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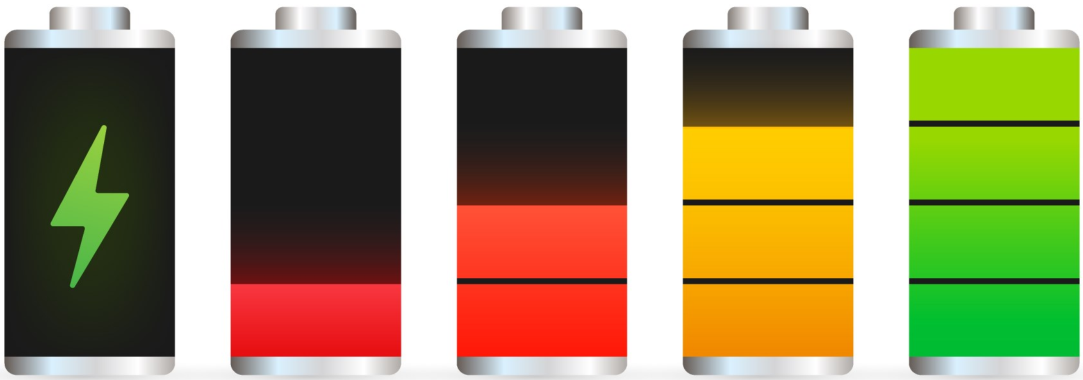

Battery charge

The rise of lithium-ion – options and implications

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The abrupt fall in Chinese electric vehicle (EV) sales in Q3 has disrupted the lithium-ion battery supply chain and reset valuations. This gives investors the opportunity to reassess the long-term buy case. We believe batteries will play a critical role in the future of the transport and power industries. Investors have numerous options to play this growth in the automotive, chemical/industrial, transport and electricity sectors.

Demand: When, not if

The sustained fall in lithium-ion battery prices over the last decade provides good visibility on EVs reaching price parity with their combustion engine equivalents by the mid-2020s. We forecast that EVs (including hybrids) will account for 38% of new car sales by 2030. Including growth in other transport modes and the electricity sector, we see lithium-ion battery revenues trebling in the next decade. The recent subsidy cuts in China highlight the importance of policy to market development. Our forecasts assume no major policy changes, but concerted global actions to cut CO_2 could accelerate adoption.

Supply: Chemistry is key

We see scale and process improvements driving down battery manufacturing costs over the next decade, but expect the bulk of the performance gains to come from improved chemistry. For transport applications, raising energy density (kWh/kg) is key. Better anode and cathode materials are capable of delivering further improvements, but gains cannot sacrifice durability, charge rates or safety. The prospects for solid state look particularly exciting, but cost and scale manufacturing challenges make deployment in the automotive sector unlikely in the near term.

How to play the battery theme

Through their impact on the transport sector in particular, lithium-ion batteries will be central to one of the most significant industrial transitions in the next 30 years. Investors can gain direct exposure via different parts of the supply chain:

- Material developers/suppliers: Versarien, Nabaltec, IBU-tec and Ohara are developing better materials which could drive improvements in battery performance. Ilika offers a way to play the transition to solid state.
- Battery manufacturers: in a fragmented market, we see scale as key to driving down costs. LG Chem and CATL currently have the highest market share.
- Battery deployers: Tesla has a 58% US EV market share and is a pure play on EV growth. BYD is the leading EV player globally with a 24% share in China; subsidy cuts have seen its shares fall 25% ytd. Energy storage funds (GRID and GSF) offer a way to play battery deployment in the UK electricity sector.

Battery growth will also have important implications for other sectors:

- Raw materials: the IEA expects EVs to drive demand for lithium, cobalt and nickel (class 1) significantly beyond current supply capacity. However, the size of the cobalt shortfall is very sensitive to battery chemistry assumptions.
- Oil and gas: we estimate that a fleet of 225m electric vehicles by 2030 trims oil demand by 4% (4.0mb/d), with the impact accelerating beyond this point.
- Electricity demand: National Grid estimates that EVs will add 23TWh (9%) to UK electricity demand by 2030 and 90TWh (35%) by 2050.

Battery demand

The key to a low-carbon future

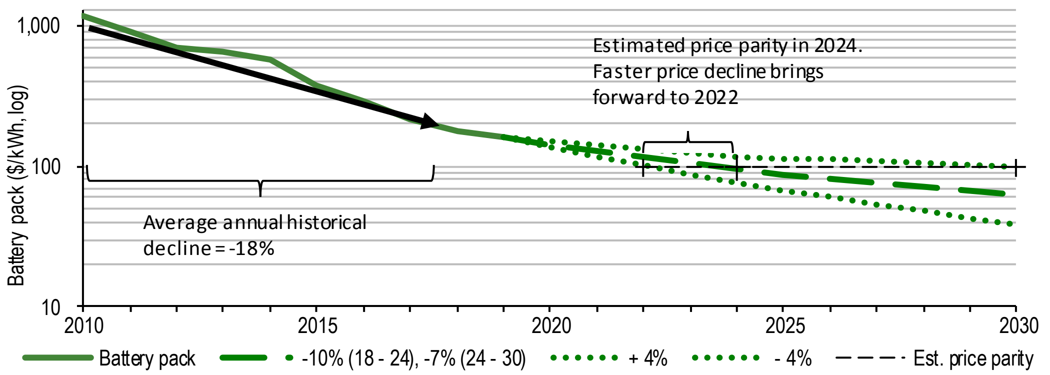
Batteries look set to play a critical role in the future of the transport and power industries. Limiting climate change to 2°C (or even lower) requires both sectors to significantly decarbonise by 2050. Batteries represent both the most feasible alternative to fossil fuels in many transport modes and an important way to balance the intermittency of wind and solar electricity generation.

It is difficult to understate the size of this transformation. Arguably, the shift to EVs will be one of, if not the most significant industrial transitions in the next 30 years. Aside from its direct impact on the car industry and its supply chain, it will affect the oil & gas, electricity and mining sectors as well as the wider urban environment. Many (mostly European) countries have set long-term targets to ban the sale of petrol/diesel cars and over 94 cities (700m inhabitants) have announced plans to restrict them. Car makers are gradually responding, spurred on by ever stricter CO_2 emissions targets.

Automotive: When not if

In our view, the pace of the transition, not whether it takes place, should be the focus of the debate. While the dramatic impact of subsidy cuts in China highlights the importance of policy, in our view the trajectory of battery costs is likely to the major determinant of this pace. Since 2010, lithium-ion battery pack prices have fallen at an average of 18% a year to $176/kWh in 2018. This trajectory should reassure investors that EVs will reach price parity (see note to Exhibit 1) with mainstream petrol/diesel equivalents at some point. Exhibit 1 suggests that even if the rate of price declines slows to 10% pa, parity will be reached in most markets by 2024. At this point it is more profitable (on average) for car makers to sell EVs and therefore adoption rates should accelerate.

Exhibit 1: Battery price declines and price parity

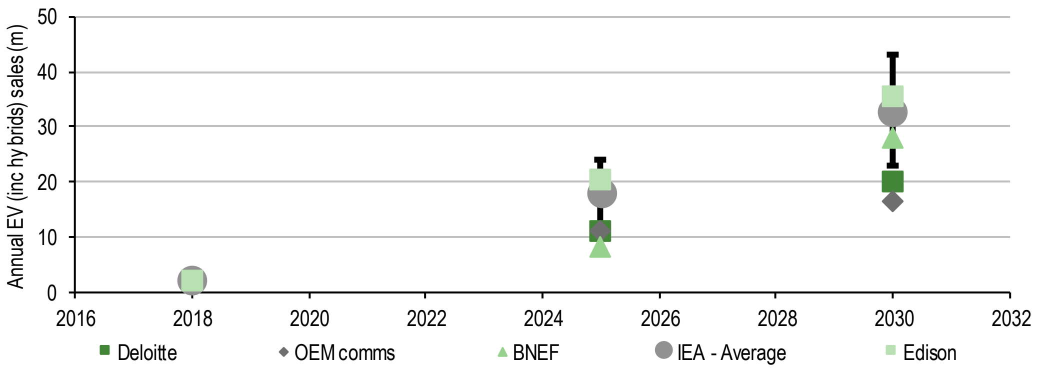


Source: BNEF historical based on volume weighted average lithium-ion battery pack price, Edison Investment Research forecasts. Note: *Price parity for mid-size EV estimated at $100/kWh based on IEA analysis assuming 180-mile range (50kWh), four-year ownership, $1.5/l gas, $0.17kWh electricity.

Small variations in the rate of cost improvements, extrapolated over the long term, have a significant impact on the timing of price parity. Increasing the rate of the dollar per kWh CAGR decline by 4pp (from 10% to 14%, for example) brings it forward to 2022; sustaining the historical (18% pa decline) could bring it forward to 2021. The circular nature of the relationship between production volumes and cost reductions is one of the large uncertainties at play. As adoption rises, more can be invested in R&D, manufacturing economies improve and the pace of learning accelerates.

As the price premium disappears, subjective factors are likely to play a bigger role in determining the pace of consumer adoption. Range anxiety is the biggest barrier in most markets currently. We see this becoming a legacy issue as battery size rises (new EVs typically offer more than a 200mile range), and the number and speed of charging points steadily increase. Ultimately, consumer attitudes towards (and preference for) EVs will be more important. A new car is a status symbol for many. In our view, the appeal of quiet, fast (instant torque offers rapid acceleration) cars offering driving with a clear conscience has the potential to drive a much faster EV 'upgrade cycle' than can be predicted by just analysing relative price points. The automotive industry offers numerous examples of features achieving widespread adoption (eg four-wheel drive, turbochargers) that are difficult to justify on economic grounds. Aesthetics are also an important buying factor. **Tesla (TSLA:US)** has (largely) succeeded in positioning its EVs as desirable consumer objects, but other brands have been less successful. As with any big-ticket purchase, consumers will need reassurance. Concerns about value retention and range anxiety may linger long after the underlying issue has been resolved.

Exhibit 2: EV (including hybrids) sales forecasts



Source: BNEF, IEA. Note: *OEM comms represent the minimum shipments based on all publicly stated commitments and assuming consistent market share.

Current forecasts from the IEA and BNEF anticipate EVs (including hybrids) growing from 2% of new cars sales in 2018 globally to 25–46% by 2030 (Exhibit 2). This would imply sales of 23–43m by 2030 and an EV fleet between 125m and 250m. The major uncertainty according to the IEA is policy. In a scenario where there are no major policy changes, China accounts for over half the market by 2030, and penetration of new sales reaches nearly 50% in Europe but just 30% in the US. Accelerating the shift to EVs tangibly reduces global CO_2 emissions. In a world where governments treat climate change as an urgent issue, a concerted policy response (subsidies, taxes, targets combined with charging infrastructure investment and parking incentives) could substantially accelerate adoption.

Demand in other transport sectors

The discussion of battery demand inevitably focuses on the passenger car market due to its size and the assumption that the pace of performance improvements here will largely drive adoption in other transport modes. In fact, the electrification of two- and three-wheel vehicles (bikes, scooters and tuk-tuks) is already well advanced. The IEA estimates there are already more than 300m electric two- and three-wheel vehicles globally (c 30% penetration) with over 85% in China. While average battery size is small (<1kWh), annual sales are c 30m already.

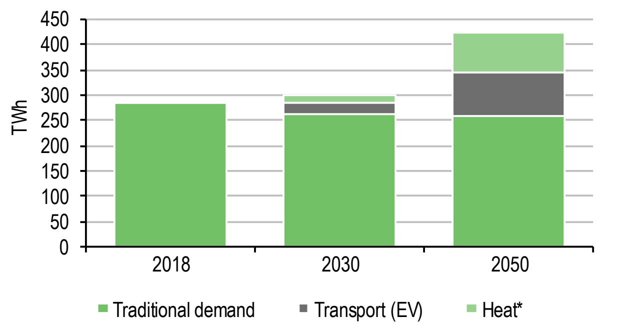
Penetration of commercial road segments and other transport modes is likely to take longer. Lithium-ion batteries still struggle to match the energy density of fossil fuels (ie kWh/kg). Solutions are being tested for short-haul trucks and buses in urban areas with established charging infrastructure and acute pollution issues (China has nearly 0.5m electric buses) but matching the range or capacity of long-distance trucks is much more difficult. Hydrogen fuel cells might ultimately prove more effective here. There is a similar situation in marine transport. Short-distance ferries with huge (1MWh+) batteries are being introduced on several Scandinavian routes but solutions for transcontinental cargo ships are some way off. Electric aviation is in the development stage. The Wright Electric initiative, supported by EasyJet, aims to develop an electric plane capable of flying 150 people 270 miles by 2030.

Power demand

Batteries are also expected to play a big role in the decarbonisation of the electricity grid. National Grid estimates that current UK electricity consumption will rise by nearly 50% by 2050, driven by EVs and heating (see Exhibit 3). Much, if not all of this must be supplied by intermittent solar and wind sources if climate objectives are to be met. The combination of demand, supply and frequency fluctuations should drive rapid storage growth. Neoen **(NEOEN:PA)** recently announced a 50% expansion of its 129MWh battery in Hornsdale, Australia – already the world's biggest. National Grid believes the UK will need a further 8GW of storage by 2030 (see Exhibit 4). Energy storage funds from **Gresham (GRID:LN)** and **Gore Street (GSF:LN)** are investing in multiple projects here.

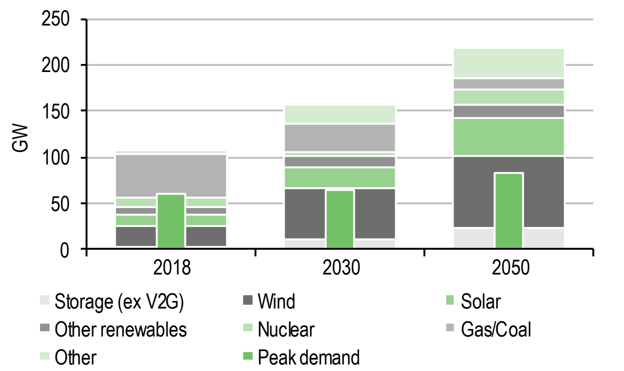
The precise role that storage will play in the electricity sector, and the extent to which it will actually create significant incremental battery demand, has yet to be defined. Lithium-ion batteries are just one form of 'flexibility': other storage technologies, demand-side responses and increased grid interconnection are valid alternatives. EV batteries are also likely to play a role in the electricity market, either via smart chargers (vehicle-to-grid) or as 'second-life' (partially degraded) batteries.

Exhibit 3: Demand for electrical energy in the UK



Source: National Grid ESO: 2°C (http://fes.nationalgrid.com/fes-document/). Note: *Heat includes electrical energy used by residential heat pumps and hydrogen conversion (some of which may ultimately be used in transport).

Exhibit 4: UK capacity required and peak demand



Source: National Grid ESO: 2°C (http://fes.nationalgrid.com/fes-document/). Note: Decarbonising requires intermittent renewable capacity to more than treble by 2050 and grid storage to rise sixfold.

Demand forecasts

In Exhibit 5, we set out our view of how lithium-ion battery demand could evolve over the next decade. Our analysis of battery chemistry and capacity investment (see page 5 onwards) suggests that reductions in battery prices are likely to continue. Even conservatively assuming a 10% pa fall in cost (nearly half the historical rate), EVs should reach price parity in most markets by 2024, spurring an acceleration in demand. We forecast a tenfold growth in annual capacity by 2030 (a 23% CAGR), driven primarily by transport (90% of demand in 2030). Factoring in our assumptions regarding the price decline (see Exhibit 5), this translates into a battery revenue CAGR of c 12%.

Our 2030 forecast of 1.8TWh/year is broadly in line with the range of scenarios envisaged by the IEA and BNEF. Our assumption that global EV penetration (including hybrids) reaches 38% by 2030 is towards the top of IEA and BNEF estimates, but this is offset by a relatively high share of hybrids in our forecast, which lowers the blended battery size per EV of 32kWh.

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Exhibit 5: Annual battery demand set to grow tenfold over the next decade driven by EVs*

	2018	2025e	2030e	Comments and assumptions
EVs (including hybrids, m)	2	21	36	2025 figure compares to 12m in IEA (NPS**) and BNEF. 2030 figure compares to 22m and 41m from IEA and c 28m from BNEF.
– Pure EVs	1	13	23	Mix of pure EVs in 2030 = 66%, consistent with IEA but below BNEF
Penetration of car sales (%)	2.3	23.0	38.0	Assume car market grows at 1% pa, consistent with historical trend.
– Pure EVs	1.6	15.0	25.0	
Average battery size (kWh)	29.0	31.6	31.7	Modest growth in average capacity due to mix (more hybrids) and improving
– Pure EVs	37.0	42.0	42.0	chemistry including solid state beyond 2025.
Battery capacity (GWh)				
– EVs (including hybrids)	57	649	1,132	Overall transport demand in 2030 of 1.7TWh pa equates to an average IEA
– Other transport	40	207	524	estimate of 2.0TWh (range 1.4TWh to 2.6TWh). Other transport primarily driven by freight (12% adoption by 2030) and buses.
– Consumer	80	85	87	
– Power	10	60	80	
Total	187	1,001	1,822	A 23% revenue CAGR between 2018 and 2030. BNEF forecasts 0.7TWh in 2025 and 2.0TWh in 2030.
Price ($/kWh)	176	88	62	We believe that technological advances and the economies of scale will allow the cost base to accommodate such a reduction in pricing.
Average annual price decline (%)	(18)	(9)	(7)	Less aggressive than historical (18% pa) rate of decline (see Exhibit 1).
Revenue ($bn)	33	88	113	A 12% revenue CAGR between 2018 and 2030.

Source: Edison Investment Research, with data from the IEA, BNEF. Note: *Our definition of EVs is all light duty vehicles (LDV) – essentially all passenger cars plus light commercial vehicles. **The IEA published two scenarios – the New Policies Scenario (NPS) and a more aggressive 30@30 scenario.

Battery production

Battery manufacturers are making extensive investments in lithium-ion production capacity to support the expected EV growth. Benchmark Mineral Intelligence estimates that total capacity is already over 250GWh pa and Exhibit 6, which details the announced capacity plans of the main players and is based on IEA data, suggests that nearly 100GWh/year of annual capacity is expected to be opened during 2020. These plans can always be delayed and often facilities are opened on a modular basis, but with demand growth expected to be modest in 2019, this implies capacity and investment is running ahead of demand currently.

6: Announced capacities of leading EV battery cell producers*

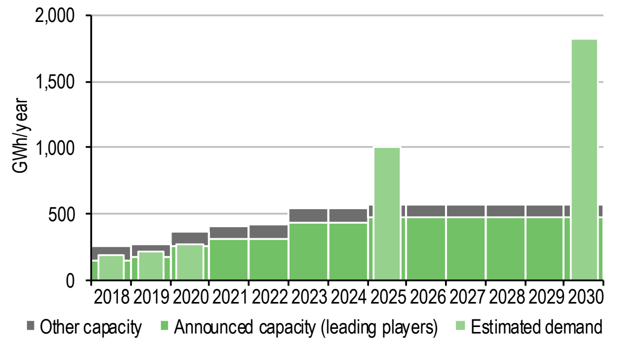
	Known EV customers	Production facilities	Announced annual production capacity (GWh/year)
BYD	BYD	China	24GWh/year currently A further 24GWh/year by 2020 50GWh/year by 2023 (two factories: Shaanxi and Chongqing) 10GWh/year (Huizhou: unknown timing)
CATL	BMW, Daimler, Honda, PSA Group, Volvo, VW	China, EU	40GWh/year currently (Liyang, Ningde). Expansion in Guangzhou planned. (12GWh 2017) 14GWh/year planned for Germany in 2021
Envision AESC	Nissan	US, Japan, UK China	7.5GWh/year already 20GWh/year in China planned for 2020
LG Chem	Audi, Daimler, GM, Porsche, Renault, Tesla, VW, Volvo	South Korea China US EU China	10GWh/year (estimated) 20GWh/year (Nanjing 1) <10GWh/year capacity (Michigan). Considering second site 15GWh/year (Poland). Plans to expand Poland site by 15GWh/year by 2022 32GWh/year in 2023
LIBCOIN/BHEL	-	India	30GWh/year planned in 2025, 2026 and 2027
Lithium Werks	-	China	8GWh/year planned for 2021
Northvolt	BMW	Germany, Sweden	32GWh/year in 2023 (16GWh for Germany and 16 GWh in Sweden)
Panasonic/Tesla	Tesla	US China Europe	35GWh/year Gigafactory 1 in Nevada (currently operating at c 23GWh) 13GWh/year opening Q419 13GWh/year (estimated). Proposed Gigafactory to commence production in 2021
Samsung SDI	-	EU	1.7GWh/year in 2020
SK Innovation	Mercedes-Benz, Hyundai, VW	South Korea US EU	5GWh/year in Q119 9.8GWh/year in 2022 7.5GWh/year by 2021 (Hungary)
Terra E	-	Germany	4 GWh/year in 2020

Source: Edison Investment Research including data collated by IEA. Note: *For a full description of listed companies, see Exhibit 14.

By 2025, this situation could be reversed. Total announced and qualified capacity of 500GWh/year is just half our demand forecast and the majority is in China (see Exhibits 7 and 8, respectively).

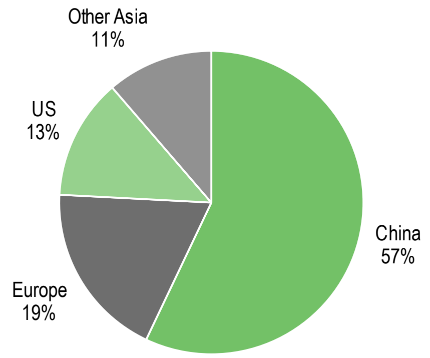
Suppliers see scale as a vital to driving manufacturing efficiencies and getting costs down. Aside from helping secure raw materials more cheaply, greater volumes lower overheads and justify investment in more efficient production technologies. In general, manufacturing facilities are getting larger and we would expect these scale economies to put smaller players under pressure over time.

Exhibit 7: Demand vs announced supply



Source: Edison Investment Research, IEA, various

Exhibit 8: Announced capacity in 2025 by region



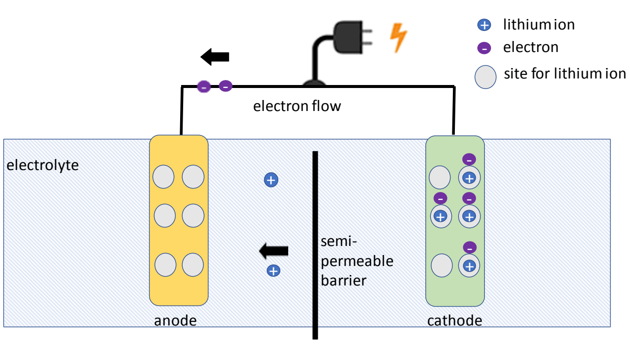
Source: Edison Investment Research, IEA, various

The rise of lithium-ion technology

There are multiple methods of storing energy and numerous battery chemistries. The advantage of lithium-ion is its energy density. Its ability to store twice the energy of a nickel cadmium (NiCd) battery of the same size and weight makes it particularly suitable for transport applications.

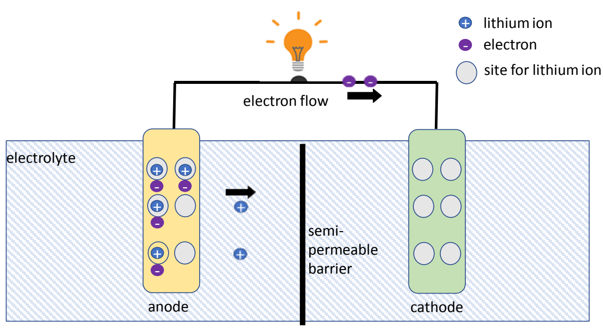
Both electrodes in a lithium-ion cell are made of materials that can absorb (intercalate) the charged lithium ions without damaging their internal structure. When the battery is flat (fully discharged), all the lithium ions are held within the cathode. During charging, they move from the cathode through the electrolyte and the separator (a semi-permeable barrier) to the anode to balance the negatively charged electrons (Exhibit 9). During discharge, the lithium ions are released from the anode, travelling back through the electrolyte and separator to be absorbed in the cathode. This also releases the electrons that were balancing the lithium ions at the anode. These flow through an external wire creating the electric current (Exhibit 10) until the cathode has become full of lithium ions again and the battery is flat.

Exhibit 9: Lithium-ion battery charging



Source: Edison Investment Research

Exhibit 10: Lithium-ion battery discharging



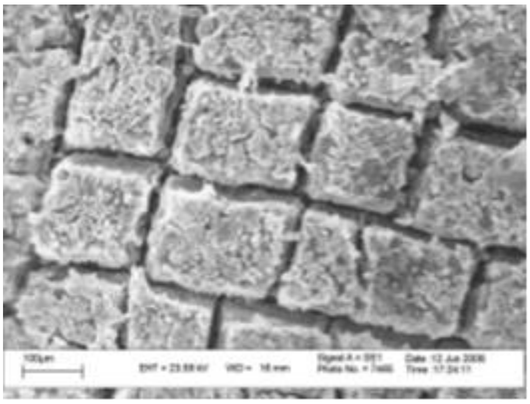
Source: Edison Investment Research

Significant R&D investment in the chemical composition of the anode, the cathode and the electrolyte (see below) aims to improve lithium-ion energy density still further. Other development programmes are focused on longevity. Battery degradation over time and charging cycles affect performance, costs and safety. Ferdinand Dudenhöffer, professor of automotive economics at the University of Duisburg-Essen and former Opel and Porsche executive, believes that improving battery chemistry, rather than greater production efficiency, offers the biggest potential to improve battery economics: 'The production value of the cell is about 15%. Sixty percent is just in the materials of cathode, and another 20% is the materials of anodes.' (source: Energy News, April 2019).

New anode materials

Anodes are usually made from graphite, which is a form of carbon. One alternative for increasing the amount of electricity an anode can store is to replace the graphite with silicon. Silicon anodes can store up to three times as much energy as a graphite anode of similar volume, but in the process can absorb so many ions that the silicon physically expands to four times its original size. Since lithium-ion batteries need to be tough and rigid to prevent the flammable electrolyte from escaping, having a component that regularly expands and contracts by such a large amount is not practical. Moreover, repeated expansion and contraction leads to surface cracks and eventually anode particles break off completely. A battery with an anode of bulk silicon will only last a few charge/discharge cycles before it is unusable (Exhibit 11).

Exhibit 11: Degradation of bulk silicon anode



Source: Nexeon

Invesco, **IP Group (IPO:LN)** and **Wacker Chemie (WCH:GR**) have all invested in UK technology start-up Nexeon which is working on alternative nanosilicon materials. These are well advanced in qualification at a number of cell makers and automotive OEMs. Nexeon is also in manufacturing partnership talks to produce this material in mass volumes. It has a second generation material under development that is partly supported by Innovate UK funding. This material is also being sampled to potential customers and can be used in higher percentages in the anode.

Shin-Etsu Chemical (4063:TYO) is also focusing on silicon-based materials for lithium-ion batteries, offering a silicon oxide material for anodes. Sila Nanotechnologies, which announced a $170m funding led by Daimler in April 2019, has developed a silicon-based anode to replace graphite in lithium-ion batteries. The company claims that its materials can improve the energy density of batteries by 20%. It started building its first production lines for battery materials in 2018 with the intention of supplying materials before the end of 2020.

Another alternative is to mix the silicon with graphene, which consists of individual layers of carbon, each one atom thick. **Talga Resources (TLG:AU)**, a vertically integrated, advanced material company with graphite mining in northern Sweden, graphene plant operations in Germany and product R&D in the UK, has recently launched a graphene/silicon battery anode product, Talnode-C, which it claims can increase the amount of energy a lithium-ion battery can store by around 70%.

In September 2018, AIM-listed **Versarien (VRS:LN)** announced that it was acquiring a 62% stake in graphene materials company Gnanomat for £2.6m. The investment will help Gnanomat scale up a pilot plant producing graphene-based electrode materials. Gnanomat's materials have demonstrated substantial improvements over conventional materials at lab scale, eg a 353% improvement in energy density and a 181% improvement in power density.

A further alternative is to replace the graphite in the anode with lithium titanate nanocrystals (LTO cells). This increases the surface area from $3m^2$/gram to around $100m^2$/gram, enabling electrons to enter and leave the anode much more rapidly, leading to faster charging/discharging and enhanced battery lifetimes. This high-power characteristic makes them suitable for transport applications where quick acceleration is needed, such as electric buses and ferries, and hybrid power systems, where batteries must step in quickly to provide a back-up supply. **Leclanché (LECN:SW)** has developed a proprietary LTO technology that can provide rapid acceleration for EVs. **Toshiba (6502:JP**) also uses LTO in the anode of its SCiB rechargeable battery to enhance safety, longevity, low-temperature performance and reduce charging time. It claims that LTO doubles the battery anode capacity, enabling a compact electric car to be charged to a range of 200 miles in just six minutes.

Changing cathode material to increase energy density

The materials used for the cathode are typically the defining characteristic of the battery. The most common lithium-ion cells combine a graphite anode with a lithium cobalt oxide cathode. While this gives a high-energy density it is also subject to thermal instability. The automotive sector predominantly deploys cells with NMC cathodes (typically one-third nickel, one-third manganese and one-third cobalt or NMC_{433}) that have a relatively high-energy density and charging rate, and better thermal stability and safety**.** Leclanché has developed G-NMC technology to complement its LTO cells, which is already being used in the grid applications and EVs. Japan-listed manufacturer of optical glass **Ohara (5218:JP)** has developed a material called LICGC (lithium-ion conducting glass-ceramic), which is technically a solid electrolyte, but if used in a cathode can accelerate the speed at which lithium ions move. It claims that adding LICGC boosts battery capacity by 25% at -20°C, and 44% at room temperature.

However, cobalt supply is potentially an issue in the long term (see page 13). **Johnson Matthey (JMAT:LN)** is developing high nickel cathode material eLNO, which it claims reduces cobalt requirements while offering a step change in energy density and lower $ per kWh/cycle.

Using boehmite to improve separator performance

The battery separator prevents the anode and cathode from touching (creating a short circuit), while permitting the passage of ionic charge carriers that complete the electric circuit. Originally, separators were made of simple plastic films that had the correct pore size to allow ions to flow through while keeping the other components blocked. The thinner the separator, the more quickly lithium ions can flow from one electrode to another and the faster the battery can charge. However, if it charges too quickly the battery gets hot, potentially causing the separator to shrink and a short circuit that could start a fire (this was suggested as the cause of the Samsung Galaxy 7 smartphone battery issues). To prevent, this retardant alumina and boehmite coatings are used to strengthen the separator. Using boehmite rather than alumina permits a substantial reduction in coating thickness without compromising thermal stability. MarketWatch estimates that the global boehmite market will increase from $140m in 2019 to $310m by 2024, a CAGR of 14.5%.

Solid electrolytes make batteries smaller and safer

A solid-state battery replaces the liquid or polymer gel electrolyte in a lithium-ion battery cell with a solid material, usually a ceramic or a solid polymer, although sulphides and glass are also used. As a solid electrolyte prevents the electrodes touching, the cost and bulk of a separator is not needed and therefore a solid-state battery can have a higher energy density. It also makes the battery safer (liquid electrolytes are more flammable). The batteries can also have faster charge times, hold charge for longer and, since all the parts are solid, can be produced in unconventional formats such as wires or ribbons. The improved safety and lower density make solid-state suitable for new medical applications. However, the technology remains substantially more expensive than conventional lithium-ion batteries at present.

Exhibit 12: Ilika's solid-state battery for electric vehicles

Source: Ilika

Ilika's (IKA:LN) batteries use a patented ceramic electrolyte that boosts energy density by 50% compared to other solid-state batteries. It is commercialising smaller Stereax batteries suitable for networked medical devices, automotive sensors, smart homes and cities and larger format cells suitable for electric vehicles, aerospace and stationary power.

Ohara's LICGC material is also proposed as a solid electrolyte, initially for small watch and smartphone batteries but also for EVs in the longer term. Its oxide-based electrolyte competes with the sulphide version being developed by rivals like **Mitsui Mining & Smelting Co (5706:JP)**. Sulphide electrolytes tend to have higher conductivity and are closer to commercialisation, while oxide-based solid electrolytes are more stable in the atmosphere.

FDK Corporation (6955:JP) announced in May 2019 that it was starting to ship samples of its small solid-state battery for certain customers. This product is targeted at internet of things (IoT) devices, wearables, chip-set reference clocks, and industrial and automotive equipment used in harsh environments. Electronics components company **TDK Corporation (6762:JP)** has also started to ship a miniature solid-state battery. The battery has a lithium-based ceramic oxide electrolyte and measures just 4.5mm × 3.2mm × 1.1mm, smaller than a grain of rice. TDK announced output of 30,000 a month in August 2018, claiming that it was 'the world's first instance of a practical application for a solid-state battery that can be incorporated into electric circuits.'

Solid-state batteries extend electric vehicle range

Many prominent car makers and their suppliers believe solid-state batteries will play a big role in EVs over time, reducing the overall weight of the battery, extending range and improving safety.

BMW (BMW:GE) is investing €200m in its Battery Cell Competence Centre in Munich and has teamed up with Solid Power, a Colorado-based developer of solid-state batteries. It aims to have solid-state powered EVs on the road in 2026. Battery manufacturer A123 Systems, which is now part of the Wanxiang Group, has also invested in Solid Power alongside Ford, Hyundai and Samsung. In June 2018, **VW (VOW:GE)** announced a $100m investment in QuantumScape, a solid-state battery start-up spun out of Stanford University, following six years of collaboration. The companies also formed a joint venture to drive volume manufacturing, with Volkswagen contributing its production expertise and know-how in scaling projects and QuantumScape its solid-state battery

IP. Volkswagen claims a switch to solid-state technology would more than double energy capacity compared with its current lithium-ion batteries, boosting the range of the e-Golf from its current 186 miles to 466 miles. Like BMW, it is aiming for its first solid-state battery vehicle by 2025.

Massachusetts-based start-up Ionic Materials develops and supplies polymer electrolyte material, lithium metal anodes, sulphur cathodes and liquid electrolytes. It is also working with A123 Systems on a solid-state battery to combine its polymer with A123's next-generation NMC/graphite lithium-ion chemistry and aims to reach volume production in 2022. In February 2018, it secured $65m in a Series C funding round from investors that included car makers (Hyundai, Nissan, Mitsubishi and Renault), Sun Microsystems co-founder Bill Joy and A123 Systems.

Japan's New Energy and Industrial Technology Development Organization (NEDO) has launched the second phase of a major solid-state lithium-ion battery project. The ¥10bn ($90m) project involves 23 automobile, battery and material manufacturers and includes Toyota, Nissan, Honda, Panasonic, GS Yuasa, Hitachi and Murata, as well as 15 universities and public research institutes. It aims to address bottlenecks in the mass production of solid-state materials and ultimately lower the battery cost to c ¥10,000/kWh ($90/kWh) by 2030. It also targets a charge time of 10 minutes, a third of that needed by lithium-ion batteries currently. **Toyota (7203:JP)** is investing ¥1.5tn ($13.9bn) in batteries and plans to commercialise solid-state technology by the early 2020s. Toyota started work on developing solid-state electrolytes more than 10 years ago and holds some joint patents with Ilika.

Tesla's battery supplier, Panasonic, continues to research solid-state technology, but believes that many obstacles to full commercialisation remain. Since its existing lithium-ion packs already give its Model S a 335-mile range, it has less incentive to invest in solid-state technology.

Lithium-air technology still at pre-commercial phase

Lithium-air batteries are similar to lithium-ion batteries in structure except in having the cathodes exposed to the atmosphere or oxygen. The technology has a theoretical energy density nine times that of a lithium-ion. However, development is still at an early stage as there are some critical barriers regarding practical application of the technology to overcome, including short cycle life. Here too, advances in the materials used in the different battery components may provide a solution.

How to play the battery theme

Lithium-ion batteries will be at the heart of one of the most significant industrial transitions in the next 30 years. We expect EV growth to drive a 12% CAGR in battery revenues until 2030. Investors can gain exposure via different parts of the supply chain or focus on vertically integrated players. We see attributes such as the proportion of revenue exposed to batteries, sustainable competitive differentiation, relative scale and sound balance sheet as indicators of long-term success.

Battery manufacturers

The mainstream EV market looks set to be dominated by commodity tech/chemical players such as LG Chem, CATL and Panasonic with the scale and the balance sheets to drive down costs (Exhibit 6). With over half the projected capacity by 2025, Chinese players are aiming to capture a big share of the market but, given the strategic significance of this industry, other national champions are likely to emerge.

Smaller players are evolving their strategies. Leclanché has broadened its focus from simply supplying battery modules (see below) to delivering turnkey solutions, which also include power conversion and energy management systems. As battery cells typically account for only half the value of a large energy storage system, this broader focus enables it to address much more of the value chain. In a future where electricity generation is increasingly dominated by intermittent sources and there is a substantial resource of distributed energy storage capacity, the role of software in balancing supply and demand will become increasingly critical. Solo Energy, which was acquired by **Smart Metering Systems (SMS:LN)** earlier this year, uses blockchain to create a peer-to-peer energy trading economy so consumers can share locally generated renewable energy.

Material developers/suppliers

While some of the fall in battery costs anticipated over the next decade will be driven by manufacturing efficiencies, we expect the bulk of the improvements to be driven by improved chemistries. Companies focused on enhancing anode performance include UK start-up Nexeon, while Talga Resources and Versarien (via Gnanomat) are exploring the potential of graphene. Leclanché and Toshiba are looking at LTO to improve power and battery lifetimes. Companies looking to improve cathode performance include Ohara, with its LICGC material, which aims to improve battery capacity, and Leclanché, with is G-NMC technology. Johnson Matthey plans to construct a plant in Poland to produce its eLNO material, which is due to open in 2021/22 and will have the capacity to produce 100,000mtpa.

Frankfurt-listed **Nabaltec's** **(NTG:GE)** separator material can help accelerate the rate of battery charging. Its products are primarily based on aluminium hydroxide and aluminium oxide currently, but it is benefiting from increasing demand for boehmite. While boehmite revenues were only €5m in H119, approximately 5% of total sales, they are high margin and growing rapidly (66% y-o-y).

Other players have a broader material focus. Frankfurt-listed **IBU-tec** **(IBU:GE)** is an international full-service provider in the field of thermal process engineering, predominantly treating inorganic materials. It recently started supplying materials to a major EV battery manufacturer in the Far East, which could drive an order of magnitude increase in its battery materials sales. It also recently started work with five partners including VARTA Microbattery on a three-year project funded by the Federal Ministry of Education and Research to develop processes for a new, iron-based, metal/air battery for stationary, high-capacity energy storage. It has developed a proprietary pulsation reactor technology to create finely divided iron oxide particles as the starting material for iron-slurry electrodes. Pro forma revenue growth of 19% y-o-y in H119 included a 150% increase in sales of battery materials. Belgium-listed chemical company **Solvay (SOLB:BB)** is a provider of key materials in lithium-ion batteries from cathode binders to high-performance electrolytes. Its fluorinated polymer, SOLEF PVDF, is used in the manufacture of separators, with the fluorine element in the compound making the battery fire-resistant.

The increased kWh/Kg and safety offered by solid state makes its long-term prospects particularly attractive in our view. Given the challenges of manufacturing at scale and cost, it looks unlikely that the technology will make a big inroad into the automotive sector until 2025. However, there are significant opportunities elsewhere. Ilika highlights the 15bn sensors deployed globally, the vast majority of which either require connection to mains power (making them expensive to install), or disposable coin cells (making them expensive to maintain). During FY19, it launched its M50 device for medical applications such as cardiac implants, contact lenses and dental braces. The company is currently generating income from a portfolio of development programmes and grant funding but aims to build an IP licensing/royalty model similar to ARM in the long term. As part of the UK's £250m Faraday battery challenge, it is collaborating with Honda, Jaguar Land Rover, McLaren and Ricardo to develop large-format, rapid charge cells for automotive applications, receiving £5m aggregate support from the programme.

However, solid-state developments also highlight the risks for investors in battery technology. Dyson acquired Michigan University spin-off Sakti3 for $90m in 2015, with the intention of deploying Sakti3's solid-state batteries in EVs it planned to launch from 2020 onwards. Sakti3 claimed its solid-state battery had an energy density of 0.4kWh/kg, almost double that of the batteries produced by Panasonic for Tesla (0.23kWh/kg), even at lower volumes. Dyson allocated $1bn to construct a factory for mass production, but in September 2018 it recorded a £46m impairment charge on its investment in Sakti3 and finally closed its EV project in October 2019. While it still has an active battery development programme, which includes solid-state technology, it is now focused on making its existing products cordless. Similarly, Bosch bought solid-state battery developer SEEO in August 2015 for an undisclosed sum, with the intention of manufacturing 50kWh battery packs that would weigh less than 200kg and offer a range of 200 miles for a compact vehicle. In April 2018, Bosch decided that building its own production facility was too risky. It estimated that the initial capital investment required for a 200GWh capacity (sufficient to command a 20% market share) would be €20bn and operating costs would run into the billions. It halted its research into cell technologies, which had cost it c €500m, put SEEO up for sale and refocused on assembling cells from third parties.

Battery deployers

The automotive sector will drive battery deployment over the next decade (over two-thirds of incremental demand by 2030). Due to its 100% EV focus and 50%+ US market share, Tesla is seen as the default way to play this trend. Despite the volatility created by its well documented corporate governance and production issues, the shares have performed well in general. Traditional automakers such as Volkswagen (VW) plan to eclipse its volumes as early as 2020, but EVs look set to remain a small proportion of their overall sales. Potentially more interesting are Chinese car makers such as **BYD (1211:HK)**, **BAIC (1598:HK)** and **NIO (NIO:US)**. The reduction in subsidies earlier this year has seen the Chinese market slow sharply and share prices fall (in July the subsidy for EVs with less than a 250-mile range has been scrapped and halved for all other EVs). However, the overall policy environment remains supportive. BYD is both the leading EV supplier globally (c 250,000 cars in 2019) and a market leader domestically (24% share). BAIC is second with a c 12% market share and is marginally outperforming BYD currently, but EVs account for just 9% of its volumes. NIO is 100% EV but its premium segment focus means volumes are lower (it expects to deliver over 30,000 cars in 2019).

There are also options outside the automotive sector. Some of the hype in personal mobility service companies may have dissipated over the last year, but growth in two-wheel electric vehicles remains. In Italy, **Askoll EVA (EVA:IM)** manufactures e-scooters and e-motorcycles and **Energica (EMC:IM)** makes high-performance e-motorcycles. In China **Niu Technologies (NIU:US)** focuses on electric two-wheelers. Just like car makers, traditional motorcycles and bike manufacturers such as **Pierer Mobility (PMAG:AV)** are also moving towards e-mobility. **Leclanché** offers a unique way to play electrification of marine transportation and **paragon** **(PGN:GE)** manufactures lithium-ion power packs for a variety of segments (including forklifts, mining vehicles, buses and 5G mobile networks) through its listed Voltabox subsidiary. The power sector also offers few pure plays, but two UK specialist energy storage funds (Gresham House and Gore Street) provide investors with an opportunity to play the rapid growth expected in grid scale storage. Grid scale storage typically generates income from a combination of 'merchant' services (eg making a margin on the spread between high and low wholesale power prices) and services to the grid, which include maintaining the demand/supply balance, frequency and voltage. Assuming the UK continues to decarbonise and the amount of intermittent generation continues to rise, National Grid estimates 3GW of storage capacity based on lithium-ion could be added in the next five years (a tenfold increase).

The impact of batteries on other sectors

The rise of batteries is likely to have a profound impact on many industries. Aside from the direct impact on car makers and their supply chains, it will affect demand for oil and gas, electricity and natural resources. The IEA estimates that increased battery production in its 30@30 scenario (slightly above our forecast and where EV penetration reaches 46% of new sales in 2030; see Exhibit 5) will require a more than threefold increase in lithium output, a doubling of cobalt production and a 40% increase in nickel output by 2030 (see Exhibit 13). Whether supply can be scaled up to reach this demand is uncertain and many analysts expect cathode chemistries will need to evolve to reduce cobalt demand in particular. At this point, we do not see a threat to the trajectory of battery price reduction from raw materials prices. Analysis by Imperial based on (much higher) 2017 prices suggested that total raw material costs for a lithium battery are c $52 per kWh, less than a quarter of the total battery pack cost in 2017 and significantly below our $88/kWh 2025 total battery cost forecast.

Exhibit 13: The impact of EV growth on raw material demand

	2018			2030 (IEA's 30@30 scenario)		
	Total production (TP, kt)	EV battery demand (EVBD, kt)	EVBD/TP (%)	EV battery demand (EVBD, kt)	EVBD/TP (%)	EVBD CAGR (%)
Cobalt	140	20	14.3	350	250.0	26.9
Lithium	95	10	10.5	310	326.3	33.1
Manganese	1,700	5	0.3	360	21.2	42.8
Nickel (class 1)	1,250	25	2.0	1,750	140.0	42.5

Source: Edison Investment Research based on IEA data

We estimate that our EV forecast would lead to a fleet of 225m (c 17% of all cars on the road) by 2030 and effectively reduce oil demand by 4.0mb/d, 4% of current demand. National Grid models electricity demand from EVs reaching 23TWh in 2030 and 90TWh in 2050 in its Two Degrees scenario in the UK, 9% and 35% of total UK electricity consumption. Not only will adoption affect overall demand, but it will also shift consumption patterns. Significant further investment in charging infrastructure will be needed to support EV adoption and grid-connected batteries could play a big role in managing peak demand and grid stability.

Exhibit 14: Listed companies featured in this report

Company name	Description	Share price (local)	Market cap ($m)	FY18 financial performance				Estimated	
				Rev ($m)	EBIT margin (%)	FCF margin (%)	Net debt/ (cash) ($m)	Market share (%)*	Battery share (%)**
Askoll	Italian manufacturer of e-scooters and e-motorbikes	€2	25	16	(60)	N/A	(11)	N/A	N/A
BAIC	Chinese car maker currently seeing rapid EV growth	HK$4.5	4,557	22,586	14	9	(1,676)	5.3	9
BHEL	India-based industrial and power equipment supplier. Announced a JV with LIBCOIN to manufacture batteries	INR44	2,174	4,368	5	(13)	(704)	N/A	N/A
BMW	First German premium car maker to launch a mass-market EV (i3 in 2013) aiming for 0.3m EV sales in 2021	€73	52,281	111,234	9	(3)	98,568	6.8	6
BYD	Vertically integrated Chinese car maker also manufacturing batteries. Global leader in EV sales	HK$37.4	15,747	18,183	6	2	7,787	12.0	42
CATL	China-based battery and battery systems manufacturer	¥91	28,729	4,431	13	16	(1,644)	16.0	100
Energica	An Italian electric motorcycle market manufacturer	¥2	45	3	(199)	N/A	2	N/A	100
FDK	A Fujitsu subsidiary primarily selling consumer batteries	¥859	273	646	N/A	N/A	95	N/A	66
Gore Street	UK fund investing in energy storage projects (GSF)	99p	64	N/A	N/A	N/A	N/A	N/A	100
Gresham H.	UK fund investing in energy storage systems	580p	212	19	(1)	N/A	(5)	N/A	100
IBU-tec	Chemical company that develops and manufactures advanced materials	€16	71	N/A	N/A	N/A	12	N/A	N/A
Ilika	Developed solid-state battery technology with many applications including IoT, medical devices and autos	26p	34	3	(104)	(116)	(5)	N/A	100
IP Group	Develops early-stage technology companies including Ceres Power (fuel cell) and Nexeon (silicon nanowire)	63p	871	(48)	245	70	(125)	N/A	N/A
Johnson Matthey	Speciality chemicals company with a division focusing on batteries fuel cells	2792p	7,102	5,312	13	1	1,139	N/A	5
Leclanché†	Swiss company specialising in electrical energy storage	CHF1.3	186	49	(86)	(110)	35	N/A	100
LG Chem	Korean chemicals supplier with large battery business	KRW300500	17,416	25,389	8	(8)	2,483	20	27
Mitsui Mining	Diversified metal/material producer developing a sulphide electrolyte for solid-state batteries	¥2900	1,524	4,535	N/A	1	1,856	N/A	32
Nabaltec	Developing/manufacturing speciality chemicals based on aluminium hydroxide/oxide, used as battery separators	€31	305	198	10	(6)	40	N/A	4
Neoen	Develops and supplies renewable energy including the largest grid storage asset in the world in Australia	€25	2,375	257	48	(144)	1,152	N/A	7
Nio	Heavily loss-making China EV manufacturer focused on the premium SUV market	$2	2,390	738	(194)	(238)	(735)	N/A	100
Niu	A leading manufacturer of smart electric scooters using Panasonic's lithium-ion battery and focused on China	$9	632	220	(3)	(2)	(78)	N/A	100
Ohara	Develops and manufactures optical glass. Its LICGC can be used as a cathode or a solid-state electrolyte	¥1480	331	248	N/A	N/A	(56)	N/A	38
Panasonic	Diverse industrial company with a large EV battery business. Customers include Tesla and Toyota	¥1061	22,760	72,918	N/A	(2)	858	9.0	11
paragon†	Listed Voltabox subsidiary makes batteries for a range of segments including forklifts, buses and 5G networks	€12	61	210	8	(55)	79	N/A	37
Pierer Mobility	A leading European motorcycle producer with a growing range of electronic vehicles	€46	1,147	N/A	N/A	N/A	363	N/A	N/A
Samsung SDI	Korea-based battery (and display) manufacturer	KRW227500	12,622	8,193	8	(21)	1,475	N/A	75
Shin-Etsu Chemical	A Japan-based chemical manufacturer specialising in PVC and semiconductors	¥11755	44,957	14,286	N/A	11	(9,270)	N/A	N/A
SK Innovation	Korean oil refining company investing heavily in boosting EV manufacturing battery capacity	KRW146000	10,792	49,047	4	1	3,137	N/A	1
SMS	Develops and deploys smart meters in the UK	548p	812	129	28	(94)	181	N/A	N/A
Solvay	Chemical and advanced materials company. Focused on cathodes and high-performance electrolytes	€102	11,690	11,661	15	(2)	3,105	N/A	29
Talga Resources	Owns multiple high-grade graphite mines in Sweden and has developed a conversion into graphene	A$0.5	69	N/A	N/A	N/A	(5)	N/A	100
TDK	Electronic components company focused on lithium polymer and has started shipping solid-state battery	¥12130	14,095	12,384	9	(2)	1,719	N/A	40
Tesla	Second largest EV manufacturer globally focused on the premium market and the US in particular	$349	62,877	21,461	2	(0)	8,286	10.0	100
Toshiba	Diverse electronics manufacturer developing new materials and investing to expand battery production	¥3705	15,460	33,793	N/A	(0)	(8,127)	N/A	NA
Toyota	Japanese car maker and pioneer of hybrid model expanding its range into EVs	¥7663	196,625	274,529	N/A	8	129,213	4.0	1
Versarien	Advanced materials company with a focus on graphene and developing materials for the battery market	92p	185	12	N/A	N/A	(4)	N/A	N/A
VW	German car maker currently investing heavily to broaden its EV range and reach sales of 3m pa in 2025	€176	97,202	267,475	6	(3)	152,857	4.0	1

Source: Edison Investment Research, Refinitiv. Note: *Market share estimated from sales of EVs or battery manufacturing capacity. **Share of revenue generated from batteries, materials going into batteries or products that include batteries. †Edison client. Prices as at 10 December 2019.

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