteries housed in EVs represent another significant source of flexibility. While uncontrolled EV charging by vehicle owners increases short-term flexibility needs because it takes place mostly at home in the evening, delaying and timing this charging in accordance with system needs (smart charging) can provide much-needed flexibility and help balance the variations introduced by other electricity consumers or variable renewables such as solar PV. In the APS, between 10% and 20% of EVs are able to adjust their charging in response to electricity prices by 2030, rising to 40-60% by 2050, depending on the region.

EV users will need incentives to engage in smart charging either by taking action themselves or by allowing some remote control of their energy use. Time-of-use tariffs provide a financial incentive to encourage the shifting of EV charging to off-peak hours and are likely to be increasingly important in the future. The flexibility potential would be even greater if EVs were able to feed electricity back into the grid (V2G), thus effectively doubling as behind-the-meter storage (see Chapter 3). In the APS, battery storage and smart charging EVs together provide 15% of the short-term flexibility needed to balance the system by 2030. Their importance continues to increase by 2050, battery storage and EVs provide over half of the total short-term flexibility needed for power systems, with demand response meeting an additional third of the requirements. Whether through different forms of batteries in EVs or storage applications, thermal energy storage or pumped hydro, storage will cover the majority of short-term flexibility requirements by mid-century.

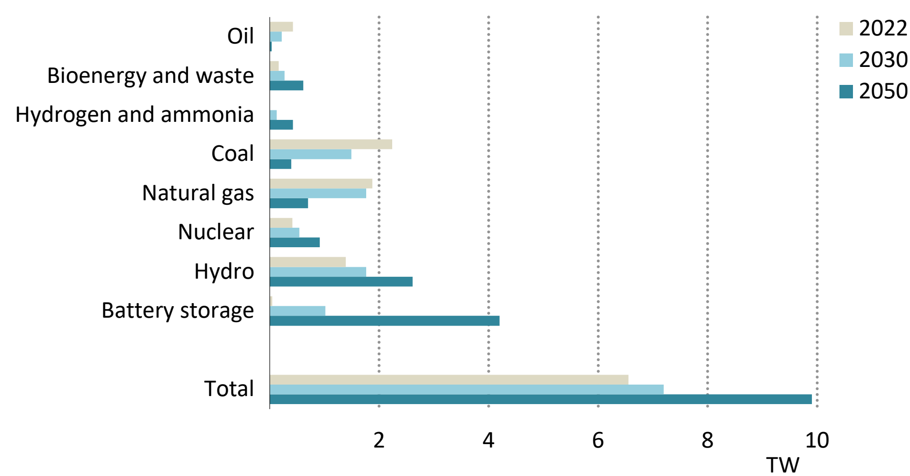
While batteries are projected to play an important role in the provision of short-term flexibility, our analysis indicates that they are poorly suited to balancing over longer periods of time, such as across weeks or seasons. Options for seasonal flexibility include reservoir hydro, the flexible operation of thermal power plants, including low-emissions thermal power plants, and further in the future, the flexibility provided by electrolysers producing hydrogen and hydrogen-based fuels. More details on the future development of flexibility needs and supply across all timescales, including across various regions located in different climatic zones, can be found in the IEA report *Managing the Seasonal Variability of Electricity Demand and Supply* (IEA, 2024b).

Contributions to capacity adequacy

Battery storage also provides secure dispatchable capacity to help meet peak demand, ensuring a stable and reliable supply of electricity. Discharging batteries during peak hours reduces the need for additional secure capacity from other sources, such as thermal peaking power plants like gas turbines.

Owing to the increasing competitiveness of utility-scale battery storage with other sources of dispatchable capacity (section 2.3.4), the share of batteries in total dispatchable power capacity is set to rise substantially (Figure 2.20). Conventional unabated fossil fuel power plants currently account for 70% of available dispatchable capacity, while hydropower and nuclear contribute a quarter between them. In the NZE Scenario, batteries constitute one-eighth of the available dispatchable capacity by 2030, while the share of unabated fossil fuels decreases to below 50%. By 2050, batteries become the primary source of dispatchable capacity globally, with installed capacity exceeding 4 TW.

Figure 2.20 ▷ Dispatchable power capacity by technology in the NZE Scenario, 2022, 2030 and 2050



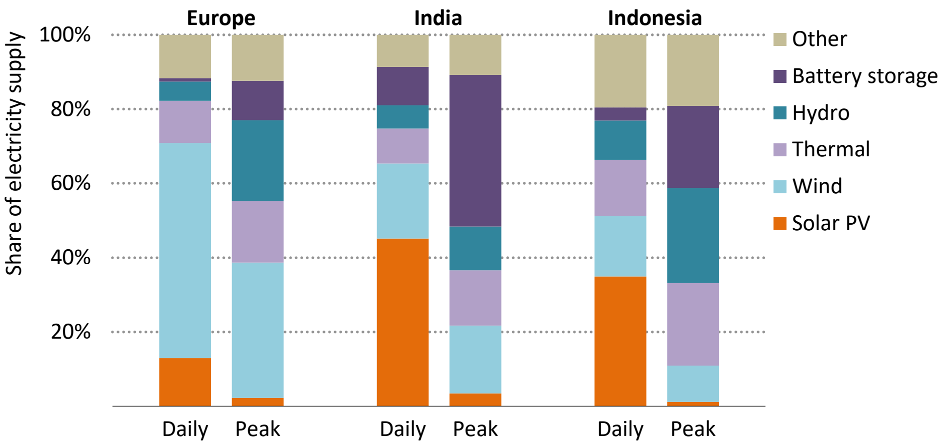
Utility-scale battery storage expands rapidly to become the largest source of dispatchable capacity by 2050

Notes: TW = terawatts. Hydrogen includes hydrogen and hydrogen-based fuel fired power plants.

As its installed capacity increases, battery storage is increasingly called upon to provide electricity in periods when the electricity system is short on capacity. Traditionally, the assessment of power system adequacy is based on its ability to meet peak demand. However, in systems characterised by high shares of variable renewables, the times during which the system is short on supply are the peak hours of the net load, when electricity demand is high, and the availability of variable renewables is low. In these hours, dispatchable sources tend to produce at close to the maximum of their available capacity.

Battery storage can make a significant contribution to the electricity supply during these hours. This is illustrated in Figure 2.21, which presents the electricity supply mix for selected regions – Europe, India and Indonesia —during the 100 hours of the year with the highest net load, compared to the average daily electricity supply mix, as projected for the APS in 2050. It highlights that battery storage is set to become a crucial provider of secure capacity when the net load peaks and systems are short on supply. This is particularly the case in systems with a high proportion of solar PV. In regions like India or Indonesia, where solar power becomes a major component of the electricity mix, battery storage can be charged during the day when solar power generation is at its peak. These charged batteries can then supply electricity during the evening when demand typically peaks, or is at any rate high, and solar generation is not available. Their ability to fulfil this role will be facilitated by the significant increase in battery storage projects with longer durations (four to eight hours) that is projected in regions with high shares of solar PV.

Figure 2.21 ▹ Daily average and peak hour electricity supply mix by region/country in the APS, 2050



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Batteries emerge as key providers of dispatchable capacity during peak hours when demand is high and variable renewable generation is lower than average

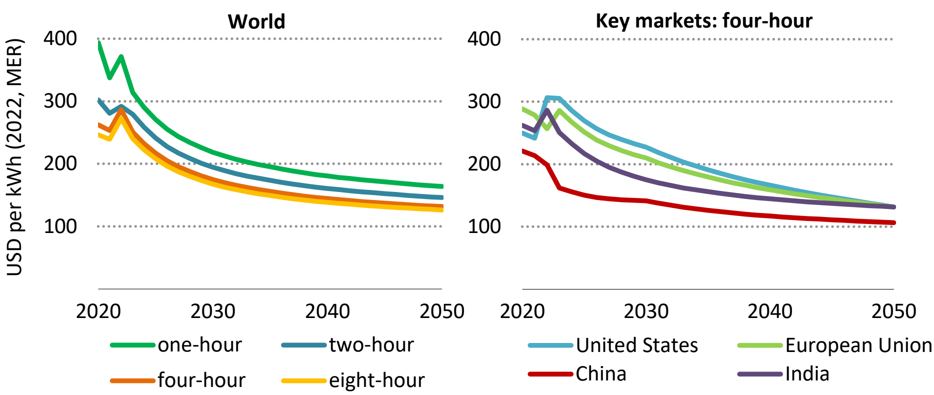
Notes: This figure shows the average electricity supply mix over a day and the electricity supply mix in the 100 hours of the year with the highest net load (electricity demand less the contribution of wind, solar PV and run-of-river hydro). Thermal includes coal, natural gas, nuclear, oil and hydrogen/ammonia. Other includes bioenergy, geothermal, marine and waste.

2.3.4 Costs and competitiveness of utility-scale battery storage

Capital costs of utility-scale battery storage

The costs for individual utility-scale battery storage projects can vary widely, depending on specific site conditions, technology choices and regulatory regimes, with some recent projects delivered for over USD 500/kWh and others for less than USD 200/kWh. However, in the STEPS, the total upfront costs of utility-scale battery storage with four-hour duration are projected to decline from a global average of USD 290/kWh in 2022 to an average of USD 175/kWh in 2030, a reduction of 40% over the period (Figure 2.22). After 2030, average utility-scale battery storage costs are projected to continue to decline, and in 2050 they are 55% below their 2022 level.

Figure 2.22 ▹ Average total system capital costs of utility-scale batteries globally and in key markets in the STEPS, 2020-2050



Total upfront costs of utility-scale battery storage decline 30-40% by 2030, with the cost range narrowing in key markets

Note: MER = market exchange rate.

This decline in average costs in the STEPS means that the upfront investment for an average battery project with a 20 MW output capacity and 80 MWh storage declines from about USD 23 million today to USD 14 million in 2030. it follows recent fluctuations in the costs of battery storage, during which supply chain issues and critical mineral prices raised the delivered cost of battery storage in several leading markets. Battery storage projects with longer duration generally have a lower cost per unit, as project costs are spread across more units and there are economies of scale for the balance of system costs. Some regions see even larger reductions in total battery project costs, including the costs of the battery pack as well as racking, cooling, management and system balance.

Regional average upfront costs for utility-scale battery storage with four-hour duration currently vary from USD 200/kWh to over USD 300/kWh, but this range narrows over time as more markets gain experience and take advantage of new technologies. China is the lowest cost region for new battery storage projects today and is projected to remain so through to 2030. Recent costs of utility-scale battery storage projects in the United States and Europe are at the higher end of the range today, but broader markets and more extensive deployment drive down future costs. In India, strong growth in the battery storage market enables deep cost reductions.

Projected cost reductions come from improvements in battery technology and manufacturing, together with reductions in the balance of system costs for battery storage, which could be accelerated by standardisation. Battery pack costs are driven down both by learning from experience as they are deployed in storage applications and by spillover reductions from their development for transport. The projected future reductions for balance of system costs are based on local and global deployment combined with an assumed learning rate of 10% per doubling of cumulative installation. However, consideration of upfront costs alone has limitations because improvements in performance, efficiency and longevity are not captured.

In the NZE Scenario, utility-scale battery storage costs are projected to decline more rapidly, falling 40% by 2030. The additional deployment of battery storage in this scenario compared with the STEPS pushes battery storage down the cost curve faster in terms of both technological innovation and the manufacturing process.

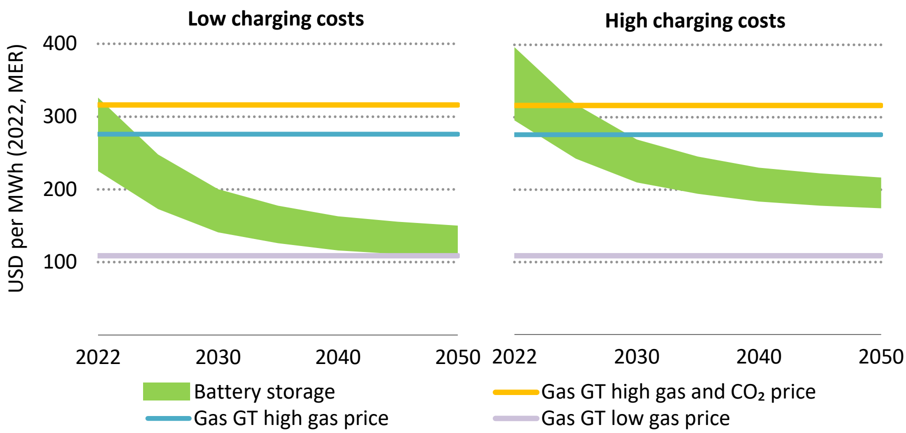
Stand-alone utility-scale storage

Levelised cost of electricity (LCOE) is a common metric encompassing all costs related to a power technology, including upfront investment, financing costs, operation and maintenance, fuel costs and carbon pricing where relevant. It is often used as a metric for power plants and can be used similarly for the average cost of battery storage, if the charging costs are considered as fuel costs. It can be applied to battery storage in stand-alone applications or when paired with other technologies, such as solar PV. For technologies that operate in similar ways, the LCOE provides a suitable metric for comparison.

For utility-scale battery storage in stand-alone applications, the global average LCOE for a project with four-hour duration declines by over 30% from 2022 to 2030 in the STEPS, falling from around USD 360/MWh to USD 240/MWh (Figure 2.23). The average cost of the same project declines to USD 180/MWh by 2050. Throughout the period, the LCOE of individual projects is projected to vary by approximately 20% from the average, depending on specific technology costs and average charging costs. In the NZE Scenario, the LCOE of battery storage is projected to decline even faster as capital costs edge down more rapidly and innovation improves performance and durability.

The cost reductions for utility-scale battery storage in the STEPS make it increasingly competitive with open-cycle gas turbines, even before considering the environmental costs of local air pollution or CO_2 emissions. This is a reasonable LCOE comparison to make, since utility-scale battery storage and open-cycle gas turbines both operate in a small number of the most valuable hours while also providing significant flexibility and supporting grid stability. Analysis indicates that four-hour duration battery storage can have a comparable level of availability as open-cycle gas turbines during peak periods, though forecast errors can substantially reduce this for batteries (often referred to as the capacity credit) (Awara et al., 2023).

Figure 2.23 ▷ Indicative LCOE of stand-alone battery storage in the STEPS compared with open-cycle gas turbines, 2022-2030



Stand-alone four-hour battery storage becomes competitive with many gas turbine plants by 2030 and competes with the even cheapest gas turbine plants by 2050

Notes: LCOE = levelised cost of electricity; MER = market exchange rate; gas GT = gas-fired turbine. Battery storage represents utility-scale battery storage with four-hour duration. Assumed capital costs for gas GT are USD 500/kilowatt. Gas GT high gas and CO_2 category assumes prices of USD 15/megawatt-hour (MWh) for natural gas and USD 60 per tonne for CO_2 emissions. Gas GT high gas category price assumes prices of USD 15/MWh for natural gas and zero for CO_2 emissions. Gas GT low gas category assumes prices of USD 3/MWh for natural gas and zero for CO_2 emissions. Low charging costs in left chart assume a USD 20/MWh electricity price for battery charging and high charging costs in the right chart assume a USD 80/MWh electricity price.

By 2025, battery storage projects at the lower end of the cost range are cost competitive with some open-cycle gas turbines operating in markets with high natural gas prices. By 2030, stand-alone battery storage is able to compete on costs with gas turbines in more markets and in a wider set of conditions, though gas turbines remain more competitive in markets with low natural gas prices, such as the United States and producer economies. By 2040, an average battery storage project is fully cost competitive with an average open-cycle gas turbine and is less expensive in markets with higher natural gas prices.

Comparing the costs of utility-scale battery storage with other storage technologies depends largely on the application and on local conditions, and many rival technologies are not yet commercially available.[6] Comparisons with pumped hydro – the largest form of energy storage in the world today – depend critically on the intended duration and annual discharge cycles. For durations of less than four hours, battery storage today generally has a lower LCOE than pumped hydro. As the duration gets longer, pumped hydro becomes more attractive. For durations beyond eight hours, pumped hydro has a clear cost advantage over battery storage in most cases. Specific site conditions, including the local geology, existing slope and land cover, are critical for the development costs for pumped hydro, and lead to a wide range of individual project costs; battery storage is better suited to a standardised project design and process than pumped hydro, and the costs of individual projects vary less. Heat storage is another promising technology, though in most cases it produces heat as a final product rather than electricity and so is difficult to compare on an LCOE basis. Gravity storage is also less developed than battery storage, and cost estimates for early projects vary widely.

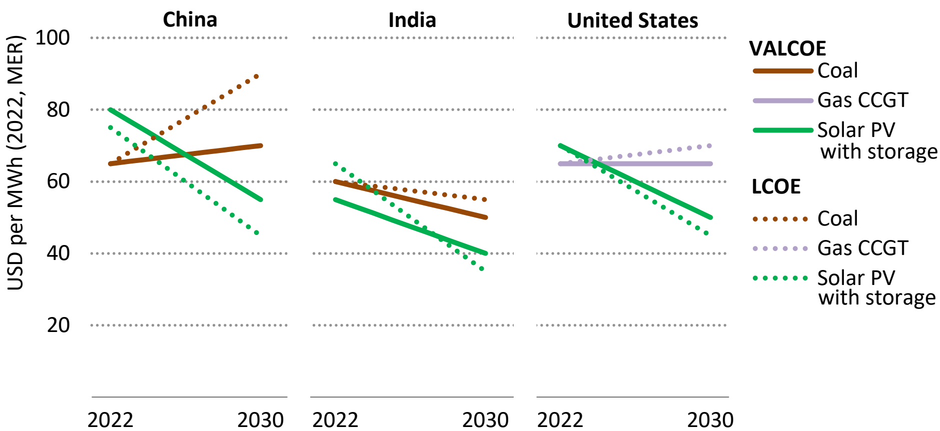
Utility-scale battery storage paired with solar PV

Battery storage is well suited to being paired with solar PV: it can charge and discharge efficiently so as to maximise the value of its output as conditions change, and it is designed for thousands of cycles, enabling it to cope with one or more cycles per day over a decade or more. The global average LCOE of an example project pairing battery storage with solar PV – 20 MW/80 MWh battery paired with 100 MW solar PV – declines from USD 75/MWh in 2022 to USD 45/MWh in 2030 in the STEPS, a 40% reduction (Figure 2.24). This combines the cost reductions for battery storage, around 40% by 2030, with those of utility-scale solar PV, about 35% by 2030. Further learning-by-doing and innovation drive down the average costs of this example project to USD 35/MWh in 2050, more than 50% below the current level.

In evaluating the competitiveness of battery storage paired with solar PV against other power technologies, the significant differences in their operations mean it is not enough to look at the LCOE alone. In these circumstances, assessment requires consideration of the value of the contribution made to power systems as well as technology costs. In the Global Energy and Climate model, the competitiveness of power technologies is based on the value-adjusted LCOE for each technology, which combines the projected LCOE with the value of the technology to the system in terms of contributions to energy markets, flexibility services and capacity adequacy. This provides a system view of the competitiveness of technologies and is analogous to investors evaluating both the costs and expected revenues of potential projects. The value-adjusted LCOE of battery storage paired with solar PV can be estimated within this framework and compared with all types of power technologies

[6] The levelised cost of storage is another metric that has been developed and applied for comparisons among the suite of energy storage technologies (Schmidt & Staffell, 2023), (Jülch, 2016), (Zakeri & Syri, 2015), but is not applied in the Global Energy and Climate model.

Figure 2.24 ▷ LCOE and value-adjusted LCOE for solar PV plus battery storage, coal and natural gas in selected regions in the STEPS, 2022-2030



Solar PV plus battery storage becomes more competitive than new coal- and natural gas-fired plants in key markets by the mid-2020s

Notes: LCOE = levelised cost of electricity; VALCOE = value-adjusted LCOE; MER = market exchange rate; CCGT = combined cycle gas turbine. Solar PV with storage = solar PV installation paired with four-hour duration battery storage, scaled to 20% of the output capacity of the solar PV.

Solar PV plus battery storage is already competitive with coal- and natural gas-fired power in some markets. Based on comparisons of the value-adjusted LCOE in the STEPS, its competitiveness will soon spread to most leading markets, opening massive potential for growth. In China, the value-adjusted LCOE of solar PV plus battery storage falls below that of coal-fired power around 2025 in the STEPS. In India, solar PV plus battery storage is already more competitive than coal, and it remains so in the years ahead. In the United States, solar PV plus battery storage outcompetes new efficient gas-fired power plants before 2025 and substantially extends its lead by 2030. In the European Union, solar PV plus battery storage already easily outcompetes natural gas-fired power, thanks in part to the relatively high natural gas prices in the European Union and relatively low utilisation rates for gas-fired power plants together with the significant price placed on CO_2 emissions.

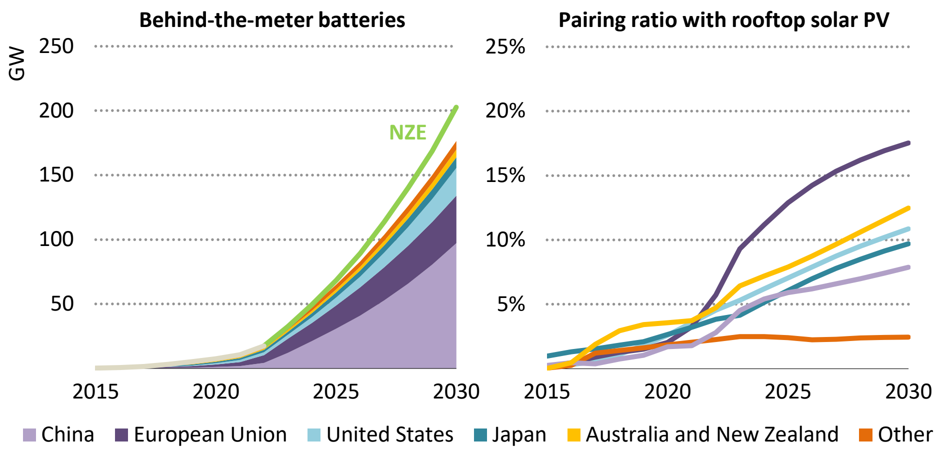
Batteries paired with solar PV are also highly competitive with other low-emissions sources of electricity that are commercially available today. The value-adjusted LCOE of solar PV plus battery storage is significantly lower than nuclear power in most markets today, though in China it does not cross this threshold until around 2025 in the STEPS. Its closest competitors are solar PV on its own, onshore wind in most markets, and offshore wind in China and the European Union. By 2030, solar PV plus battery storage in the STEPS has a value-adjusted LCOE that is equal to or lower than that of solar PV alone in the United States, European Union, China and India, with the added value provided by the battery fully compensating for its added cost. This indicates that the most cost-effective option for new solar PV projects in these markets is likely to be to pair with battery storage.

Beyond 2030, additional low-emissions power technologies are on track to become commercial, including carbon capture, hydrogen and ammonia and advanced nuclear designs such as small modular reactors. While the costs of these technologies are less certain, it is likely to be difficult for them to compete successfully in most parts of the world with solar PV plus battery storage.

2.3.5 Behind-the-meter battery storage

Behind-the-meter batteries are set to expand strongly to 2030 in key markets as a result of their increasing affordability and potential to lower consumer bills and earn revenue, together with supportive policy measures. They are linked in particular with rooftop solar PV in all scenarios. In the STEPS, global installed capacity reaches 175 GW by 2030, with half of that in China and another third in the European Union and the United States combined (Figure 2.25). In the NZE Scenario, global installed capacity ramps up even faster to reach 200 GW in 2030, and about 10% of rooftop solar PV is paired with behind-the-meter battery storage in most major markets by that date.

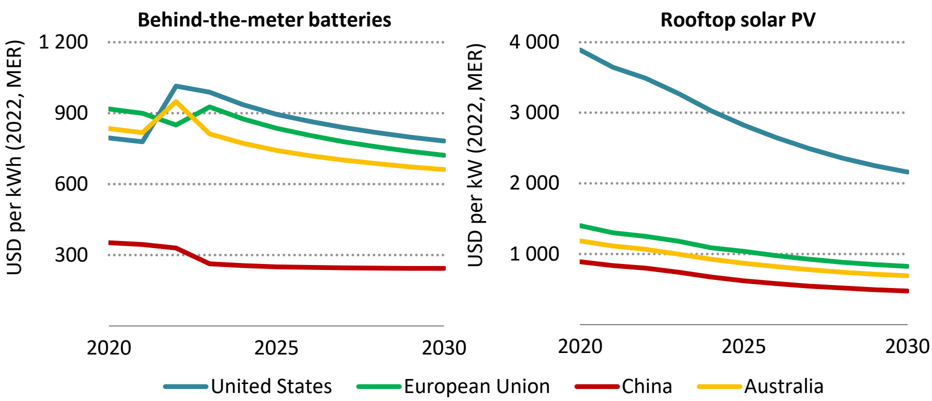
Figure 2.25 ▷ Installed capacity of behind-the-meter battery storage in the STEPS, 2015-2030



Behind-the-meter batteries continue to expand strongly to 2030 and are increasingly paired with rooftop solar PV in leading markets

Across these markets, there are a few key factors that improve the prospects for behind-the-meter batteries to 2030. One is that the investment costs of behind-the-meter batteries continue to decline in the STEPS to 2030, with those in China declining by 30% from 2020 levels and those in the European Union by 20% (Figure 2.26). As behind-the-meter systems generally involve almost no operating expenses, the initial investment and cost of capital determine total costs. The investment costs for rooftop solar PV, which can help behind-the-meter systems unlock their full potential, also decline by at least 40% from 2020 levels across major markets to 2030 in the STEPS. In China, where costs are already among the lowest in the world, they fall by nearly 50% from 2020 levels by 2030. This lowering of the barrier to entry for consumers reduces the payback period as well, making it more attractive to consumers in all regions.

Figure 2.26 ▷ Costs of behind-the-meter batteries and rooftop solar PV in the STEPS, 2020-2030



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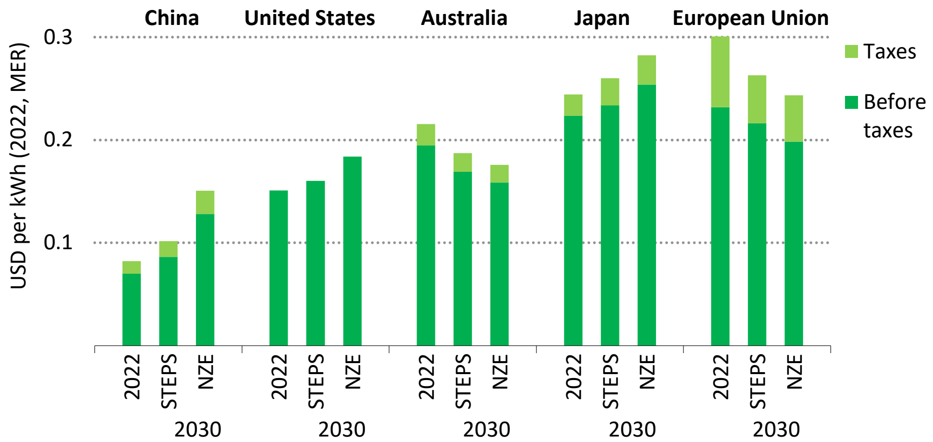
Costs continue to decrease to 2030 in key markets for both behind-the-meter batteries and rooftop solar PV

Note: MER = market exchange rate.

Another major factor in the rise of behind-the-meter batteries to 2030 is the evolution of end-user electricity prices, which in the STEPS remain broadly stable or increase in most major markets (Figure 2.27). Higher retail electricity prices, especially when combined with time-of-use pricing, incentivise the uptake of behind-the-meter systems paired with rooftop solar PV because the two together offer consumers a way to lower their reliance on the grid and give them some control over when they use it. Time-of-use tariff structures value behind-the-meter systems more highly than net metering or flat tariff structures and therefore provide a bigger incentive for their use. As many markets move towards more dynamic pricing and time-of-use tariffs, behind-the-meter batteries and rooftop solar PV are paired together with increasing frequency in major markets. In the NZE Scenario, a combination of lower technology costs, higher pressure on electricity prices in the near term, and more time-of-use pricing means that use of behind-the-meter ramps up more quickly than in the STEPS.

Figure 2.27 ▷ End-user electricity prices in key markets by scenario, 2022 and 2030



Broadly stable or increasing end-user electricity prices in the majority of leading markets help to drive up customer savings from the use of behind-the-meter storage

Note: MER = market exchange rate.

Behind-the-meter systems offer multiple ways for consumers to reduce their electricity bills without requiring changes in consumption habits. In regions with dynamic time-of-use pricing, they can charge their batteries either from their rooftop solar PV system or from the grid during off-peak hours and then discharge as needed during peak hours, thereby obtaining the cost savings of demand shifting without actually changing the times when they use energy. Consumers will be further incentivised to invest in solar PV and behind-the-meter batteries, and to make the fullest use of them, if grid feed-in is not prohibited or restricted, and if selling back excess solar PV generation is remunerated at full retail prices. Used in this way, behind-the-meter systems offer a way to maximise the use of what would otherwise be wasted generation to the benefit of consumers while also reducing peak demand. In reducing grid reliance, in addition, behind-the-meter systems offer the potential for consumers to downsize the grid connection itself, minimising another monthly charge.

In regions with tariff structures that include full retail value and dynamic pricing, consumers with behind-the-meter battery storage are not necessarily limited only to engaging in arbitrage and selling excess energy to the grid at peak times. When aggregated into virtual power plants, small residential behind-the-meter units can also participate in additional markets for ancillary services, thereby unlocking new revenue streams. As renewables ramp up, these flexibility and grid stability services will become increasingly valued. However, the revenue potential of these schemes is tariff-dependent and should therefore be weighed against the potential for self-consumption cost savings in order to maximise overall consumer benefits and optimise the payback period for investments.

Box 2.4 ▷ Batteries as backup power supply

During network outages or emergencies, battery storage can serve as critical backup generators, ensuring uninterrupted power supplies to critical facilities such as hospitals, emergency response centres and infrastructure like substations and communication networks. These systems offer several distinct advantages over conventional diesel generators. They have faster start-up and response times. Generally they also have lower maintenance requirements as they have fewer moving parts, reducing the likelihood of mechanical failures and the need for regular maintenance. They operate silently, which is helpful in urban and residential areas where noise restrictions may apply, and they emit zero emissions. Battery storage also eliminates the need for fuel storage, delivery and procurement, thereby simplifying logistics. This is particularly advantageous in remote or off-grid locations where access to fuel may be limited or costly. Electricity for charging can be sourced from renewables installed onsite, or from the grid, further enhancing their sustainability.

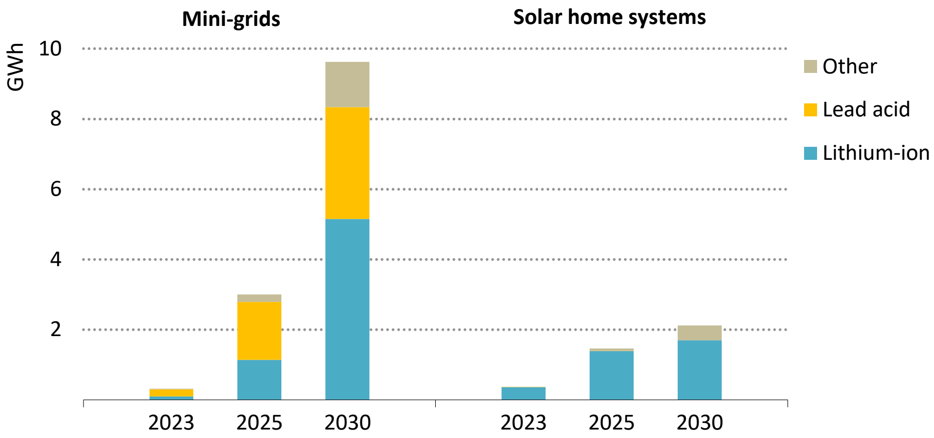
Battery storage can also play a pivotal role in facilitating islanding, in which localised portions of the grid operate autonomously from the main network. This capability proved invaluable when Hurricane Maria devastated Puerto Rico, for example: battery storage systems were quickly delivered to the island nation to enable the creation of microgrids to power critical facilities and communities amid widespread outages. Battery storage has also been deployed as part of a microgrid project on Ocracoke Island in North Carolina in the United States: the microgrid, made up of solar panels, diesel generators and a 0.5 MW/1 MWh battery storage system, enables the island to operate independently during network disruptions caused by hurricanes. By leveraging battery storage and renewable resources, such as solar and wind, microgrids enhance local resilience, reduce dependency on centralised generation, and expedite post-disaster recovery efforts.

However, there are situations where battery storage may not be the most appropriate option, particularly if local regulations require longer periods of backup power. This is the case when the electricity supply is usually very stable and, like in many parts of Europe, power outages are very rare. The emergency regulations for critical infrastructure in these countries often require longer bridging times in the rare event of a long duration failure of the electrical supply. Sizing batteries to supply power for multiple days is generally prohibitively expensive. In these cases, diesel generators, which, unlike batteries, can be easily and quickly refilled with fuel, will still be needed in order to ensure the power supply over longer periods.

2.3.6 Battery storage to achieve universal access to electricity

Almost half a billion people gain energy access through decentralised systems by 2030 in the NZE Scenario, most of them relying on solar PV and battery storage obtain a reliable, high-quality electricity supply. Over half gain access via mini-grids, driving annual battery capacity additions for mini-grids to a peak of nearly 10 GWh by 2030 (Figure 2.28). This is more than eight-times the current total mini-grid installed capacity, and 30-times more than additions in 2023, but it is by no means impossible if compared with the global battery storage market, which in 2023 alone saw the deployment of over 90 GWh of new capacity.

Figure 2.28 ▷ Battery storage by type for new electricity access with decentralised systems in the NZE Scenario, 2023, 2025 and 2030



Lithium-ion batteries dominate in decentralised systems, though lead-acid batteries continue to play a role in mini-grids and the share of other battery types rises

Notes: Other includes sodium-ion, flow batteries and other battery chemistries/technologies. Technology mix can vary drastically depending on market evolution.

Sources: IEA analysis based on the IEA access database and model, and ESMAP (2023) and GOGLA (2023) resources.

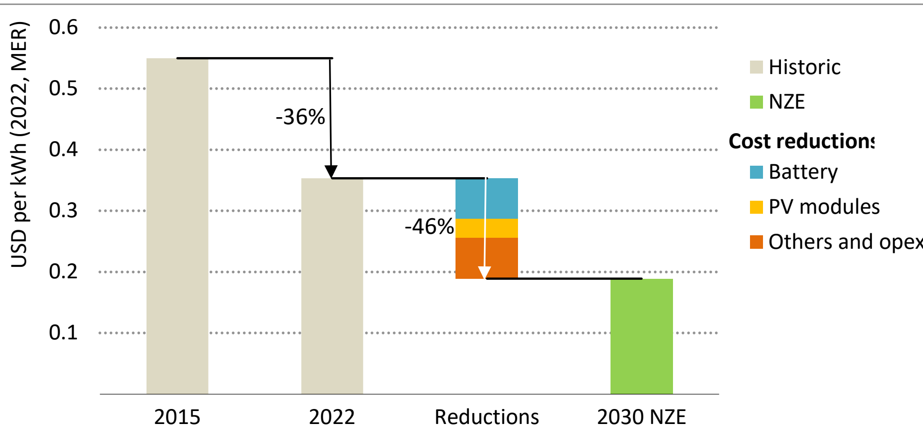
An additional 220 million people gain access through solar home systems (SHS) by 2030 in the NZE Scenario, nearly 90% of which live in Africa. This entails a sixfold increase in annual SHS battery capacity additions, which surpass the 2 GWh mark by 2030. Where policy and financing have been favourable, SHS deployments have increased very fast in previous years. Creative financing models and adequate targeted incentives schemes are critical to address affordability challenges.

These capacity additions only include households gaining access for the first time, and they exclude smaller solar lighting and lantern systems not matching the IEA definition of access. Demand for additional capacity will also come from households that purchase larger or additional systems to increase their access to energy services, from grid-connected customers seeking backup in the face of unreliable grid supply, and from commercial and other non-household users.

Projections of battery technology splits are uncertain. However, there is broad consensus that lithium-ion batteries will remain the dominant choice for SHS and will secure more than half of the min-grid market by 2030. In the same period, lead-acid batteries generally are expected to maintain a sizeable share of the mini-grid market to 2030: up to one-third, according to a recent report (ESMAP, 2023). The staying power of the lead-acid battery is attributable to its safety, its ability to tolerate higher temperatures and its relatively low capital cost. Emerging chemistries could also gain ground over time if their capital costs continue to decline. The long lifespans of sodium-ion and flow batteries could make both promising candidates. Second-life EV batteries could also be an option, given that they retain 70-80% of their initial capacity. If administrative and technological barriers such as a lack of standardisation can be overcome, they could be competitive with lead-acid batteries in price, or even become cheaper.

The scale of battery deployments required by the NZE Scenario to deliver universal energy access by 2030 is set to be supported by continuing cost declines in battery storage in tandem with cost declines for other technology components. The LCOE delivered by mini-grids and larger SHS is already competitive with that of diesel or petrol generators, especially in remote regions. Practical considerations add to the attractiveness of mini-grids and SHS over diesel backup generators, which are noisy, inconvenient, polluting and require ongoing fuel purchases and refill which is prone to theft, plus are subject to volatile diesel prices. As grid-connected customers in Africa are estimated to spend USD 28-50 billion annually on fuel for diesel backup generation, switching to solar-based systems could enable vast collective savings (International Finance Corporation, 2019).

Figure 2.29 ▷ Historical and projected LCOE from solar PV plus battery storage in mini-grids to 2030



Average generation costs for mini-grids with PV plus battery storage have declined by over one-third since 2015 and are projected to nearly halve from 2022 levels by 2030

Notes: LCOE = levelised cost of electricity; NZE = Net Zero Emissions by 2050 Scenario; MER = market exchange rate; opex = operating expenditure.

We estimate that the LCOE of an average solar PV plus battery mini-grid or large SHS could nearly halve by 2030, taking the costs of the former to below USD 0.20/kWh (Figure 2.29). This is lower than current residential tariffs in many European countries and several countries in Africa, including Kenya, Rwanda and Mali. While falling battery costs contribute significantly to LCOE reductions (40% of the total), batteries remain a key contributor to the capital costs of mini-grids and SHS. They need to be efficiently sized to enhance affordability.

LCOE for mini-grids can be significantly reduced by shifting electrical loads whenever possible to the daytime, when solar generation can be used directly without needing to be cycled through a battery. In one model, increasing the daytime load factor from 20% to 40% leads to a reduction in LCOE by 25% (ESMAP, 2023). Big evening peak demand, on the other hand, can heavily undermine system affordability by increasing the storage capacity required. This means that storage costs need to substantially decline further to increase the affordability of end-uses that heighten evening peaks, such as electric cookstoves. Creative business models and pilot projects meanwhile are promoting more effective and economical design and use of battery systems across the off-grid sector (Box 2.5).

Box 2.5 ▷ Models for mini-grids and solar home systems

Operational models for mini-grids and SHS vary widely. Batteries play specific roles in all of them. Innovative models are critical to improve affordability and long-term value.

Approaches that integrate utility and off-grid development efforts can stimulate demand and lower costs through co-operation (World Bank, 2024). In its Utilities 2.0 programme, Power for All brings together utilities and solar mini-grid developers for faster and least cost access to electricity, with the former fielding upfront investment and the latter responsible for customer relationships and billing. The mini-grid provides initial access and stimulates demand until the arrival of the grid, after which its role switches to enhancing local reliability. Some mini-grid components can be re-deployed at a new site. In this model, batteries transition from providing off-grid reliability to supporting grid services.

Battery oversizing is a challenge for many mini-grids. Batteries that are oversized and underused substantially increase costs for all customers. To avoid this, developers take various approaches. Some promote additional, income generating night load (such as telecommunications) to monetise overcapacity. Others incentivise daytime demand, such as agricultural processing, to lower storage capacity needs per kWh sold. Time-varying pricing models encourage daytime demand through an explicit economic signal that reflects the reality that it costs more to cycle electricity through storage than to use direct solar power production.

Some mini-grids are designed to run in parallel with the main grid from the start. In a pilot project in Nigeria, small mini-grids incorporating renewable generation and storage are built alongside the grid to provide reliability guarantees to industrial customers. These systems benefit from serving well-developed and high-load levels, and can have outsize economic value for industrial processes that suffer significant setbacks from power interruptions. They can also displace high volumes of diesel consumption and reduce bulk grid overloading.

Reliability and resilience guarantees are attractive features of off-grid systems that are enabled by battery storage, yet can be disrupted by battery failure. An interesting model aims to combine the modularity of SHS with the scaled resilience of a mini-grid through "mesh grids". Mesh grids interconnect several SHS with smaller and cheaper lines, creating a decentralised network of generation and storage, and are able to provide up to 3.6 kW per connection to remote communities where commercial mini-grids are not viable. Their design makes them resilient to the failure of a single component and enables capital and operating expenditure savings on poles and distribution lines. Spreading battery capacity across multiple households and small commercial customers also helps to reduce the risk of oversizing.

2.4 Investment outlook for batteries

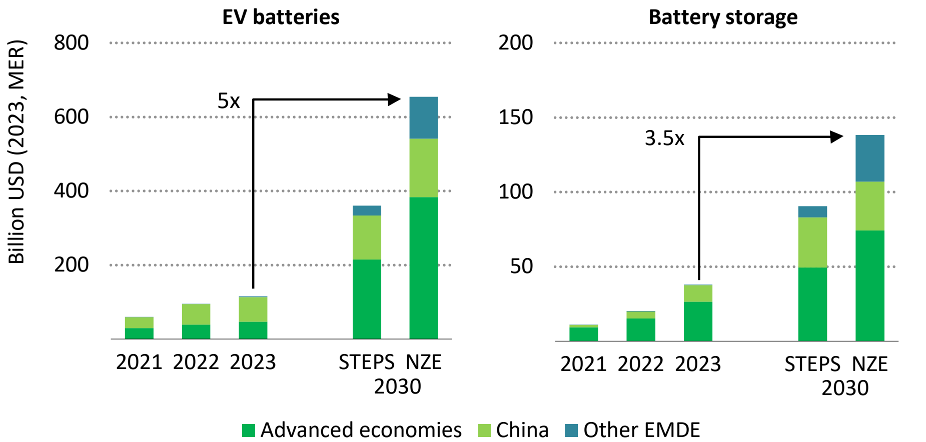
2.4.1 Global and regional investment outlook

Batteries in EVs and storage applications are key to the electrification of transport and to the maintenance of reliable electricity supply as countries increase the level of variable renewables in their electricity systems. In the NZE Scenario, total spending on batteries across all applications is set to increase to USD 800 billion by 2030, an increase of almost 400% compared with 2023 (Figure 2.30). This means doubling the share of batteries in overall clean energy investment within seven years. In the STEPS, the increase in spending is less steep, but nevertheless battery investment rises to almost USD 500 billion by 2030.

In the NZE Scenario, there is a shift in the share of the investment that goes to emerging market and developing countries outside China, with annual spending in these countries expanding to more than USD 110 billion for EV batteries and USD 30 billion for battery storage by 2030. This means that for every USD 1 invested in batteries in advanced economies and China, almost USD 0.20 – compared to USD 0.02 today – will be invested in batteries in emerging market and developing economies outside China by 2030, rising further to USD 0.40 by 2050.

The fact that spending on batteries in other emerging market and developing economies grows faster in relative terms than in advanced economies and China underlines the importance of battery storage and EV batteries in helping to meet increasing electricity and mobility demand in these countries in a way that is in line with climate and energy access goals. Battery storage is critical to the integration of large amounts of variable renewables and to achieving universal access to electricity by 2030, while EV batteries are the key to the electrification of road transport.

Figure 2.30 ⊳ Investment in batteries by type, region and scenario, 2021-2030



Investment in batteries increases to USD 800 billion in the NZE Scenario to support electrification in transport and integration of variable renewables

Note: Other EMDE = emerging market and developing economies outside China; MER = market exchange rate.

2.4.2 Risks to scaling batteries investment

Achieving the scale of annual investment required to get onto and maintain a 1.5 °C-compatible pathway will not be easy. There are a range of risks that stand in the way of further increasing spending on EV batteries and battery storage on the scale required. This is especially true for emerging market and developing countries, where country and macro factors in some cases are a major contributor to the high cost of capital for clean energy projects (IEA, 2024c). Potential investors harbour concerns about the rule of law and the sanctity of contracts in some countries, and also about high inflation, currency fluctuations and convertibility. Over the longer term, addressing these concerns requires efforts to strengthen national institutions, reduce inflation and deepen local capital markets.

However, there are also project- and sector-specific risks that could potentially undermine investment in battery storage projects and hinder the uptake of EVs (Table 2.2). Regulatory risk for electric mobility includes the lack of clear policy signals related to emissions and air pollution reduction targets for the transport sector, and lack of support for the development of EV and battery manufacturing. On the battery storage side, regulatory risks include battery storage not always having equal access to power markets compared with other technologies, and lack of a strategy to renumerate flexibility services such as frequency regulation, spinning and not-spinning reserves. Regulations need to outline how battery storage operators are to be remunerated for providing services such as frequency regulation and support in meeting peak load demand, as well as for their participation in power markets.

Table 2.2 ▻ Investment risk related to batteries

Key risk	Applicability	Description
Regulatory	Both	Lack of a clear and stable regulatory environment, including absence of clear policy signals, manufacturing support, equal access to power markets for battery storage and a strategy for the remuneration of services provided.
Financing and affordability	EV batteries	Ability to afford the high upfront costs of EVs and higher financing costs due to higher interest rates and limited access to debt financing, especially in emerging market and developing economies.
Framework conditions	EV batteries	Absence of adequate EV charging infrastructure and lack of proven business models.
Renumeration	Battery storage	Delayed payments or under-recovery from distribution companies for energy storage services provided.

There are also other risks that affect investment in EV batteries. Acquiring an electric car often has high upfront costs; the average EV purchase price is around USD 10 000 to 15 000 higher than an ICE alternative in many markets apart from China. In some emerging market and developing economies, this is aggravated by higher financing costs that reflect higher interest rates and limited availability of affordable debt financing, as well as of service models such as leasing. Other EV-specific risks relate to the development of adequate charging infrastructure.

Battery storage faces additional risks that could threaten the extent of investment needed. One is off-taker risk for battery storage, which relates to payments made to battery operators for the energy storage services they deliver. Operators are dependent on being quickly and predictably remunerated for the services they provide to the grid, but in many countries the payments are the responsibility of transmission companies which may be in poor financial health, and they are sometimes delayed or fail to appear at all. In countries without wholesale power markets, this risk is compounded by utility-scale battery storage operators being unable to earn money from energy arbitrage, which is often potentially their single largest source of revenue.

2.5 Battery supply chain

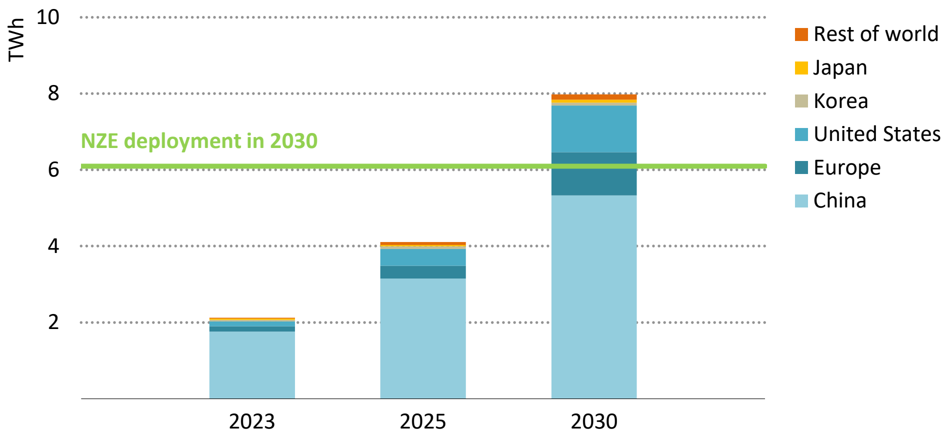
2.5.1 Future plans for battery manufacturing

Battery manufacturing capacity is set to increase nearly fourfold from today to 2030 if all announced plants are built in full and on time. This would increase capacity to about 9.4 TWh, with over 7.5 TWh from companies that are already certified to serve the EV market (Benchmark Minerals, 2024). This level of battery manufacturing capacity would be sufficient to meet the battery requirements of the NZE Scenario by 2030 and would be able to produce 8 TWh per year, assuming a global utilisation factor of 85%. Over 70% of this battery manufacturing capacity is already committed, meaning that plants have reached a final investment decision and construction has been initiated or is underway. This underscores the readiness of the battery industry to produce the necessary volumes of batteries to meet expected rising demand from now to 2030.

Battery production is also set to diversify in the coming years, though the share of China in lithium-ion battery manufacturing capacity will remain high. It decreases from nearly 85% today to 67% in 2030 (Figure 2.31). This shift is mainly driven by significant investment in Europe and North America. By 2030, both regions are home to around 15% each of global battery manufacturing capacity, up from around 6% each today.

2

Figure 2.31 ▷ Maximum lithium-ion battery manufacturing capacity by region and needs in the NZE Scenario, 2023, 2030 and 2050



If announcements materialise, battery manufacturing capacity more than triples by 2030 and is sufficient to meet future battery demand in the NZE Scenario

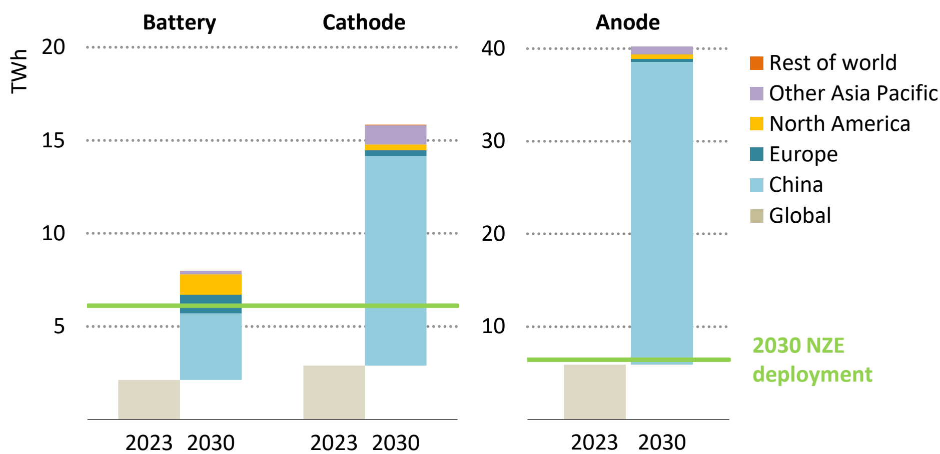
Notes: TWh = terawatt-hours. The analysis assumes a utilisation factor of 85%. Battery manufacturing capacity refers to battery cells.

Source: IEA analysis based on Benchmark Minerals data.

Battery production relies on critical components such as cathodes and anodes. China currently dominates global manufacturing capacity: nearly 90% of 98% of all cathode and anode active material manufacturing capacity is located in China. Most other cathode active materials are produced in Korea or Japan. The various battery chemistries in use require different battery components: LFP is the prevalent battery chemistry in the Chinese market and NMC in Europe and North America.

In contrast to the case of battery cells, the Chinese dominance of the cathode and anode active material manufacturing capacity does not see any significant reduction by 2030 (Figure 2.32). However, manufacturing capacity for cathode and anode active materials in 2030 is about two- times and five-times that of battery cells, which indicates a risk of future overcapacity. If this were to materialise, it might result in a more diverse supply chain thanks to the manufacturing capacity built outside of China. However, nearly 80% of the additional manufacturing capacity for cathode active materials and over 90% of the additional manufacturing capacity for anode active materials outside of China is still at the announcement stage, underscoring the importance of close attention to these components of the battery supply chain.

Figure 2.32 ▷ Maximum output of lithium-ion battery and components by region, and demand in the NZE Scenario, 2023 and 2030



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Announced plans for manufacturing battery components are sufficient to meet the 1.5 °C scenario needs but offer less prospect of supply diversification than battery production

Notes: TWh = terawatt-hours. The analysis assumes a utilisation factor of 85%. Battery manufacturing capacity refers to battery cells. Cathode and anode refer to cathode and anode active materials.

Source: IEA analysis based on Benchmark Minerals and BNEF data.

Manufacturing capacity alone does not determine which supplier battery manufacturers will choose. For manufacturers in China in the coming years, the primary challenge will be to identify a sufficiently large export market to absorb their considerable current overcapacity and to improve current low margins. Conversely, manufacturers in regions such as the European Union and the United States must demonstrate their cost competitiveness. The quality, cost and characteristics of cells and components provided by various suppliers, alongside local regulatory requirements and environmental, social and governance standards, will be crucial in determining market winners and losers.

Overcapacity across the battery supply chain is a double-edged sword. While it helps to decrease prices for end-consumers and thus support climate goals, it also results in lower cash flows and narrower margins for mining, refining and manufacturing companies. For instance, the decline in battery mineral prices in 2023 led to a nearly 14% decrease in the average battery pack price, but it also posed risks for operating and planned mining projects. Many of these firms are now struggling to remain solvent, with several announcing cutbacks in expenditure and job losses in 2024 (IEA, 2024a).

Box 2.6 ▹ Artificial intelligence may improve battery production by accelerating innovation and sustainability

Artificial intelligence (AI) in general and machine learning in particular may influence battery production by bringing about reductions in development timelines and fostering innovation.

AI may be able to expedite the discovery and commercialisation of new battery materials, significantly cutting the typically lengthy R&D phase (Financial Times, 2024). Machine learning can accelerate the screening of vast chemical combinations to optimise battery performance, as demonstrated by recent breakthroughs in electrolyte discovery (Science News, 2024). Generative AI can design novel materials beyond the current spectrum in a way that is akin to methodologies in drug discovery (MIT Technology Review, 2023).

A number of companies are already innovating in ways that could be relevant to battery production. Supported by AI and edge computing, the Chinese company CATL has developed a high-precision quality inspection model capable of achieving nearly 100% detection in seal pin welding processes, improving detection rates of defective parts per million to defective parts per billion levels (CATL, 2023). Microsoft managed to narrow down 32 million materials for possible use in a battery to 18 candidates in 80 hours, showcasing the potential of AI (Financial Times, 2024). This led to the creation of a hybrid material, slashing lithium usage by up to 70%, promising improved battery sustainability (NewScientist, 2024). Umicore has now entered an AI platform agreement with Microsoft in the hope of reducing material research timelines and to advance solid-state materials (Umicore, 2024).

In EV manufacturing, Renault is aiming to streamline vehicle development, to reduce the typical timeframe from three years to two (Transport Topics, 2023). AI could also potentially be used to improve the cost effectiveness of EV and battery production lines as well as to help identify innovative materials.

Technical synergies for battery manufacturing for EVs and storage applications

The battery storage market so far has largely been served by products similar to those used in EVs. This partly because the EV battery market is much larger, with battery storage applications accounting for around 10% of annual battery volumes in the energy sector in 2023. This relative difference in size is expected to persist in the coming years.

Technical innovation driven by EV batteries has been a significant factor in the rapid decrease in the cost of batteries for storage applications. This cost reduction would not have been possible without the exponential growth experienced by EVs in recent years. One of the key advantages of lithium-ion batteries, which are widely used in both markets, is their modularity. This characteristic allows such batteries to achieve economies of scale, leading to rapid cost reductions. It also facilitates their use in a variety of applications.

Future growth of the battery storage market has prompted many battery suppliers to begin developing products specifically for storage applications. While energy density is the primary consideration for EV batteries, it is less relevant for battery storage, where low cost and low degradation over a high number of cycles are more important. As a result, battery storage mostly uses less expensive LFP batteries rather than the high-nickel chemistries that dominate the EV battery market.

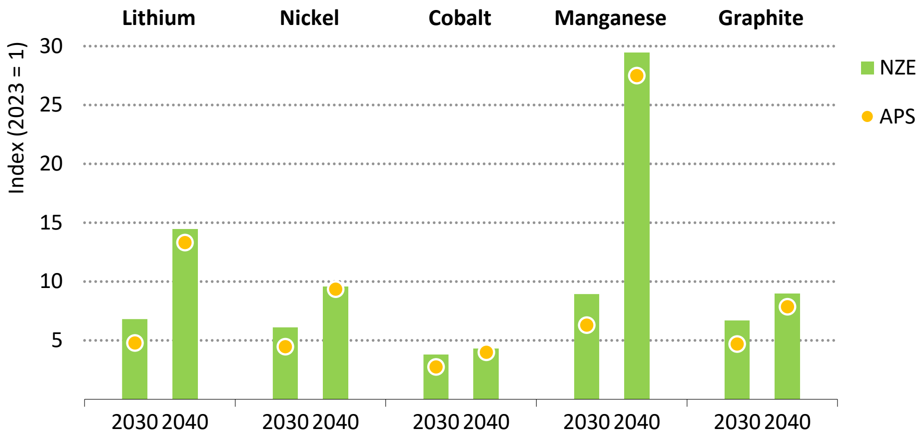
Looking ahead, a more distinct specialisation between the manufacturing facilities used to produce batteries for EVs and storage applications seems likely. However, the shared technologies used in both types of batteries will continue to facilitate the transfer of technological advances from one product to the other, and it may also be possible to re-purpose production lines in response to shifting demand. The cross-fertilisation of technology is expected to continue to accelerate innovation and further reduce prices of batteries for both EVs and storage applications.

2.5.2 Rising demand of critical minerals for batteries

The rapid rise in battery demand for EVs and storage implies a correspondingly significant increase in demand for the critical minerals used in them. In the APS, battery mineral demand in 2030 increases between 2.5- and six-times from current levels, depending on the individual mineral concerned (Figure 2.33). Demand for cathode materials such as lithium or nickel rises by around 4.5-times during this period. Demand for cobalt rises less than for other critical minerals, up by slightly more than 2.5-fold by 2030: in part this reflects efforts that battery manufacturers have been making to use less of it in lithium-ion batteries. Manganese sees the largest growth rate, with demand multiplying sixfold by 2030. While lithium and manganese demand increases are smaller in absolute terms than those for other critical minerals – a little over 300 kilotonnes (kt) additional demand for each of the minerals – their growth rates are two of the largest, reflecting their pivotal roles in cathode active material production. This is especially the case for lithium, which is used in cathodes for a range of battery chemistries. Graphite, the most prominent anode material, also sees particularly rapid demand growth: demand rises more than fourfold, which translates to 2.8 million tonnes (Mt) of additional absolute demand.

In the NZE Scenario, demand for critical minerals for batteries is more rapid, ranging from 3.5-times to as much as eight times the current level by 2030. Among cathode materials, lithium and manganese show the biggest demand growth, six and eight times respectively, and nickel sees the largest demand addition of more than 1.5 Mt in absolute terms by 2030. Cobalt, despite having the smallest level of demand growth, still increases 3.5-times compared with the 2023 level by 2030. Graphite sees additional demand of 4.2 Mt by 2030, with demand rising by over six times from the current level.

Figure 2.33 ▷ Relative increase in demand for critical minerals used in batteries by scenario, 2030 and 2040



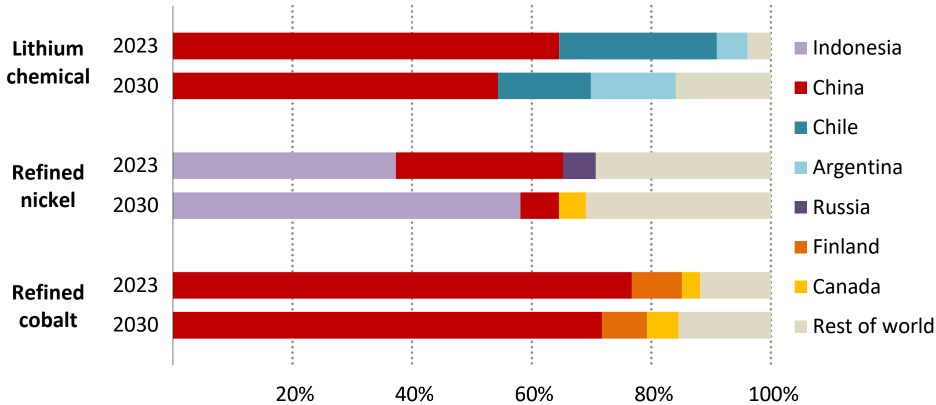
Demand for critical minerals for EV and storage batteries is set to surge to 2040

Note: NZE = Net Zero Emissions by 2050 Scenario; APS = Announced Pledges Scenario.

Meeting these demands requires a significant ramp up in mining, refining and recycling activities. While some positive signs in terms of investment in new supply, limited progress so far has been made in diversifying supply sources. In some cases, such as that of nickel, the situation is getting worse. Our analysis of project pipelines indicates that concentration levels in 2030 are set to remain high, especially for refining operations, which is where the current geographical concentration is the strongest (Figure 2.34). LFP batteries – the chemistry of choice for most storage battery applications – are not immune to supply chain concerns (Box 2.7). In addition to concerns surrounding geopolitical disruptions, a rise in announced export control measures from several resource-owning countries in recent years has highlighted the importance of accelerating progress on supply diversification. For example, the Indonesian government prohibited exports of nickel ore to direct nickel mining sectors in 2020 in order to build domestic processing capacity (Nikkei Asia, 2023), and China strengthened export controls on graphite and began requiring government approval for exports in December 2023 (Reuters, 2023).

Lithium-ion battery recycling offers a secondary supply of materials while creating a more sustainable solution to address waste generated from the massive scale-up in battery deployment. For bulk materials like aluminium, recycling practices are well established, but this is not yet the case for many battery minerals such as lithium, nickel, and cobalt. Recyclable battery feedstock is dominated by scrap from manufacturing processes, but this is set to change by the end of the decade as the first generation reaches the end of their life. Nearly 80 GWh of end-of-life batteries will be available for recycling in 2030 in the STEPS from EVs (Box 2.2). (This topic will be explored in depth in a forthcoming IEA publication on clean energy technology recycling.)

Figure 2.34 ▹ Top-three country share of key mineral refining in 2023 and in 2030 based on announced projects



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Project pipelines indicate that, in most cases, the geographical concentration of mineral refining operations is likely to remain high to 2030

Box 2.7 ▹ Does the rise of LFP batteries imply a more secure future for global battery markets?

LFP batteries are rising fast to a position of prominence among the suite of lithium-ion batteries. They now have a larger share of the market for battery storage than any other battery chemistry, and their use is rising rapidly in the EV market, largely due to the preference for this chemistry in China. While it is unaffected by the supply chain disruptions stemming from nickel, cobalt and manganese markets, there are other potential risks to its supply chain.

One risk stems from its use of phosphorus. As phosphorus is used in large quantities in fertiliser production, the surge in demand from battery manufacturing could potentially lead to competition with fertiliser producers and the agriculture sector, unless production increases sufficiently fast to satisfy both areas.

Phosphorous also presents the challenge of high geographical concentration. In terms of extraction, around 70% of phosphate rock reserves are in Morocco and the Western Sahara region, though exploration of deposits in Canada and Norway could potentially identify additional reserves. On the processing side, there is only one known refining method able to produce the high purity phosphorous required for LFP batteries, and only four countries have such production capacity: China, the United States, Kazakhstan, and Viet Nam.

Another consideration is price. LFP batteries are significantly less expensive than other variants of lithium-ion batteries. That is one of the key reasons for their current success. However, in 2022, during a period of extremely high lithium carbonate prices, LFP battery prices saw a larger relative jump in price than batteries using NCA and NMC chemistries. While LFP batteries remained cheaper per kilowatt-hour than NCA and NMC batteries even during this time, future price volatility could have an impact on their affordability.

An important concern relates to battery recycling. Once sufficient feedstock from retired EVs is available for recycling or reuse, the recycling industry will have more financial incentive to recycle NCA and NMC batteries than is the case for LFP batteries because they use higher value materials. Adequate volumes of scrapped batteries and expanded processing lines are essential to make recycling competitive and economically viable. New regulations may be necessary to ensure that LFP batteries are recycled. LFP recycling primarily targets lithium because it is the most valuable component of the battery in the absence of nickel and cobalt. Of the two main process currently used for recycling, pyrometallurgical processes are not suited for lithium recovery, and hydrometallurgical processes must adjust their flowsheets to enhance recycling efficiency from LFP batteries. With the anticipated rise in the proportion of LFP batteries in recycling feedstock, distinct treatment processes for LFP batteries and manufacturing waste are likely to emerge.

Policy implications and recommendations

Key measures to foster battery deployment

SUMMARY

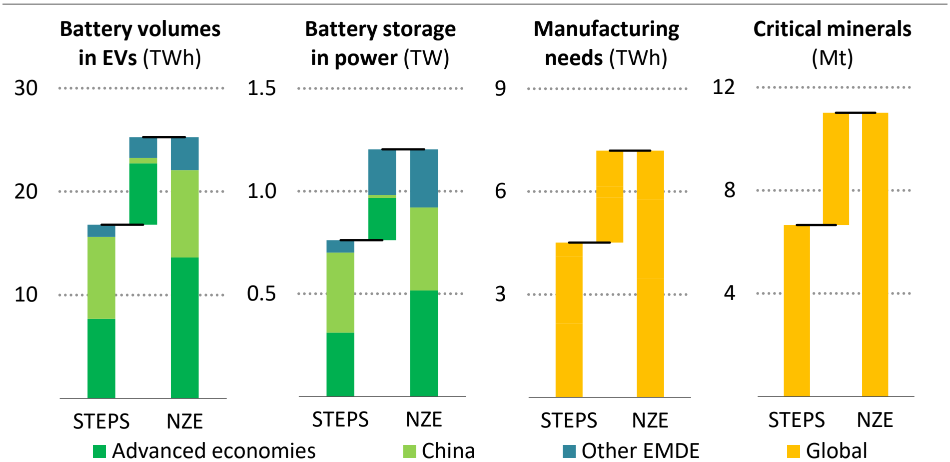
- Batteries are an essential building block of the clean energy transition. They can help to deliver the key energy targets agreed by nearly 200 countries at the COP28 in 2023. The IEA Net Zero Emissions by 2050 Scenario sets out the pathway. For batteries to realise their potential to contribute, policy makers need to establish effective frameworks for market access, ensure fair competition among technologies, and recognise the varied contributions that batteries make to sustainability, security and affordability of energy.
- Batteries for electric vehicles (EVs) are essential for the clean energy transition in road transport. Increasing the uptake of EVs requires accessible and affordable charging infrastructure as well as reinforced electricity networks. It needs increased focus on affordable EV models that require smaller batteries. Avoiding the oversizing of average electric car batteries could save 2 TWh of batteries until 2030, which is similar to current global EV battery capacity. Promoting smart EV charging is another priority, unlocking the ability of EVs to contribute to flexibility needs of power systems.
- Battery energy storage facilitates the integration of solar PV and wind while also providing essential services including grid stability, congestion management and capacity adequacy. Current regulations and policies in many jurisdictions pose significant risks that constrain development of battery energy storage which threaten the global goal of tripling of renewable energy capacity by 2030. In a Low Battery Case, the uptake of solar PV in particular is slowed, prolonging the use of unabated coal and natural gas in power systems, stalling emissions reductions in the 2030s and putting the 1.5 °C target out of reach, as well as increasing fossil fuel imports bills.
- To unlock the full potential of battery storage, policy makers and regulators need to ensure that regulatory systems recognise the full value of the services that it offers, enable market access and establish price signals that accurately reflect its various contributions. To capture the full benefits of behind-the-meter batteries, regulatory systems need to better align consumer and system benefits through cost-reflective variable electricity tariffs. Where feasible, they should also allow the aggregation of behind-the-meter batteries into virtual power plants that can offer services akin to utility-scale projects.
- Growing demand for critical minerals for batteries puts a focus on creating secure, resilient and sustainable supply chains. This requires the development of diversified international networks, and of environmental, social and governance standards for mining and processing. Success depends crucially on international co-operation. Encouraging innovation through research and development on battery chemistries and design is needed, as are regulatory frameworks that promote battery recycling.

3.1 Introduction

Batteries have the potential to facilitate higher shares of solar photovoltaics (PV) and wind in power generation, support electric vehicle (EV) deployment, and provide access to electricity for all. This makes major contributions to support the clean energy transition in a cost-effective way and to enhance energy security. Tapping this potential requires action from policy makers and regulators to minimise the barriers and bottlenecks for wider battery deployment.

The gap between battery uptake in 2030 in the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 (NZE) Scenario illustrates the scale of the task ahead. Global battery volumes in use across the energy system expand from nearly 2.5 terawatt-hours (TWh) today to 19 TWh in the STEPS by 2030. The NZE Scenario requires a further increase to nearly 30 TWh in 2030 to meet the targets set at the 28th United Nations Conference of the Parties (COP28) in December 2023 to triple renewable energy capacity and double energy efficiency progress by 2030 and accelerate the transition away from fossil fuels. Battery deployment to the NZE Scenario level must be underpinned by significant growth in manufacturing capacity and critical minerals availability (Figure 3.1). Major increases in batteries are also needed after 2030. Careful planning is required to ensure that this ambitious transition occurs in an equitable, sustainable and timely manner.

Figure 3.1 ▻ Closing gaps across the battery ecosystem between the STEPS and NZE Scenario, 2030



Emerging market and developing economies other than China play a pivotal role to close the gap in battery volumes between the two scenarios for EV and energy storage

Note: TWh = terawatt-hours; TW = terawatt; Mt = million tonnes; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; Other EMDE = emerging market and developing economies excluding China.

The battery volumes in use gap that needs to be to be filled requires action in both the transport and power sectors and throughout the battery supply chain. In road transport, the electric vehicle fleet in the NZE Scenario in 2030 is 50% bigger than in the STEPS, requiring steep increases in the volumes of batteries in use in advanced economies (+80%), China (+10%) and other emerging market and developing economies (+170%). Battery storage in the power sector needs to increase significantly beyond the STEPS in all regions: installed capacity rises to 1 200 gigawatt (GW) by 2030 in the NZE Scenario, requiring a 170% increase in annual capacity additions by 2030 compared to the STEPS.

3.2 Electric vehicles

EVs equipped with batteries play a crucial role to decarbonise road transport, contribute to energy efficiency goals, cut air pollution and reduce oil demand. Today EV uptake is concentrated in a few key markets – China, the European Union and United States. The accelerated EV deployment projected in the NZE Scenario depends on taking timely action to address the factors that hinder EV penetration in a number of emerging markets and developing economies beyond China. This includes scarce availability of low cost EV models and charging infrastructure, and absent or weak fuel economy standards.

3.2.1 Expanding EV adoption beyond key markets

Affordability is a crucial determinant of demand for EVs. The average retail price of EVs in the United States and Europe has increased since 2021 and hampered EV uptake (JATO, 2023). Yet, in China the EV price trend is downward, and today the least expensive new cars on the market are electric. These affordable electric car models, supported by no or low vehicle registration taxes, are boosting China's road transport electrification efforts and driving global battery demand. The increasing availability of affordable models is likely to increase EV sales, particularly in other emerging market and developing economies.

Insufficient grid infrastructure is an important barrier to advancing electromobility, especially in emerging market and developing economies other than China. Ensuring viable and equitable charging infrastructure often requires expansion of the electricity grid, especially in rural areas. Even in advanced economies like Australia, where urban grids can handle EV penetration levels of up to 80% without upgrades, already overloaded rural grids cannot support any additional load from EVs (IEA, 2023a). Large-scale adoption of EVs requires the roll-out of charging infrastructure with grid connectivity. In addition to conventional grid enhancements, renewables-based decentralised grids in combination with vehicle-to-grid technology could help to address the charging hurdle.

To sustain increased penetration of EVs in mature markets, policies that stimulate demand should transition to targeted measures that focus on production and purchase incentives for small EVs to enhance affordability for more consumers while also reducing material demand. Environmental standards, weight-based taxation and parking charges are measures that can incentivise both producers and consumers in this direction.

On the other hand, emerging market and developing economies other than China require broad policy support and demand-side incentives to accelerate EV uptake. These countries are home to approximately 65% of the world's population, but today account for only 8% of the global EV fleet. However, they are key players in the outlook for increased battery demand. In the STEPS, total battery volumes in use in EV fleets increase nearly twenty-fold in emerging market and developing economies other than China by 2030. In the NZE Scenario, they increase more than fifty-fold. This highlights the significant role that accelerated EV deployment in emerging market and developing economies other than China has to advance the clean energy transition.

Trends in battery pack size for EVs will influence the magnitude of additional demand for batteries. Appropriately sized batteries for personal transport, well planned charging infrastructure and electrification of mass transit will foster development of a sustainable road transport sector. Charging infrastructure that is perceived as inadequate, for example, contributes to range anxiety and to customers opting for larger batteries than actually needed. Optimising the use of EV batteries is important to decarbonise transport. For example, large batteries for electric buses, which are sized at around 200 kilowatt-hours, provide more energy service demand per kilometre than a private car (see Chapter 1). Having a widespread public charging network and implementing policies designed to encourage smaller cars are effective steps to reduce EV battery size and to manage critical mineral availability.

3.2.2 Impact of average battery pack size on future demand

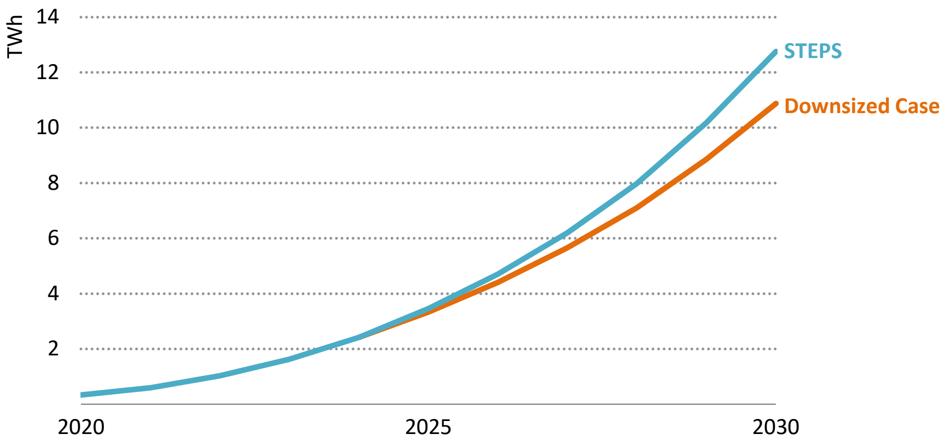
The number of electric car models available globally surged by 15% to almost 600 in 2023. Two-thirds of these models were large cars, sport utility vehicles (SUVs) or pick-up trucks, accounting for 50% of all electric car sales in China, 60% in Europe and 75% in the United States in 2023, compared with around 20-25% five years earlier. New EVs also tend to be larger than their internal combustion engine (ICE) vehicle counterparts. In Europe, for example, large EVs have over twice the market share of ICE vehicles in the same category. In China, new models focus more on SUVs and large vehicles than on small and medium-size electric models.

Preferences for large EVs are driving up demand for large batteries, which in turn puts additional pressure on critical mineral supplies. In 2023, the sales-weighted average electric SUV in Europe featured a battery almost twice the size of that in the average small electric car, significantly increasing critical mineral requirements. Promoting small EVs can curb demand for the critical minerals that go into batteries. There is significant potential to downsize batteries even in small EVs, as indicated in China where the average battery size in small EVs sold in 2022 was less than half the size of similar models sold in the United States.

The Downsized Case explores a case where the global average size of batteries in new battery electric cars is reduced by less than 30% by 2030. This would yield substantial benefits, saving a cumulative 2 TWh of batteries between today and 2030 when compared to the STEPS –

almost equal to the total battery capacity of the global EV fleet today (Figure 3.2). To put it another way, it would avoid the use of around 1.6 million tonnes of graphite, 700 kilotonnes (kt) of nickel, 200 kt of lithium and 100 kt of cobalt. For these battery minerals, this cumulative amount is equivalent to more than half of the total demand in 2030 for all clean energy technologies. It would also save nearly 160 kt of manganese, equivalent to around 85% of clean-energy related manganese demand today.

Figure 3.2 ▷ Global battery volumes used in battery electric car fleets in the STEPS and Downsized Case, 2020-2030



Reducing the average size of batteries in new battery electric cars by less than 30% by 2030 lowers cumulative battery needs by nearly 2 TWh

Note: TWh = terawatt-hours.

3.2.3 Electric vehicles and power systems

As the adoption of EVs accelerates, policy makers need to ensure co-ordination across the entire value chain. Key elements include EV owners, grid operators, charging stations, charging management software providers and energy management systems. For instance, optimal charging practices depend on effective communication between charging stations and EV drivers.

Policy makers need to make certain that regulatory frameworks are fit for purpose. Among other elements, regulatory frameworks need to ensure that grid connections and behind-the-meter electrical infrastructure in new buildings are adequately equipped to accommodate the expanding fleet of EVs. Also, that they promote inter-operability via open protocols for data sharing in order to help create a secure and scalable system that addresses the evolving cybersecurity and connectivity requirements of both hardware and software components. Dynamic tariffs and flexible pricing models should be widely implemented to incentivise efficient resource allocation and drive sustainable growth to maximise benefits for both consumers and system operators.

3.3 Power

Batteries provide essential services to power systems, improving their flexibility through the provision of bulk energy shifting, ancillary services and capacity adequacy. They also increase the resilience of grids and can be tapped to manage grid congestion, thereby minimising the need for transmission or distribution capacity expansion or upgrades. However, there is a risk that current policies and regulations will not enable battery storage to scale up at the pace that is necessary to support ambitious clean energy transitions. In order to reduce this risk, we recommend making changes as necessary to policy and regulatory frameworks to ensure that batteries are eligible to provide the services they can offer and that their contribution is properly valued.

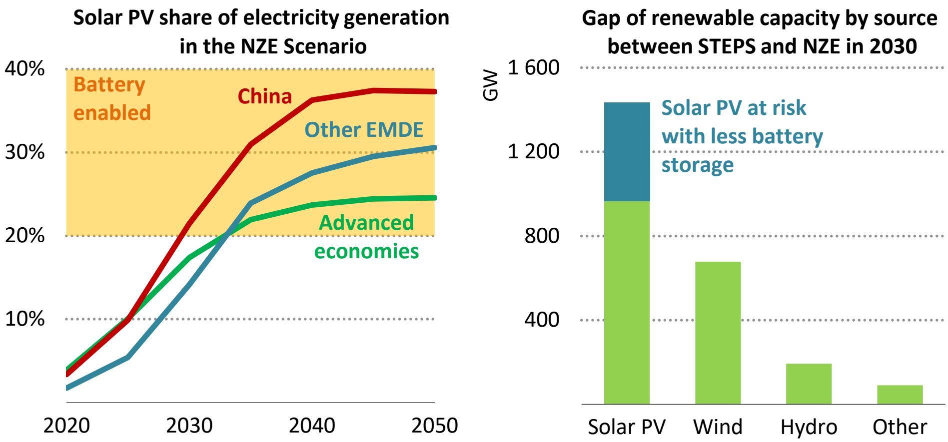
3.3.1 Risks of delayed battery storage expansion

If the right conditions are not in place to scale up battery storage in the power sector at the pace envisioned in the NZE Scenario, there is a significant risk that this will put a brake on clean energy transitions. A lack of battery storage would have implications for the uptake of renewables, and as a result for the transition away from fossil fuels and the reduction of carbon dioxide (CO_2) emissions.

Battery storage is particularly critical to the scaling up of solar PV, the most important technology to achieve the goal of tripling of global renewables by 2030. Our analysis indicates that successfully integrating new solar PV becomes increasingly strongly linked to the availability of energy storage as the share of solar PV in electricity generation rises, and that much of this storage is best delivered by batteries, which are ideally suited to provide the flexibility over periods of several hours that solar PV needs. At a share of around 20%, the analysis finds that energy storage becomes critical to enable further increases in solar PV penetration. In the Announced Pledges Scenario, several countries cross this threshold before 2030 – Australia, Chile, United States and China – while several others see a solar PV share of over 15% by 2030, including India, Korea, Japan and several African countries, such as South Africa and Nigeria. In the NZE Scenario, more countries cross the 20% threshold before 2030, and more approach that threshold. Wind power also calls for enhanced power system flexibility. But our analysis indicates that batteries are less well suited to provide this than other forms of storage and sources of flexibility because wind power calls for flexibility over longer periods of time, up to and including whole seasons.

To better understand the risks of delayed development of battery storage, we explore a “Low Battery Case”, where a 20% share of solar PV in electricity generation becomes a limitation. This is an indicative threshold based our detailed hourly analysis of multiple power systems around the world.[1] In such a case, we find that close to 500 GW of solar PV deployed by 2030 would be at risk. This represents 20% of the additional renewable energy capacity needed to bridge the gap between the renewables capacity in 2030 projected under current policies, laws and market forces in the STEPS, and the capacity needed to reach the global target of tripling renewables (Figure 3.3). This is equivalent to nearly the total renewables capacity installed in 2023. If the limitation were to persist long term, it would put at risk over 6 000 GW of solar PV in 2050, which is over 40% of the solar PV envisaged in the NZE Scenario in that year.

Figure 3.3 ▷ Solar PV share of electricity generation in the NZE Scenario (left) **and the gap of renewable energy capacity by source between the STEPS and the NZE Scenario in 2030** (right)



Failure to scale up battery storage would put at risk up to 500 GW of the solar PV needed to triple renewable capacity by 2030

Note: Other EMDE = emerging market and developing economies other than China; GW = gigawatt.

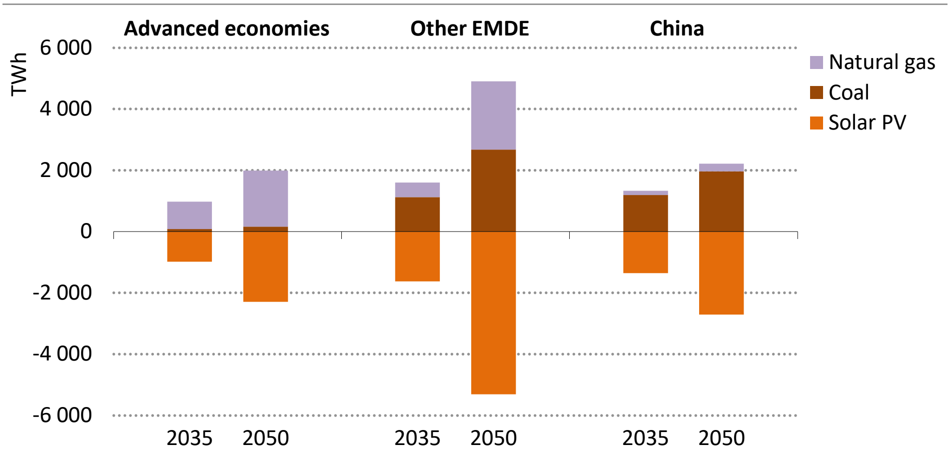
In the Low Battery Case, the lost output from the limited level of solar PV would amount to over 10 000 TWh globally in 2050 and represent an enormous risk to internationally agreed emissions reduction goals if it were replaced by unabated coal or natural gas power generation. The volume of electricity generation affected would be modest in the near term but would become significant by 2035 and continue rising afterwards. In the Low Battery Case, we find that global electricity generation from coal would be cut by only half by 2050

[1] This indicative threshold is applied to quantify the risks that might be associated with failing to scale up battery storage in a timely manner. However, there is no precise value for the share of solar PV that accurately represents a limitation for all power systems. Each system, with its own unique set of electricity demand patterns, resource and technology mix, interconnections, grid infrastructure and regulations will face integration challenges at different shares of solar PV.

compared with today, whereas it reaches zero in 2040 in the NZE Scenario. This is despite the fact that some of the lost output from solar PV would not need to be replaced due to the modest levels of curtailment found to be cost optimal in the NZE Scenario. While efforts could be made to step up deployment of other low-emissions technologies in place of the lost solar PV, this would be difficult as high ambitions across the board are already included in the NZE Scenario.

The balance of unabated fossil fuels in the Low Battery Case varies across regions based on their policy commitments, resource availability and power plant fleets. In those advanced economies with firm commitments to phase out unabated coal, there is risk of a continued need for natural gas in place of the lost solar PV. In these countries, natural gas-fired generation would be over three-times higher in 2035 in the Low Battery Case than in the NZE Scenario, and only 40% lower than in the STEPS (Figure 3.4). In China, coal-fired power would be used in place of most of the lost solar PV output in the Low Battery Case: it would add some 1 200 TWh in 2035, which would mean coal use two-times higher than in the NZE Scenario. In other emerging market and developing economies, a mix of coal and natural gas would be used to replace the lost solar PV output. In such regions, including India, Southeast Asia, Africa and much of Latin America, the increased need for both natural gas and coal would be larger than elsewhere, indicating the critical importance of solar PV and battery storage for their energy transitions.

Figure 3.4 ▻ Difference in electricity generation by source and region in the NZE Scenario and Low Battery Case, 2035 and 2050

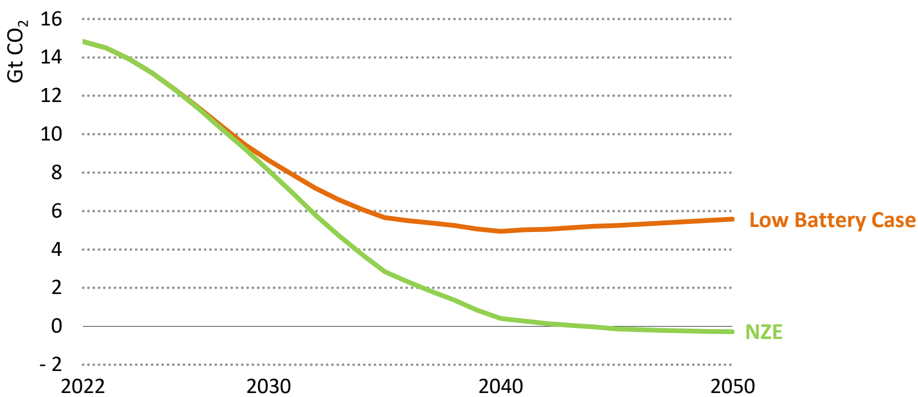


Lost output from solar PV in the Low Battery Case risks substantially increasing the use of unabated coal and natural gas in the power sector

Note: TWh = terawatt-hours; Other EMDE = emerging market and developing economies other than China.

Clean energy transitions in the power sector could easily stall in the Low Battery Case. As a result of increased use of unabated coal and natural gas that it projects, emissions reductions in the power sector could slow in the 2030s and stall at around 5 gigatonnes (Gt) through to 2050, rather than reducing steeply throughout the 2030s as envisioned in the NZE Scenario (Figure 3.5). Cumulative power sector emissions are 83 Gt higher over the period to 2050, equivalent to the cumulative emissions of the global power sector over the last six years, and enough to raise the median global average temperature increase to 2100 to well above 1.5 °C. This represents a serious risk for clean energy transitions, especially since the power sector is the largest CO_2 emitting sector and clean electrification plays a vital role in cutting emissions in other sectors.

Figure 3.5 ▹ Global power sector CO_2 emissions in the NZE Scenario and Low Battery Case, 2022-2050

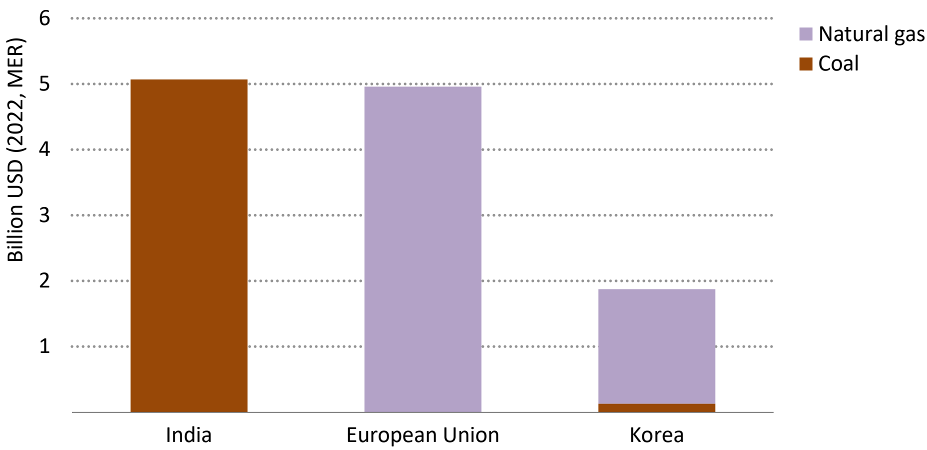


More unabated coal and natural gas use in the Low Battery Case causes CO_2 emissions reductions from the power sector to plateau in the 2030s, stalling clean energy transitions

Note: Gt CO_2 = gigatonnes of carbon dioxide.

The additional use of natural gas and coal in the Low Battery Case would have implications for trade in energy and as well as for energy security. Fossil fuel import bills in importing countries are on average USD 12.5 billion higher per year from 2030 to 2050 in the Low Battery Case than in the NZE Scenario. Additional natural gas imports would increase the most, costing importing nations USD 7 billion per year extra, with most of the additional gas for use in the European Union and Korea (Figure 3.6). In India, the additional need for coal imports alongside increases in domestic production would raise coal import bills by USD 5 billion per year from 2030 to 2050, with the high cost reflecting its heavy reliance on solar PV and battery storage to transition away from fossil fuels.

Figure 3.6 ⊳ Additional annual average fossil fuel imports in selected countries in the Low Battery Case relative to the NZE Scenario, 2030-2050



IEA. CC BY 4.0.

In a Low Battery Case, average annual fossil fuel import bills could be USD 12.5 billion higher in key markets from 2030 to 2050

Note: MER = market exchange rate.

3.3.2 Utility-scale battery storage

In liberalised electricity markets, the deployment of battery storage is often hampered by regulatory and other barriers (see Chapter 1). Market access restrictions can prevent battery storage systems from participating in energy markets, including short-term electricity markets, capacity mechanisms, and markets for balancing and congestion management. Restrictions on market participation and providing services may also prevent value stacking across various revenue streams, thereby reducing potential profitability of battery storage projects. These restrictions should be lifted to allow full market participation by battery storage systems.

There are other issues too. The unique nature of battery storage as both generation and load can lead to double taxation, putting it at a systemic disadvantage compared with other sources of flexibility and capacity adequacy. This could be addressed through adjustments to tariff structures that take account of the dual character of storage and reflect the value storage assets can provide to the electricity grid. Moreover, battery storage may not receive the right price signals to incentivise optimal deployment and operation. This could be addressed by ensuring that clear signals are provided about where grid congestion is happening, incentivising renewable integration through more frequent dispatch and settlement periods in wholesale markets (sub-hourly intervals), and applying adequate carbon pricing.

For some services that can be provided by batteries, such as the provision of black start capability or inertia, remuneration opportunities are not yet in place or are only being tested in pilot projects, as traditionally these services were provided at no cost by conventional power plants, which are progressively disappearing from the scene in many markets. Reforms that allow battery storage systems to provide a wider range of products and services would help overcome this barrier. In systems that are transitioning from regulated to liberalised markets, batteries are often not able to participate fully in the competitive procurement of system services and energy arbitrage opportunities in wholesale markets. It is essential that the benefits batteries can provide to power systems are recognised and that power market reforms establish electricity and ancillary service markets that send the appropriate signals and adequately value their contribution.

Long-term power system planning helps to set priorities for all power system actors, including in competitive markets. Although market mechanisms and investment signals are of central importance, clarity from policy makers about the long-term role of various technologies, including sources of electricity, battery storage and other forms of flexibility, can provide valuable guidance for companies and investors, and set the stage for innovation. It can also help grid operators with long-term planning. To make the most of the potential for batteries to facilitate deferral of new investment in transmission and distribution, they need to be considered in grid planning exercises, and their capabilities and costs need to be reflected in the associated modelling. In addition, remuneration mechanisms for transmission and distribution system operators need to be updated to incentivise network investment deferral using batteries or other non-wire alternatives to grid reinforcement and expansion.

A related issue where clarity is needed concerns the question of who can own and operate battery storage systems. This can be an issue when transmission or distribution system operators seek to make use of storage to minimise the need for new grid investment. Clear rules for ownership, system-optimising operation and services procurement are necessary to stimulate investment in these assets. In jurisdictions with strict unbundling between transmission/distribution and generation, such as the European Union, enabling and incentivising system operators to procure grid services from third parties, such as through bilateral contracts or on local flexibility markets, could be a potential solution. A good example is local flexibility markets in the United Kingdom, in which distribution system operators now routinely procure flexibility services to manage grid congestion. For developers of storage, this approach could open an additional revenue stream to supplement renumeration from commercial operations on wholesale electricity and ancillary service markets. However, regulatory frameworks need to be adjusted carefully to minimise the risk of storage assets receiving regulated payments and undercutting the competitive power market.

In regulated, vertically integrated power systems – the model in many emerging market and developing economies – it is essential to have integrated planning that recognises the multiple benefits battery storage can provide to power systems alongside other options such as demand-side response, power plant retrofits, smart grid measures and other technologies that boost flexibility. If done well, integrated planning can ensure that the scaling up of battery storage is aligned with the broader evolution of an electricity system, in particular the increase in renewables capacity and the phase-out of coal. Integrated planning also helps to set targets for battery storage and provide a roadmap for its deployment to mobilise the necessary investment.

3.3.3 Behind-the-meter battery storage

Behind-the-meter battery storage is quickly gaining momentum, with 30 GW installed worldwide already. However, its competitiveness is highly dependent on elements such as tariff structure, proper policy and regulatory frameworks, which are vital to their continued deployment. Tariff structures should incentivise optimal behind-the-meter deployment and provide fair remuneration that reflects the value of its contributions to the electricity system. In competitive markets, this remuneration should be based on the market value of the services provided.

Wherever possible, the use of behind-the-meter battery storage should align consumer preferences and system benefits so as to make the most of investment and physical assets. This includes expanding access to virtual power plant participation for consumers and ensuring that they are remunerated in proportion to the system value of the services, thereby providing income to consumers while also promoting system flexibility. Tariff regimes should also account for the local grid structure and incentivise behind-the-meter storage deployment that is useful to the needs of the specific grid. It is imperative that support measures for behind-the-meter storage avoid or limit cost shifting from households that reduce their reliance on the power grid to those that remain wholly reliant on grid service. Continued progress on grid digitalisation, which will allow higher visibility of real-time system needs, is crucial to garner maximum benefit from the system flexibilities that behind-the-meter batteries can provide.

3.3.4 Energy access

The vast majority of people projected to gain access to electricity via off-grid options by 2030 live in Africa. Deploying batteries at the required volumes demands significant battery manufacturing and assembly, maintenance, recycling and disposal capacity on the continent. Much needs to be done for this to happen: at present developers have a web of import duties on battery cells and pack to navigate, local expertise for maintenance is insufficient and battery recycling and disposal services have not yet been sufficiently developed. The development of local capacity in Africa spanning manufacturing, operations and maintenance will be key to achieving access goals by 2030 and stimulate local economies.

Some deployment practices can hinder rather than help: today, for instance, developers focus on capital expenditure and make inadequate provision for maintenance. This contributes to the unnecessarily large number of off-grid systems that fail prematurely and permanently. For a variety of reasons, batteries are often the root cause of these failures. Battery lifespans are generally shorter than those of other system components, and also more sensitive to field conditions, such as amount of cycling, depth of discharge and temperature. Battery management systems, which are embedded components to optimise battery charging and discharging, can improve lifespans but must be robust in order to do so. Some developers report system failures originating in the battery management systems themselves, and these are particularly difficult to debug and fix in the field, especially in rural and remote areas. Plus, there is a lack of consensus around what should be expected in terms of the performance and lifespan of newer battery chemistries, including lithium-ion batteries, in actual on-the-ground conditions. More realistic testing and the sharing of experiences should help developers make better investment and operational decisions regarding batteries.

Battery recycling and disposal capabilities and incentives are nascent in Africa. The challenge is especially acute for very small and very large lithium-ion batteries. Lithium-ion is especially difficult to recycle because opening the batteries safely requires specific expertise and adherence to strict safety protocols. Small lithium-ion batteries, such as those used in solar lighting, are practically and financially challenging to gather and process. For these technical and logistical reasons, currently there is no lithium-ion battery recycling on the African continent.

The NZE Scenario projects that over time most people that gain first electricity access through off-grid systems eventually will benefit from a grid connection. This presents both challenges and opportunities for decentralised access projects. Transparency in grid extension plans, effective grid-integration regulations and partnerships with utilities can help to deliver technical and economic benefits for all parties, including consumers (see Chapter 2, Box 2.5). It is also worth noting that subsequent to gaining grid connection, there is scope for interconnected mini-grids to continue operating in order to enhance local reliability and provide grid services.

3.4 Investment in batteries

Achieving the scale of annual investment in EV batteries and battery storage required to get on a 1.5 °C-compatible pathway will not be an easy feat. A range of risks stand in the way, including the high cost of capital, especially in the emerging market and developing economies, and a variety of regulatory and policy barriers. These risks need to be addressed in order to help scale up investment in batteries. Doing this successfully requires several key issues to be adequately addressed.

Establish clear and stable regulatory frameworks that define the role of EVs and battery storage in the energy transition. This involves clarifying the role over time of these technologies in the context of clean energy transition plans and emissions reduction targets. For EVs, it includes creating an integrated transport sector decarbonisation strategy within a national transport plan (IEA, 2023b), accompanied by supportive policies and measures for the emerging second-hand EV market and forward-looking infrastructure planning for EV charging infrastructure. For battery storage, it includes granting non-discriminatory access to electricity markets and provision of services, and defining permissible use cases so as to facilitate planning by investors and operators and to make it easier for them to assess likely revenues. Where feasible, it would also mean reforming power markets to establish wholesale markets that help deliver cost-effective short- and medium-term flexibility, and can be a significant revenue driver for battery storage projects, especially where variable renewables account for a large share of power generation.

Develop the battery market for EV and energy storage through fiscal incentives and procurement programmes, including concessional support in emerging market and developing economies where necessary. Fiscal incentives can speed up the transition from ICE vehicles to EVs by bringing forward the break-even point between the two technologies, especially if combined with carefully managed reductions in fossil fuel subsidies. Such incentives could be accompanied by electric bus public transportation procurement programmes with government support and, where necessary, concessional finance from development finance institutions. They could also be paired with competitive capacity auctions that provide capacity payments at a fixed rate. These would help to minimise the cost of such payments, while also enabling battery storage services to significantly improve their financial viability, especially if combined with concessional debt in very immature battery storage markets.

Expand consumer access to EVs and mitigate off-taker risk. The purchase price of an EV is a substantial expense for most households around the world, and low cost EV models remain scarce outside China. Focusing incentives on the construction and sale of small and less expensive EV models and expanding access to low cost and standardised financing and leasing models could go a long way to increase affordability of EVs. For battery storage operators, lowering the risk of delayed payments or failure to pay for services provided to transmission networks would help to provide a more secure investment environment, which could be done by expanding off-taker guarantee and credit enhancement mechanisms.

3.5 Manufacturing and supply chains

Building secure, resilient and sustainable battery supply chains necessitates a comprehensive approach that encompasses all stages of the supply chain. This includes raw material extraction, refining, manufacturing, end-of-life product management and recycling.

3.5.1 Developing resilient, sustainable and affordable supply chains

Establishing a secure supply chain for EVs and battery storage demands a multifaceted strategy. Today a number of stages in the battery supply chain, from material mining and refining to battery component and cell manufacturing, are heavily concentrated in a few regions, notably in Asia. This concentration remains a concern as it can make the entire supply chain vulnerable to individual country policy choices, company decisions, natural disasters or technical failures. Mitigating this risk entails diversifying all facets of battery production to build a more robust and resilient supply chain. Diversification encompasses not only manufacturing but also knowledge and skills. Currently most of the expertise needed to produce high quality lithium-ion batteries at scale is concentrated in China, Korea and Japan.

Diversification should be pursued in ways that seek to avoid the geoeconomic fragmentation of the battery supply chain. There is a need to recognise the value of open trade in enabling cost reductions and promoting efficiency. It is not realistic or efficient for most countries to seek to compete in all parts of all supply chains. Identifying relative strengths and seeking complementary partnerships should be at the heart of the development of diversified and resilient battery supply chains.

Recycling is increasingly important and will become much more so in the coming years, especially after 2030 as battery volumes swell. Rapid and continuing expansion of the EV market underscores the need for effective recycling strategies to manage end-of-life batteries and to recover valuable materials. Recycling fosters a more sustainable and circular economy and mitigates potential supply constraints for critical minerals. The case of lead-acid batteries demonstrates that battery recycling rates close to 100% can be achieved with appropriate market incentives and regulations. This highlights the importance of implementing effective frameworks to incentivise recycling.

3.5.2 Ensuring secure, reliable and resilient critical minerals supplies

All scenarios point to rising demand for the critical minerals needed for batteries. Concerted efforts are needed to increase sustainable and reliable mineral supplies by bringing new projects online across diverse geographical regions, facilitating cross-investment opportunities between producer and consumer countries, and introducing financial tools to de-risk investment.

In recent years, governments have introduced policy measures to diversify and strengthen critical mineral supply chains. For example, the US Inflation Reduction Act of 2022 offers a tax credit of USD 3 750 for EVs that meet specified criteria related to domestic critical mineral extraction or processing, or are sourced from a country with which the United States has a free trade agreement. This tax credit, which includes critical minerals that are recycled in North America, is in addition to a USD 3 750 credit for a certain proportion of the EV battery components that have been produced or manufactured in North America. The European Union Critical Raw Materials Act aims by 2030 to reach the point where its member states extract 10%, process 40% and recycle 25% of annual consumption of critical minerals deemed strategic by the EU. It also aims to limit its imports of any of these minerals to a maximum of 65% of the Union's annual consumption from a single exporting country. Canada's Critical Minerals Strategy aims to boost the supply of responsibly sourced critical minerals and to develop domestic value chains. It is backed by CAD 3.8 billion (USD 2.8 billion) in federal funding: one support measure is a 30% Critical Minerals Exploration Tax

Credit. Major producer countries have introduced mining policies to boost domestic production, expand into the downstream value chain and improve environmental and social performance. The IEA Critical Minerals Policy Tracker has identified nearly 450 policies and regulations in more than 35 countries to help governments explore existing and new critical mineral policies (IEA, 2023c).

Balanced markets do not just depend on supply. There is also significant scope for action on the demand side to ease potential strains through recycling, technology innovation, and behavioural change, e.g. choosing smaller cars with smaller batteries. Investment in facilities to recycle minerals extracted from end-of-life batteries to battery-grade quality will be crucial, as will investment to recycle scrap materials from battery production.

Recycling alone will not eliminate the necessity for additional investment in primary supply, especially as it is likely to take at least several years to obtain adequate levels of feedstock to scale up recycled volumes. Nevertheless, the very large volumes of end-of-life batteries that will become available in the years ahead mean that the market for producing recycled minerals in the next decade is poised for significant expansion, paralleling the growth of the EV and battery storage markets. End-of-life lithium-ion battery management is essential for proper collection and recycling. For example, in the European Union extended producer responsibility scheme, battery manufacturers and EV manufacturers must ensure compliant end-of-life battery handling, which is expected to incentivise creation of battery collection centres for consumers and stakeholders.

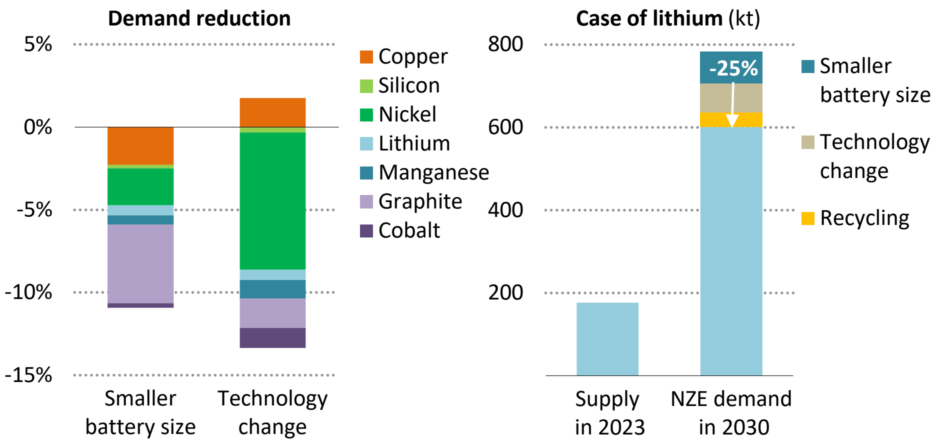
The reuse of end-of-life EV batteries for storage applications could further enhance the effectiveness of circular economy strategies. In addition, secondary battery material production supported by recycling of manufacturing scrap and of end-of-life batteries could result in a further drop in demand for primary supply of critical minerals from mining in 2030. Battery recycling offers significant potential as a secondary source of critical minerals that is more sustainable and reliable, and less geographically concentrated than primary mined resources. Targeted policies such as minimum recycled content requirements and tradeable recycling credits could help to foster secondary battery production in the short term.

Changes in consumer behaviour can also play a part to reduce battery demand. For example, in 2022 – for the first time ever – electric SUVs accounted for more than half of global electric car sales and for 16% of total SUV sales (IEA, 2023d). Today's consumer preference for SUVs with their large batteries contributes to increased demand for critical minerals. A shift away from SUVs and other large vehicles significantly reduces demand for critical minerals used in batteries. Measures to promote smaller electric cars lead to a more than 10% reduction in battery mineral demand by 2030 projected in the NZE Scenario, compared to a counterfactual case where SUV demand continues to grow (Figure 3.7).

Battery chemistries could also make a difference. Nickel-manganese-cobalt (NMC) batteries are still dominant in the market, but other battery chemistries have potential to increase wider adoption. A sensitivity case assuming wider and accelerated adoption of lithium iron phosphate (LFP) cathodes and sodium-ion batteries could reduce critical mineral demand for batteries by 13% in 2030 and nearly 18% in 2050, compared with the NZE Scenario.

In the case of lithium, the combination of smaller EV battery sizes, alternative chemistries as well as recycling could reduce demand for lithium chemicals by 25% in 2030, saving an amount similar to today's supply of these chemicals.

Figure 3.7 ▷ Mineral demand reduction potential for EV batteries and battery storage, 2030



Demand for minerals used in batteries can be reduced through many pathways: using smaller batteries, increasing use of LFP and sodium-ion batteries, and recycling

Note: LFP = lithium-iron phosphate.

Rising demand for critical minerals highlights the importance of addressing the negative environmental and social impacts of mining operations. There is growing recognition that sustainable and responsible mining and refining processes are needed in the interest of a sustainable and equitable clean energy transition. Critical mineral supply chains cannot be truly secure, reliable and resilient unless they are also sustainable and responsible. Policy makers must continue to actively assess the impacts of mining on water, greenhouse gas emissions, biodiversity, human rights, local communities, and corruption. The IEA has developed detailed guidance for policy makers to ensure sustainable and responsible mineral supplies (IEA, 2023e). Recommendations include ensuring robust regulatory regimes are put in place, promoting the development of best practices, strengthening the collection and tracking of granular data to enable progress tracking, and supporting supply chain traceability.

ANNEXES

Definitions

This annex provides general information on terminology used throughout this report including: units and general conversion factors; definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

Units

Batteries	Wh/kg	watt hours per kilogramme
Distance	km	kilometre
Emissions	t CO_2	tonnes of carbon dioxide
	Gt CO_2-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
	g CO_2/km	grammes of carbon dioxide per kilometre
	g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
	kg CO_2/kWh	kilogrammes of carbon dioxide per kilowatt-hour
Energy	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
Mass	kg	kilogramme
	t	tonne (1 tonne = 1 000 kg)
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	Gt	gigatonne (1 tonne x 10^9)
Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/t CO_2	US dollars per tonne of carbon dioxide
Oil	barrel	one barrel of crude oil
	kb/d	thousand barrels per day
	mb/d	million barrels per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

General conversion factors for energy

		Multiplier to convert to:					
		EJ	Gcal	Mtoe	MBtu	bcme	GWh
Convert from:	EJ	1	2.388×10^{8}	23.88	9.478×10^{8}	27.78	2.778×10^{5}
	Gcal	4.1868×10^{-9}	1	10^{-7}	3.968	1.163×10^{-7}	1.163×10^{-3}
	Mtoe	4.1868×10^{-2}	10^{7}	1	3.968×10^{7}	1.163	11 630
	MBtu	1.0551×10^{-9}	0.252	2.52×10^{-8}	1	2.932×10^{-8}	2.931×10^{-4}
	bcme	0.036	8.60×10^{6}	0.86	3.41×10^{7}	1	9 999
	GWh	3.6×10^{-6}	860	8.6×10^{-5}	3 412	1×10^{-4}	1

Note: There is no generally accepted definition of barrel of oil equivalent (boe); typically the conversion factors used vary from 7.15 to 7.40 boe per tonne of oil equivalent. Natural gas is attributed a low heating value of 1 MJ per 44.1 kg. Conversions to and from billion cubic metres of natural gas equivalent (bcme) are given as representative multipliers but may differ from the average values obtained by converting natural gas volumes between IEA balances due to the use of country-specific energy densities. Lower heating values (LHV) are used throughout.

Definitions

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Ammonia (NH_3): Is a compound of nitrogen and hydrogen. It can be used as a feedstock in the chemical sector, as a fuel in direct combustion processes in fuel cells, and as a hydrogen carrier. To be considered a low-emissions fuel, ammonia must be produced from hydrogen in which the electricity used to produce the hydrogen is generated from low-emissions generation sources. Produced in such a way, ammonia is considered a low-emissions hydrogen-based liquid fuel.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to a main power grid may also have a source of back-up power generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline. Capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off-grid systems that are not connected to a main power grid.

Battery storage: Energy storage technology that uses reversible chemical reactions to absorb and release electricity on demand.

Behind-the-meter battery storage: Batteries installed at residential, commercial or industrial end-user locations, generally without a dedicated connection to the grid. They are usually, but not always, significantly smaller than utility-scale batteries.

Buildings: The buildings sector includes energy used in residential and services buildings. Services buildings include commercial and institutional buildings and other non-specified buildings. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Capacity credit: Proportion of the electricity network capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS)**:** The process of capturing carbon dioxide emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore, or used as an input or feedstock in manufacturing.

Carbon dioxide (CO_2)**:** A gas consisting of one part carbon and two parts oxygen. It is an important greenhouse (heat-trapping) gas.

Clean energy: In *power*, clean energy includes: renewable energy sources, nuclear power, fossil fuels fitted with CCUS, hydrogen and ammonia; battery storage; and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry and transport, excluding aviation bunkers and domestic navigation. In *end-use applications*, clean energy includes: direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; CCUS in industry and direct air capture. In *fuel supply*, clean energy includes low-emissions fuels, and measures to reduce the emissions intensity of fossil fuel production.

Coal: Includes both primary coal, i.e. lignite, coking and steam coal, and derived fuels, e.g. patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas works gas, coke-oven gas, blast furnace gas and oxygen steel furnace gas. Peat is also included.

Critical minerals: A wide range of minerals and metals that are essential in clean energy technologies and other modern technologies and have supply chains that are vulnerable to disruption. Although the exact definition and criteria differ among countries, critical minerals for clean energy technologies typically include chromium, cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, platinum group metals, zinc, rare earth elements and other commodities. See the Annex in the IEA special report on the *Role of Critical Minerals in Clean Energy Transitions* available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Decentralised systems: Refers to off-grid connections.

Electric vehicles (EVs)**:** Electric vehicles comprise of battery electric vehicles (BEV) and plug-in hybrid vehicles.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmission and distribution losses.

Electricity generation: Defined as the total amount of electricity generated by power only or combined heat and power plants including generation required for own use. This is also referred to as gross generation.

End-use sectors: Include industry, transport, buildings and other, i.e., agriculture and other non-energy use.

Energy-related and industrial process CO_2 emissions: Carbon dioxide emissions from fuel combustion, industrial processes, and fugitive and flaring CO_2 from fossil fuel extraction. Unless otherwise stated, CO_2 emissions in this report refer to energy-related and industrial process CO_2 emissions.

Energy sector greenhouse gas (GHG) emissions: Energy-related and industrial process CO_2 emissions plus fugitive and vented methane (CH_4) and nitrous dioxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

E-waste: Electrical or electronic equipment that's been discarded.

Fossil fuels: Include coal, natural gas and oil.

Front-of-the-meter: Assets connected directly to the transmission or distribution networks.

Geothermal: Geothermal energy is heat from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use): Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating, and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply): Obtained from the combustion of fuels, nuclear reactors, large-scale heat pumps, geothermal or solar resources. It may be used for heating or cooling or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation.

Heavy-duty vehicles (HDVs): Include both medium freight trucks (gross weight 3.5 to 15 tonnes) and heavy freight trucks (gross weight >15 tonnes).

Hydrogen: Hydrogen is used in the energy system as an energy carrier, as an industrial raw material, or is combined with other inputs to produce hydrogen-based fuels. Unless otherwise stated, hydrogen in this report refers to low-emissions hydrogen.

Hydrogen-based fuels: See low-emissions hydrogen-based fuels.

Hydropower: Refers to the electricity produced in hydropower projects, with the assumption of 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, aluminium, and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under other energy sector. There is an exception for fuel transformation in blast furnaces and coke ovens, which are reported within iron and steel. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

Investment: Investment is capital expenditure for energy supply, infrastructure, end-use and efficiency. Fuel supply investment includes the production, transformation and transport of oil, gas, coal and low-emissions fuels. *Power sector* investment includes new construction and refurbishment of generation, electricity grids (transmission, distribution and public electric vehicle chargers), and battery storage. *Energy efficiency* investment includes efficiency improvements in buildings, industry and transport. *Other end-use* investment includes the purchase of equipment for the direct use of renewables, electric vehicles, electrification in buildings, industry and international marine transport, equipment for the use of low-emissions fuels, and CCUS in industry and direct air capture. Data and projections reflect spending over the lifetime of projects and are presented in real terms in year-2023 US dollars converted at market exchange rates unless otherwise stated. Total investment reported for a year reflects the amount spent in that year.

Levelised cost of electricity (LCOE): LCOE combines into a single metric all the cost elements directly associated with a given power technology, including construction, financing, fuel, maintenance and costs associated with a carbon price. It does not include network integration or other indirect costs.

Light-duty vehicles (LDVs): Include passenger cars and light commercial vehicles (gross vehicle weight < 3.5 tonnes).

Low-emissions electricity: Includes output from renewable energy technologies, nuclear power, fossil fuels fitted with CCUS, hydrogen and ammonia.

Low-emissions fuels: Include modern bioenergy, low-emissions hydrogen and low-emissions hydrogen-based fuels.

Mini-grids: Small electric power systems, connected or not connected to main electricity networks, linking a number of households and/or other consumers.

Modern energy access: Includes household access to a minimum level of electricity (basic bundle equivalent to range of 50-75 kWh per household per year); household access to less

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harmful and more sustainable cooking and heating fuels, and improved/advanced stoves; access that enables productive economic activity; and access for public services.

Natural gas: Includes gas occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both non-associated gas originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil production as well as methane recovered from coal mines (colliery gas). Natural gas liquids, manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg (Standard Conditions). Gas data expressed in exajoules are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Nuclear power: Refers to the electricity produced by a nuclear reactor, assuming an average conversion efficiency of 33%.

Off-grid systems: Mini-grids and stand-alone systems for individual households or groups of consumers not connected to a main grid.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Includes both conventional and unconventional oil production. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirits, lubricants, bitumen, paraffin, waxes and petroleum coke.

Passenger car: A road motor vehicle, other than a moped or a motorcycle, intended to transport passengers. It includes vans designed and used primarily to transport passengers. Excluded are light commercial vehicles, motor coaches, urban buses and mini-buses/mini-coaches.

PayGo model: Contracts or subscriptions for off-grid solar systems that aim to reduce the initial upfront cost for solar energy access by allowing customers to make instalment payments to purchase units for using solar electricity instead of paying upfront for solar home systems. (Also referred to as Pay-as-you-go model.)

Power generation: Refers to electricity generation and heat production from all sources of electricity, including electricity-only power plants, heat plants, and combined heat and power plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Rare earth elements (REEs)**:** A group of seventeen chemical elements in the periodic table, specifically the fifteen lanthanides plus scandium and yttrium. REEs are key components in some clean energy technologies, including wind turbines, electric vehicle motors and electrolysers.

Renewables: Include bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking.

Road transport: Includes all road vehicle types (passenger cars, two/three-wheelers, light commercial vehicles, buses and medium and heavy freight trucks).

Services: A component of the buildings sector. It represents energy used in commercial facilities, e.g. offices, shops, hotels, restaurants, and in institutional buildings, e.g. schools, hospitals, public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking and desalination.

Shipping/navigation: This transport mode includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or people on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar: Includes both solar photovoltaics and concentrating solar power.

Solar home systems (SHS)**:** Small-scale photovoltaic and battery stand-alone systems, i.e. with capacity equal to or higher than 10 watt peak (Wp) supplying electricity for single households or small businesses. They are most often used off-grid, but also where grid supply is not reliable. Access to electricity in the IEA definition of access to electricity considers SHS of 10 Wp and above as providing access to electricity.

Solar multi-light systems: Solar PV-based lighting systems of 3 Wp to 9 Wp that provide more than one lighting point and mobile phone charging.

Solar photovoltaics (PV)**:** Electricity produced from solar photovoltaic cells including utility-scale and small-scale installations.

Stand-alone systems: Small-scale autonomous electricity supply for households or small businesses. They are generally used off-grid, but also where grid supply is not reliable. Stand-alone systems include solar home systems, small wind or hydro generators, diesel or gasoline generators. The difference compared with mini-grids is in scale and that stand-alone systems do not have a distribution network serving multiple costumers.

Total energy supply (TES)**:** Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC)**:** Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens); transport; buildings (including residential and services); and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC)**:** Is a variable defined primarily for tracking progress towards target 7.2 of the United Nations Sustainable Development Goals (SDG). It incorporates total final consumption by end-use sectors, but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (indicator SDG 7.2.1), where TFEC is the denominator.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes: fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes all size categories of commercial vehicles: light trucks (gross vehicle weight < 3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (gross vehicle weight >15 tonnes).

Unabated fossil fuel use: Consumption of fossil fuels in facilities without CCUS.

Utility-scale battery storage: Large battery applications connected directly to transmission or distribution networks (front-of-the-meter), typically ranging from several hundred kilowatt-hours to multiple gigawatt-hours in size.

Value-adjusted levelised cost of electricity (VALCOE)**:** Incorporates information on both costs and the value provided to the electricity system. Based on the LCOE, estimates of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies.

Variable renewable energy (VRE)**:** Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero emissions vehicles (ZEVs)**:** Vehicles that are capable of operating without tailpipe CO_2 emissions (battery electric and fuel cell vehicles).

Regional and country groupings

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus,[1,2] Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, The People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Bolivarian Republic of Venezuela (Venezuela), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay and other Central and South American countries and territories.[4]

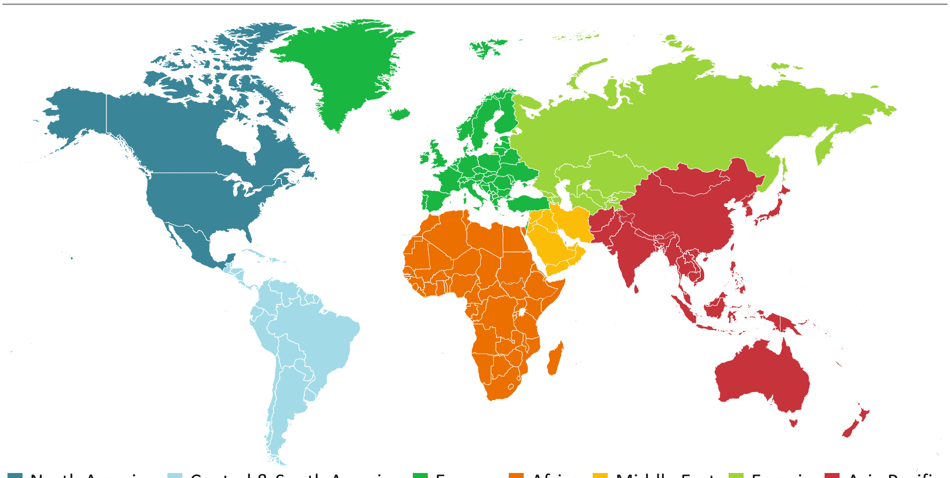
China: Includes (The People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Figure A.1 ▷ Main country groupings



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency)**:** OECD regional grouping excluding Chile, Colombia, Costa Rica, Iceland, Israel, Latvia and Slovenia.

Latin America and the Caribbean (LAC)**:** Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development)**:** Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom and United States.

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Kingdom of Eswatini, Madagascar, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Uganda, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Republic of Türkiye: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten (Dutch part), Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Mauritania, Sao Tome and Principe, Seychelles, Sierra Leone and Somalia.

Abbreviations and acronyms

AI	artificial intelligence
APS	Announced Pledges Scenario
AUD	Australian dollar
BEV	battery electric vehicle
BMS	battery management system
BSS	battery swapping station
BTM	behind-the-meter
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage
Co	cobalt
COP	Conference of the Parties (UNFCCC)
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CTP	cell-to-pack
DRC	Democratic Republic of the Congo
EMDE	emerging market and developing economies
EU	European Union
EV	electric vehicle
FID	final investment decision
FiT	feed-in tariff
GEC	Global Energy and Climate (model)
GT	gas turbine
GHG	greenhouse gases
Gr	graphite
HDV	heavy-duty vehicle
ICE	internal combustion engine
IEA	International Energy Agency

IRA	Inflation Reduction Act (United States)
LCO	lithium-cobalt oxide
LCOE	levelised cost of electricity
LDV	light-duty vehicle
LFMP	lithium-manganese-iron phosphate
LFP	lithium-iron phosphate
Li	lithium
LIB	lithium-ion battery
LME	London Metals Exchange
LMO	lithium-manganese oxide
MDV	medium-duty vehicle
MER	market exchange rate
NCA	nickel-cobalt-aluminium
Ni	nickel
NMC	nickel-manganese-cobalt
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OPEX	operating expenditure
pkm	passenger-kilometre
PLDV	passenger light-duty vehicle
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
SHS	solar home systems
SSB	solid-state battery
STEPS	Stated Policy Scenario
SUV	sport utility vehicle
US	United States
USD	United States dollar
V2B	vehicle-to-building
V2G	vehicle-to-grid
VALCOE	value-adjusted levelised cost of electricity
VC	venture capital
VPP	virtual power plant
WEO	World Energy Outlook
ZEV	zero emissions vehicle

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Batteries and Secure Energy Transitions

World Energy Outlook Special Report

Batteries are an important part of the global energy system today and are poised to play a critical role in secure clean energy transitions. In the transport sector, they are the essential component in the millions of electric vehicles sold each year. In the power sector, battery storage is the fastest growing clean energy technology on the market. The versatile nature of batteries means they can serve utility-scale projects, behind-the-meter storage for households and businesses and provide access to electricity in decentralised solutions like mini-grids and solar home systems. Moreover, falling costs for batteries are fast improving the competitiveness of electric vehicles and storage applications in the power sector.

The IEA's Special Report on *Batteries and Secure Energy Transitions* highlights the key role batteries will play in fulfilling the recent 2030 commitments made by nearly 200 countries at COP28 to put the global energy system on the path to net zero emissions. These include tripling global renewable energy capacity, doubling the pace of energy efficiency improvements and transitioning away from fossil fuels.

This special report brings together the latest data and information on batteries from around the world, including recent market developments and technological advances. It also offers insights and analysis on leading markets and key barriers to growth. By looking at the entire battery ecosystem, from critical minerals and manufacturing to use and recycling, it identifies synergies and potential bottlenecks across different sectors. The report also highlights areas that call for greater attention from policy makers and industry.