EDISON

EV outlook #2

Driving better performance from EV batteries

Sector report

9 August 2021

The electric vehicle (EV) market is currently attracting investors because of its high growth prospects, with Bloomberg NEF predicting that passenger EV sales will rise from 3.1m in 2020 to 14m in 2025. Since battery performance is critical to widespread EV adoption and an individual EV model's competitiveness, we believe that companies involved in the development and manufacture of battery materials and components should receive at least as much attention as automotive manufacturers. This report reviews the battery technology options, identifies companies engaged at this level of the supply chain and suggests a framework for making investment decisions.

Battery performance key to EV adoption

Widespread EV adoption is predicated on reducing the cost of vehicles so that they are broadly comparable with conventionally powered forms of transport. Cost parity will be achieved through a combination of improvements in battery performance and the realisation of economies of scale. Adoption also requires charge time to be cut so it becomes equivalent to filling a conventionally powered vehicle's petrol tank and the elimination of range anxiety. Improvements in battery performance are key to achieving these goals. Moreover, battery performance will be the differentiator for EV performance, hence the substantial investment in the sector by automotive OEMs and others. The introduction of novel battery chemistries also addresses issues with sourcing materials such as cobalt and safety.

Improving battery chemistry supports adoption

This report looks at the different components of a lithium-ion EV battery and presents companies such as Nano One that are developing innovative materials and technologies with the potential to improve the performance of these battery components, as well as companies such as Ilika and QuantumScape developing solid-state batteries based on novel electrolytes. The report also profiles companies such as Phinergy that are developing alternatives to the incumbent lithium-ion technology that could potentially displace it in future.

Investing in sustainable differentiators

Since share prices of stocks in this sector have risen sharply over the last year, many have very high valuations. This makes them sensitive to any setbacks in either their technology development or overall market growth. Moreover, many are pre-profit, or indeed pre-revenue, so justifying these high valuations without a view of future cash flows relating to potential product roll-out is tricky. Against this backdrop, we suggest that investors look for companies with technologies that deliver a demonstrably superior performance to the competition that can be sustained through the use of patented IP and proprietary know-how and, for preference, partners that provide a clear route to market.

One option for reducing the risk while still participating in the sector is to consider established companies that provide essential chemicals used to create innovative battery materials and components. Typically, these supply multiple customers, reducing the risk of a single company's technology not being widely adopted.

Companies in this report	
Bolloré	BOL:FP
Directa Plus	DCTA:LN
Electrovaya	EFL:CN
Evonik Industries	EVK:GE
Enovix	ENVX:US
EVE Energy	300014:SZ
Ganfeng Lithium	002460:SZ
IBU-tec	IBU:GE
Ilika	IKA:LN
Johnson Matthey	JMAT:LN
Leclanché	LECN:SW
Lion E-Mobility	LMI:GR
Martinrea International	MRE.V
Nabaltec	NTG:ETR
Nano One Materials	NANO:TSX
NanoXplore	GRA:V
Net Element	NETE:US
Ohara	5218:JP
Phinergy	PNRG:TLV
QuantumScape	QS:US
Samsung	005930:KS
Solvay	SOLB:BB
Talga Resources	TLG:AU
Tesla	TSLA:US
Toshiba	6502:JP
Toyota	7203:JP
Trackwise Designs*	TWD :LN
Versarien	VRS:LN
Zinc8 Energy Solutions	ZAIR:CNSX

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How to play the battery materials theme

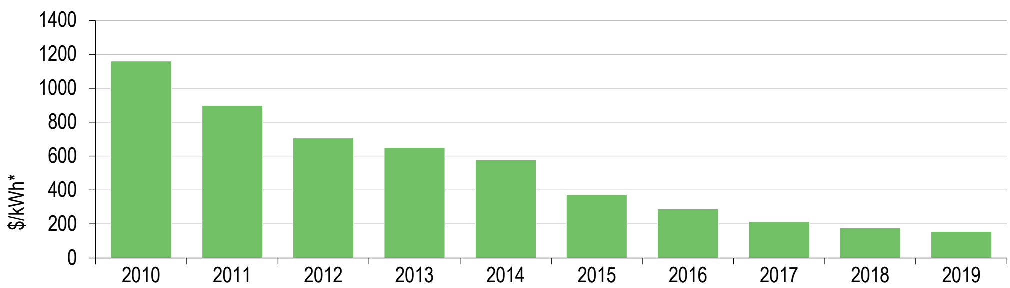
Improved battery performance is critical to EV adoption

As discussed in our previous report in this series EV outlook #1: Growth, policy and net zero, many governments have recently announced decarbonisation targets, backed by timescales for phasing out vehicles powered by fossil fuels, funding for charging infrastructure and consumer incentives. These high-level commitments, together with individual consumers making environmentally informed purchase decisions are resulting in rising demand for EVs. Investors can gain exposure at different stages of the supply chain: EV manufacturers; battery system manufacturers and integrators; and battery materials and components manufacturers and raw material suppliers.

This report focuses on companies involved in the development and manufacture of battery materials and components. We believe that these merit investor attention because widespread EV adoption is predicated on reducing the cost of vehicles so that they are broadly comparable with conventionally powered forms of transport, on eliminating range anxiety and on cutting charge time so it becomes equivalent to filling a car's petrol tank. Improvements in battery performance are key to achieving these three goals.

Innovative battery materials and manufacturing efficiencies help reduce EV cost

Exhibit 1: Battery pack prices 2010–19



Source: Statista. Note: *Average prices weighted on volumes sold.

The battery system is a major proportion of the cost of an EV. In December 2020 Bloomberg NEF (BNEF) estimated that it accounted for around 30% of the total cost to consumers, down from 57% in 2015 as the cost of battery packs has dropped. After adjusting for inflation, BNEF noted that the average price of battery packs for cars dropped from $1,160/kWh in 2010 to $156/kWh in 2019 and predicts a drop to below $100/kWh by 2024. For a Tesla Model 3 with a 75kWh battery pack, the cost reduction equates to a cut in battery price from almost $90,000 10 years ago to around $11,700 today. If this trend continues, Elon Musk's intention, stated at Tesla's Battery Day in 2020, to bring a $25,000 electric car to market within the next three years that would be 'on par' or 'slightly better' than a comparable gasoline car, appears feasible.

The reduction in battery prices is partly attributable to improvement in manufacturing efficiency as production is scaled up and processes modified. For example, Tesla is investigating the use of dry coating techniques, higher levels of machine integration and new methods for extracting lithium from naturally occurring mineral deposits. The price reduction is also attributable to the development of improved battery materials, which increase energy density (ie the amount of energy that can be stored per kilogram or litre of battery), meaning the same amount of charge can be supplied from a smaller, lighter battery.

The total cost of ownership of an EV depends not just on the upfront cost of the vehicle's battery pack but also on battery cycle life (ie the number of charge/discharge cycles that a battery can go through before performance is degraded to such a point that the pack needs to be replaced). Here too, the development of innovative materials is key to achieving the desired performance.

Innovative battery materials also address range and charging issues

Improving the energy density of batteries by developing new materials also helps solve the problem of EV range. A Tesla model 3, which is the company's most affordable model with a starting price of £40,990, has a range of 263 to 353 miles, depending on the specification. In contrast, Euro Car Parts states that the most popular car in Britain, the Ford Fiesta, can cover up to 821 miles on a full tank. A Ford Focus can travel the furthest, reaching up to 1,112 miles on a full tank. The practical range and payload of a battery-powered EV is limited by an effect called process mass compounding, in which for every kilogram of battery mass added to increase range, the size and weight of other vehicle components must also be increased to maintain the performance and safety of the vehicle, so the incremental range provided by additional batteries decreases as each battery is added. This effect is particularly problematic for heavier vehicles such as delivery trucks or buses, which may make fuel-cells a better option for these types of vehicles.

The UK Automotive Council has set a target of an energy density of 350Wh/kg by 2025 to encourage EV adoption. Technologies such as solid-state lithium-ion batteries that are able to deliver these energy densities are available (see Exhibit 2), but only in low volumes. The development of enhanced battery components is also key to creating batteries that can withstand being charged at the high currents required to give faster charge times.

Exhibit 2: Energy density for different battery technologies

Technology type	Energy density (Wh/kg)	Availability
Lead-acid	35–40	Widely available
Ni-Cd (nickel-cadmium)	50–75	Widely available
NiMH (nickel metal hydride)	70–100	Widely available
LTO (lithium titanate)	50–80	Widely available
LFP (lithium ferro-phosphate)	90–120	Widely available
Sodium-ion (Faradion)	150–160	Under development
LCO (lithium cobalt oxide)	150–200	Widely available
NMC (lithium nickel manganese cobalt oxide)	150–220	Widely available
NCA (lithium nickel-cobalt-aluminium oxide)	200–260	Widely available
Solid-state lithium	c 350	Low volumes available
Lithium-sulphur	471	Low volumes available
Lithium-air (theoretical)	5,000–11,000	Low volumes available

Source: Edison Investment Research

Since battery performance will be the key determinant of vehicle performance, automotive manufacturers will be keen to ensure that they continue pushing parameters such as energy density, charge and discharge speed (which determines how quickly a vehicle can accelerate) and cycle life. Reducing charge time helps address range anxiety. Automotive OEMs are already making substantial investments in battery technology, either through third parties or their own in-house R&D, to ensure that they have access to industry-leading battery packs. This is likely to continue.

Choosing between battery materials suppliers

This report looks at the different components of a lithium-ion EV battery: anode, cathode, electrolyte and separator in turn, and presents companies that are developing innovative materials in each of these areas, as well as companies incorporating these materials in novel types of batteries. The report also presents companies developing alternatives to the incumbent lithium-ion technology that could displace it in future. We note that many of the materials that are being developed to improve the performance of conventional lithium-ion batteries may also be used to improve the performance of solid-state batteries and also emerging technologies such as lithium-air. These improvements to the basic lithium-ion technology, as well as alternatives, are summarised in Exhibit 3.

Exhibit 3: Technology developments

Approach	+/-	Companies developing technology
Use of silicon in anode	Improved energy density/issues with structural stability	Amprius Technologies, Enevate, Enovix, OneD Material, Silia Nanotechnologies, Talga Resources
Creating anode from organic matrix	Improved charge-time/early stage	EVE Energy, StoreDot
LTO anode	Improved charge time/ lower energy density	Leclanché, Toshiba
Addition of graphene to anode/cathode	Improved energy density/potentially higher cost	Directa Plus, NanoXplore, Versarien
NMC cathode	Higher energy density/lower cycle life	Electrovaya, Leclanché, Nano One Materials, Tesla
LMNO cathode	Cobalt-free, fast charging	Johnson Matthey, Nano One Materials
Solid-state battery (solid electrolyte)	Smaller, safer, faster charge, longer lifetime/more expensive	BlueSolutions, Ganfeng Lithium, Ilika, Ionic Materials, LiNa Energy, QuantumScape, Samsung, Solid Power, Toyota
Metal-air	Very high energy density/unconventional recharging	Phinergy, Zinc8 Energy Solutions
Lithium-sulphur	High energy density, cobalt free/early stage	NexTech Batteries, OXIS Energy, Sion Power
Sodium-ion	Safer, lower cost/early stage	Faradion, Tiamat Energy

Source: Edison Investment Research

Since all of the companies mentioned in this report are engaged in a potentially large and high-growth market, they are of potential interest to investors. However. none are acting in isolation, so it is not just the absolute progress an individual company achieves with regards to parameters such as energy density and cost, but also how these compare with the competition. For investors, this means looking for technology that delivers a demonstrably superior performance to the competition, which can be sustained through the use of patented IP and proprietary know-how. For preference, we recommend companies that have set out a programme with timescales for reaching commercialisation and have secured ipartners that give them a clear route to market. Normally, we would recommend potential investors to check on balance sheet strength, but note that companies in the process of commercialising a new technology are likely to need additional funding to achieve this, so this requirement may be waived, provided investors recognise the risk of share dilution and business failure. In fact, institutional investors may find that a transformational capital raise such as the final tranche required to reach commercialisation is a good opportunity to build a meaningful stake in an otherwise illiquid stock.

While it is relatively easy for investors to assess balance sheet strength and routes to market, we have found that company presentations and websites tend to major on the attractiveness of the EV sector and provide relatively little information about technical performance, possibly because this is regarded as commercially sensitive. This has hampered our analysis.

Our other concern is the high valuations of companies in this sector. As with companies engaged in the hydrogen economy (see our report Hydrogen, rising fast in the global energy mix), the share prices of pure-play battery companies rose sharply during 2020. This has made them sensitive to any setbacks to either market growth or technology development as well as to a change in market sentiment. For companies that are pre-profit, or indeed pre-revenue, a full reverse discounted cash flow (DCF) analysis examining what level of output would be required to justify the current share price would be needed, and even then, the potential for further fund-raisings to finance volume production, which would be dilutive, would need to be considered.

Exhibit 4: Key data for profiled stocks

Name	2020 share price change (%)	Ytd share price change (%)	Market cap (US$m)	Historical sales (US$m)	Historical EBIT margin (%)	Position in supply chain
Directa Plus	14.1	40.7	96	7.8	N/A	Graphene manufacturer
Electrovaya	727.8	(24.8)	126	14.5	N/A	Battery manufacturer
Evonik Industries	(0.9)	8.5	15,914	14,760.8	7.3	Speciality chemicals manufacturer
IBU tec advanced materials	97.3	63.7	267	39.9	6.3	Speciality chemicals manufacturer
Ilika	522.2	(30.1)	276	0.5	N/A	Developer of solid-state batteries
Johnson Matthey	(18.9)	26.1	8,067	5,530.0	12.9	Speciality chemicals manufacturer
Leclanché	(20.0)	(12.5)	319	24.0	N/A	Battery manufacturer and energy storage system integrator
Lion E Mobility	N/A	(21.1)	36	21.0	N/A	Battery systems design and testing
Nabaltec	(19.1)	20.7	339	193.1	N/A	Speciality chemicals manufacturer
Nano One Materials	423.1	(31.0)	316	0.0	N/A	Developer of battery processing technology
Phinergy	N/A	N/A	264	0.8	N/A	Developer of metal-air batteries
QuantumScape	N/A	(71.3)	9,837	0.0	N/A	Developer of solid-state batteries
Solvay	(5.8)	13.9	13,756	10,847.7	12.4	Speciality chemicals manufacturer
Tesla	696.5	(7.1)	631,261	31,536.0	11.8	Manufacturer of EVs and batteries
Trackwise Designs	249.7	(42.5)	72	4.1	8.9	Manufacturer of alternative wire harness technology and advanced printed circuit boards
Versarien	(49.7)	(28.7)	79	11.7	N/A	Graphene manufacturer
Zinc8 Energy Solutions	307.1	(44.7)	30	0.0	N/A	Developer of metal-air batteries

Source: Edison Investment Research, Refinitiv. Note: Prices at 22 July 2021.

High risks and high returns

The increased kWh/kg and safety offered by solid state makes its long-term prospects particularly attractive in our view, as demonstrated by the high valuations of **Ilika (IKA:LN)** and **QuantumScape (QS:US)**. However, the history of solid-state investment illustrates the risks of investing in relatively early-stage technologies. For example, 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. Sakti3 claimed its technology had an energy density of 400Wh/kg, almost double that of the batteries produced by **Panasonic (6752:JP)** for **Tesla (TSLA:US)** (230Wh/kg). 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. The company finally closed its EV project in October 2019, noting that while its engineers had developed a 'fantastic electric car', it would not hit the roads because it was not 'commercially viable'. 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.

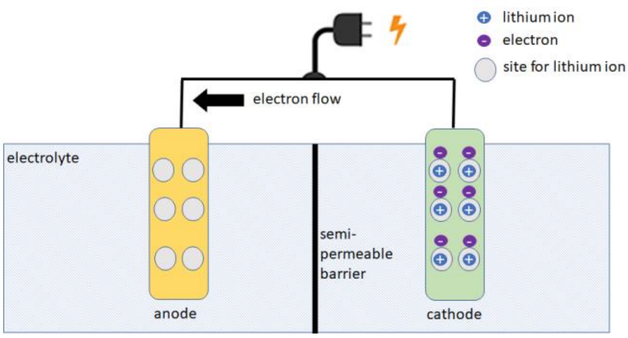
One option for reducing the risk while still participating in the battery materials market is to consider established companies such as **Evonik (EVK:GE)**, **IBU-tec (IBU:GE)**, **Nabaltec (NTG:GE)** and **Solvay (SOLB:BB)** that provide the essential chemicals used to create innovative battery materials and components or **Umicore** (**UMI:BB)**, which manufactures battery materials for a wide range of applications. Typically these supply multiple customers, reducing the risk of a single company's technology being widely adopted. Manufacturing a material such as boehmite (aluminium oxide hydroxide) used in ceramic separators (see below) does not necessarily command a lower margin than manufacturing a battery with a novel chemistry, because the skills required to output materials with the uniformity required for battery manufacture at scale are relatively rare and sought after.

Why lithium-ion technology has become so pervasive

The advantages of lithium-ion chemistry

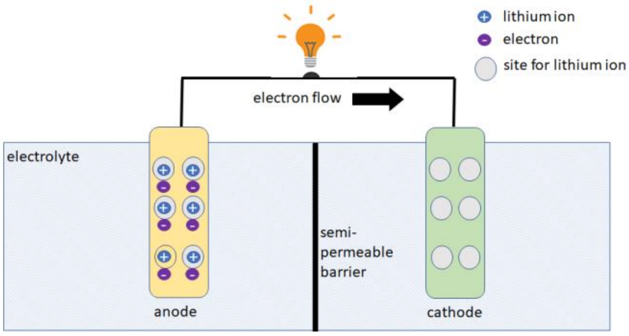
There are multiple methods of storing energy and numerous battery chemistries. The advantage of lithium-ion technology is its energy density. Lithium-ion technology's ability to store twice the energy of a nickel cadmium (NiCd) battery of the same size and weight makes it particularly suitable for transport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

Exhibit 5: Lithium ion battery charging



Source: Edison Investment Research

Exhibit 6: Lithium ion battery discharging



Source: Edison Investment Research

There are many variants of lithium-ion chemistry, but all are based on the transfer of lithium ions through an electrolyte between a positive and a negative electrode (the anode and cathode respectively). Both electrodes in a lithium-ion cell are made of materials that can absorb (intercalate) the charged lithium ions without damaging their internal structure. 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 multiple charging cycles affects performance, costs and safety. Decreasing the speed at which a battery can discharge, which affects vehicle acceleration, is also important, as is safety.

Improving anode performance

One of the principal ways of improving the energy density of a battery cell is to increase the amount of charge that the anode can store by changing the material it is made from. Anodes are usually made from graphite, which consists of multiple layers of carbon one atom thick. Popular approaches involve replacing some or all of the of the carbon with silicon, which is a neighbouring element in the periodic table and thus has similar properties. Other approaches involve storing the charged lithium ions in an organic matrix, using iron oxides and replacing the graphite with lithium titanate nanocrystals.

Replacing graphite anode with silicon anode

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, a component that regularly expands and contracts by such a large amount is not practical. Moreover, the 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, a phenomenon referred to as self-pulverisation.

One way of avoiding this degradation is to use silicon nanowires. VC-backed Amprius Technologies has developed an anode that is 100% silicon, in which the silicon is deposited as nanowires on a substrate, covering it like carpet pile. Each individual wire is a double-walled tube of silicon with a tough outer coating of silicon oxide. The silicon oxide stops the nanotube from expanding outwards. Instead the silicon expands into the interior of the tube where there is sufficient space to do that without creating undue stress within the structure. Amprius claims to have achieved an energy density of 1,400Wh/l (500Wh/kg), which is double that of the Galaxy S10 smartphone. Its batteries are currently being used in premium and mission critical applications such as the Airbus Zephyr high-altitude pseudo-satellite. **Enovix (ENVX:US)**, which is scheduled to become a public company through a merger with Rodgers Silicon Valley Acquisition Corp, has also developed and produced a next-generation lithium-ion battery with a 100% silicon anode. Enovix's battery has an energy density of 900Wh/l and can pass through over 500 full-depth discharge cycles before capacity is degraded by 80%. While Enovix is primarily targeting the portable electronics market, in August 2020 it was selected by the US Department of Energy for a $3.2m grant to develop silicon-rich (95%+) anodes for EVs, with a goal of achieving energy density of over 350Wh/kg, greater than 1,000 cycle life and 10-year calendar life. Enovix is working with **Mitsubishi Chemical (4188:JP)**, which will be optimising the electrolyte chemistry, on this project.

VC-backed Sila Nanotechnologies has developed a silicon-based anode to replace graphite in lithium-ion batteries. The company claims that its anode materials can improve the energy density of batteries by 20%. In January 2021 it raised $590m Series F funding at a $3.3bn post-money valuation. The funds will be used to begin development of a new 100GWh plant in North America to produce silicon-based anode material and serve smartphone and automotive customers. The company, which has partnerships with BMW, Daimler and battery manufacturer Amperex, aims to start production at the new plant in 2024, with its materials powering electric vehicles by 2025.

VC-backed Enevate's business model is different and is based on licencing its technology to battery and automotive manufacturers. Its anode active materials use significantly more than 70% pure elemental silicon. The company claims that its XFC-Energy technology supports five-minute charging and energy densities of 350Wh/kg. In June 2021 the company announced a new production licence with South Korean battery manufacturer Enertech, with commercialisation scheduled for 2022. Investors include the Renault Nissan Mitsubishi group, **LG Chem (051910:KS)** and **Samsung (005930:KS)**.

Enhancing performance by adding silicon to graphite

An alternative to pure silicon anodes is to combine silicon and graphite. Privately backed OneD Material attaches silicon nanowires to commercial graphite powders using a chemical vapour deposition process. The nanowires are flexible and expand into the pores between the graphite resulting in only modest swelling. The silicon nanowire/graphite material can be mixed with pure graphite in different proportions. It was evaluated by several EV companies during 2019 and 2020. Invesco, **IP Group (IPO:LN)**, **Schroders (SDR:LN)** and **Wacker Chemie (WCH:GR)** have all invested in UK technology start-up Nexeon, which is working on alternative nano-silicon materials. These are well advanced in qualification at a number of battery cell makers and automotive OEMs. Nexeon is also in manufacturing partnership talks to produce the materials in mass volumes. Its first-generation nano-silicon material is used to enhance the performance of existing graphite anode electrode active materials, providing improved cell capacity. 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 to give significant increases in anode capacity.

Talga Resources (TLG:AU) is a vertically integrated advanced material company with graphite mining in Northern Sweden, a test process facility in Germany and product R&D in the UK. It is building a graphite anode facility in Sweden running on 100% renewable electricity. Talga has already launched an anode product that enhances the capacity of graphite electrodes by using a naturally occurring form of graphite that can absorb more lithium. It claims that this increases the amount of energy a lithium-ion battery can store by around 70%. Recognising that further capacity improvements are still needed to extend the range of EVs, it is developing a composite silicon/graphene/graphite anode that uses lower-cost metallurgical-grade silicon for a high-energy density anode with mass-producibility potential. Positive results from initial tests conducted under confidentiality and material transfer agreements with multiple battery manufacturers and auto OEMs in Europe and the United States have encouraged the company to scale-up sample production capacity. Talga's technology roadmap also includes a graphite-composite anode for solid-state batteries (see below). The company has recently signed a memorandum of agreement with FREYR, which intends to develop up to 43GWh of battery cell production capacity in Norway by 2025. Under this agreement, the two partners will work towards the commercial supply of Talga's Talnode range of anode materials for FREYR's planned operation.

Enhancing performance by adding graphene to anode

Another approach is to mix the silicon with graphene. Graphene consists of individual layers of carbon, each one atom thick, which gives it an exceptionally high surface-to-mass ratio. Since graphene also exhibits high electrical conductivity and mechanical strength, it is an ideal candidate for an anode material. AIM-listed **Versarien (VRS:LN)** has a 62% stake in Gnanomat, which is developing nanomaterials based on graphene. In October 2020 Gnanomat launched two graphene-based nano-composites. One of these, a graphene coated with nanoparticles of zinc oxide, is intended for use in electrodes for energy storage devices, among other applications in fields such as adding antibacterial properties to products. Gnanomat believes its nanomaterials can improve the energy capacity of existing lithium-ion batteries to around three times the energy capacity of current market reference products. It is working with companies in the United States, Japan and South Korea to commercialise its products. In addition, some of its nanomaterials have shown significant benefits in other energy storage applications such as supercapacitors and metal/air batteries (see below). Graphene specialist XG Sciences offers a graphene-stabilised silicon anode material for enhanced run-time in drone aircraft, portable electronics and other high-density energy storage applications, based on its proprietary graphene nano-platelet technology. AIM-listed **Directa Plus (DCTA:LN)** is supplying its graphene nanoplatelets to improve the performance of lithium-sulphur chemistry (see below). Graphene specialist **NanoXplore (GRA:V)** has conducted research into adding graphene to current lithium- ion chemistries, with a focus on silicon-enabled anodes. Together with **Martinrea International (MRE:V)**, NanoXplore has formed a joint venture (JV) to develop and produce graphene enhanced EV batteries with the intention of building and commissioning a 10GWh battery cell manufacturing facility in Canada.

Organic matrix cuts charge time to five minutes

Charging time is one of the key factors holding back adoption of EVs. If a conventional lithium-ion battery is charged up too quickly, the lithium metal starts to build up as spikes or dendrites on the anode. These eventually puncture the separator, causing a short circuit. In 2019 Israeli start-up StoreDot demonstrated that its proprietary battery technology could enable an electric scooter to be charged in five minutes. The anode consists of coated layered nanoparticles embedded in a conductive organic matrix. In January 2021 the company announced the availability of its first-generation engineering samples of batteries. The samples are intended to prove that StoreDot's technology can be mass-produced on existing lithium-ion production lines. The launch paves the way for the introduction of StoreDot's second-generation prototype battery for EVs later this year, with plans to move to mass production by 2024. The company is backed by BP, Daimler, **EVE Energy (300014:CH)**, Samsung and TDK. In May 2021, StoreDot announced a new framework agreement with Eve Energy including scale-up activities of StoreDot's technology, followed by the production of engineering samples. The framework agreement also covers the intention to set up a JV for mass production.

Exhibit 7: Charging a drone in five minutes (please click for video)

Source: StoreDot

Iron slurry option improves energy density

Iron oxide has also been proposed as a material for enhancing the energy density of anodes because of its high theoretical capacitance, low cost and natural abundance. Frankfurt-listed IBU-tec is an international full-service provider in the field of thermal process engineering, predominantly treating inorganic materials. It has developed a proprietary pulsation reactor technology, which, among other applications, creates finely divided iron oxide particles, which are the starting material for iron-slurry electrodes. IBU-tec is more widely involved in the battery sector as well. In 2019 it 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. While historically IBU-tec has manufactured bespoke product for third parties, it has already secured customers for its proprietary material designed for use in lithium ferro-phosphate (LFP) battery cells, which will be available from Q421 onwards. IBU-tec has won German battery company Varta as a customer for its new product and is experiencing high levels of interest from international companies. Management is targeting a more than tenfold increase in sales of battery materials to c €21m by 2025. IBU-tec is benefiting from its ability to produce materials with the uniformity required for battery manufacture at scale because battery performance depends on access to highly homogenous input materials.

Exhibit 8: IBU-tec's indirect rotary kilns are ideal for processing very fine powders

Source: IBU-tec

Lithium titanate nanocrystals give faster acceleration

A further alternative, which is already deployed in commercial battery systems, 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, yet without disrupting the anode structure, leading to faster charging/discharging and enhanced battery lifetimes (3,000–7,000 charge cycles), although this is at the expense of energy density (50–80Wh/kg), which is less than half that of technologies such as lithium nickel manganese cobalt oxide (NMC), which have been optimised for energy density (150–220Wh/kg). This high-power characteristic of LTO cells 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. Often LTO cells are used in conjunction with NMC cells (see below), which have a higher energy density, to give the best of both worlds. The material is also resistant to thermal runaway when short-circuits are induced by external forces.

Leclanché **(LECN:SW)**, a vertically integrated provider of complete energy management systems for the utility-scale and e-transport sectors, has developed a proprietary LTO technology that can provide rapid charging for electric vehicles. It is currently supplying fully certified rail battery systems based on both LTO and NMC (see below) technologies to Alstom, Bombardier Transportation and Canadian Pacific Railway for around 15 different railway projects. Its framework agreements and MoUs in place with these companies could potentially lead to revenues well in excess of €100m over the next few years. In addition, Leclanché has supply agreements in the commercial vehicle segment with Ausa, FCC, SwRI and Urovesa as well as a European OEM of refuse trucks with a global presence, for the supply of high-energy and cycle life G-NMC battery packs which are made in Europe. **Toshiba (6502:JP)** also uses LTO in the anode of its SCiB rechargeable battery to enhance safety, longevity and low-temperature performance and reduce charging time. Toshiba is promoting the product for use in plug-in hybrid electric vehicles, noting that the higher energy density battery pack occupies less volume in a compact passenger car, where space is at a premium. It is also promoting the technology for all-electric buses, pointing out that this enables vehicles to be charged while passengers are disembarking and embarking at bus stops, reducing the number of battery chargers required at the bus depot, and makes it possible to provide wider passenger space and reduce the vehicle weight and cost.

Modifying cathode materials for EVs

Much of the focus of battery development is on the structure of the cathode because this is a key determinant of how much charge a battery cell can hold. Also, the cathode typically constitutes around 25% of cell costs so cost reductions here can be significant in lowering the cost of the battery overall.

The first commercial lithium-ion cells combined a graphite anode with a lithium cobalt oxide (LCO) cathode. The technology was introduced by Sony in 1991 and is still widely used in mobile phones, laptops and digital cameras. It gives a high energy density (150–200Wh/kg) but has a relatively short life span (500–1,000 cycles) and is also subject to thermal instability as an overheating anode can cause the cathode to decompose, releasing oxygen and potentially causing a fire. Batteries can also burst into flames if the protective package round the cell is damaged. Neither the short life span nor safety issues are acceptable for automotive applications. (The cause of the fire that destroyed a Tesla Model S Plaid in June 2021 has yet to be investigated.) The high cost of cobalt is also an issue, more so for the automotive industry than consumer applications because much larger quantities of cathode materials are required for a car than a phone. Alternative cathode chemistries are therefore being developed for the automotive sector.

NMC cathodes enable longer-range EVs

Nano One Materials' (NANO:TSX) product portfolio highlights the evolution of cathode chemistries for the automotive sector. The company has developed a patented and scalable industrial process for the production of high-performance cathode powders. Its 'One-Pot' process uses fewer steps, cutting the cost of production. The process is being used for three types of cathode material: LFP, NMC and lithium nickel manganese oxide (LNMO). LFP has an energy density of (90–120Wh/kg), which is lower than LCO but has a longer cycle life (2,000 cycles and higher) and good thermal stability. It is also relatively low cost because the cathode does not contain cobalt. The technology was introduced in 1996 and is still dominant in e-buses, e-bikes, fleet vehicles and entry-level mass market EVs. LFP is being displaced by NMC, which was introduced in 2000 and gives higher energy densities (150–220Wh/kg) than LFP, enabling longer-range vehicles, though cycle life (1,000–2,000 cycles) remains an issue. Nano One has patented a coated single crystal NMC material that resists cracking during charge/discharge cycles, thus improving cycle life. LNMO is an attractive potential cathode material because it is cobalt-free and operates at higher voltages than the other two technologies, making it a strong candidate for fast charging applications. Nano One has demonstrated a thousand cycles with its single crystal version of LNMO, resolving the cycle life issues known to affect this class of material. The company has built a demonstration pilot plant and is partnered with global leaders including Saint-Gobain and Volkswagen and an undisclosed global manufacturer of cathodes.

Exhibit 9: Nano One Materials' coated single crystal cathode materials (please click for video)

Source: Nano One Materials

In April 2021 Nano One announced that it had successfully completed the first two phases of a joint development programme with an undisclosed multi-billion-dollar Asian cathode material producer. Having validated the LNMO material, Nano One's focus is now shifting to scale-up considerations, detailed economic analysis, third-party evaluation and preliminary planning for commercialisation. In June 2021 Nano One and Johnson Matthey announced a JDA under which the two companies will co-develop next-generation products and processes for Johnson Matthey's eLNO family of nickel-rich advanced cathode materials using Nano One's patented One-Pot process and coated nanocrystal technology.

Exhibit 10: Nano One Materials' M2CAM process changes how the world makes battery materials

Source: Nano One

Nano One has adapted its One-Pot process to enable cathode materials to be produced directly from metal powder and lithium carbonate feedstocks. This eliminates the costly and energyintensive conversion of nickel, cobalt and manganese metal feedstocks to sulphates and of lithium carbonate to lithium hydroxide. It also reduces the emissions, energy consumed and costs of shipping material from where it is mined by four or five times because shipping a metal sulphate involves shipping sulphur and water as well as the metal. It also enables the formation of a lithiated NMC precursor, which eliminates an extra lithiation step, as well as the economic and environmental cost of removing and disposing of the sulphur and water when making the NMC precursor.

Leclanché has developed G-NMC technology to complement its LTO cells. This is already being used in EVs including marine vessels as well as utility-scale storage applications. NMC technology is also used in **Tesla (TSLA:US)** Powerwalls. Tesla vehicles use lithium nickel-cobalt-aluminium Oxide (NCA) cathodes, which are primarily nickel with 10% cobalt and a small proportion of aluminium to give stability. This gives a better energy density (200–260Wh/Kg), but at the expense of cycle time (500 vs 1,000–2,000).

FTSE 100 chemicals group **Johnson Matthey** has developed a high-nickel cathode material, eLNO, specifically for EV applications, that is, with a view to enabling long-range driving between charges, faster acceleration than a conventional car, faster recharging times and lower cost per kWh/cycle. In June 2020 the group announced it was refocusing its LFP business on eLNO and higher-performance LFP grades. In August 2020 the group announced that it had received a combined €135m investment from two leading development banks for its new battery materials facility in Konin, Poland. This will become the world's first production site for eLNO, with production capacity of 10,000 tonnes per year, enough for around 100,000 fully electric vehicles. The site, which is scheduled to start production in 2022, has the potential to expand tenfold through further investment. Construction of the plant began in 2020. The company intends to open a second site for eLNO production in Finland, which will be powered by renewable energy, use responsibly sourced nickel, cobalt and lithium raw materials, and deploy an innovative effluent treatment solution. It expects to start construction of the second plant later this year.

Improving separator performance

Preventing thermal runaway

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 charging is too rapid, the battery gets hot, potentially causing the separator to shrink, creating a short circuit that can start a fire. (This was suggested as the cause of the Samsung Galaxy 7 smartphone battery issues.)

Flame retardant alumina and boehmite coatings are used to strengthen the separator, preventing thermal runaway. As soon as overheating starts, the micro-pores in the separator membrane close, interrupting the flow of lithium ions so the cells stop conducting and gradually cool down. German speciality chemicals company Evonik Industries has developed a range of fine-particulate, metal oxides with high specific surface area that can be used to coat the battery separator. This AEROXIDE material can also be used to coat NMC cathodes, thus increasing life cycle time as well as modifying the electrolyte (see below) by turning the liquid into a safer gel format. Chemical company Solvay manufactures a fluorinated polymer, SOLEF PVDF, which is used in the manufacture of separators, with the fluorine element in the compound making the battery fire-resistant. Solvay also offers cathode binders and high-performance electrolytes.

Lithium-ion battery specialist **Electrovaya (EFL:CN)** uses patented ceramic composite cell separator materials along with proprietary electrolyte and other components to improve the safety of its NMC based lithium-ion cells, which are certified to UL standards. Its first customers included companies such as Walmart Canada, which uses its battery packs to power forklifts in distribution centres. In March 2021 Electrovaya entered the electric bus sector with the launch of a new battery tailored for this market. The ceramic separator material was initially developed by Evonik subsidiary Litarion, which Electrovaya acquired in 2015.

Switching to boehmite saves space

Using boehmite rather than alumina permits a substantial reduction in coating thickness without compromising thermal stability. In February 2021 MarketWatch predicted that the global high-purity boehmite market would grow from US$140.1m in 2020 to reach US$315.7m by 2026, a CAGR of 14.5%. Nabaltec (**NTG:ETR)**, a chemicals company that develops, manufactures and distributes specialised products based primarily on aluminium hydroxide and aluminium oxide, is benefiting from increasing demand for boehmite. Boehmite sales accounted for around 10% of Nabaltec's total FY20 sales and grew by 48% year-on-year during FY20.

Solid electrolyte doubles as alternative separator

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 (see below). Since the material is non-flammable and, according to Ohara, has one of the highest lithium ion conductivities for a solid electrolyte, it can also be used both as an electrolyte in solid state cells and a separator in ones with a liquid electrolyte.

Solid-state lithium-ion batteries

Solid electrolytes make batteries safer and improve EV range and charging times

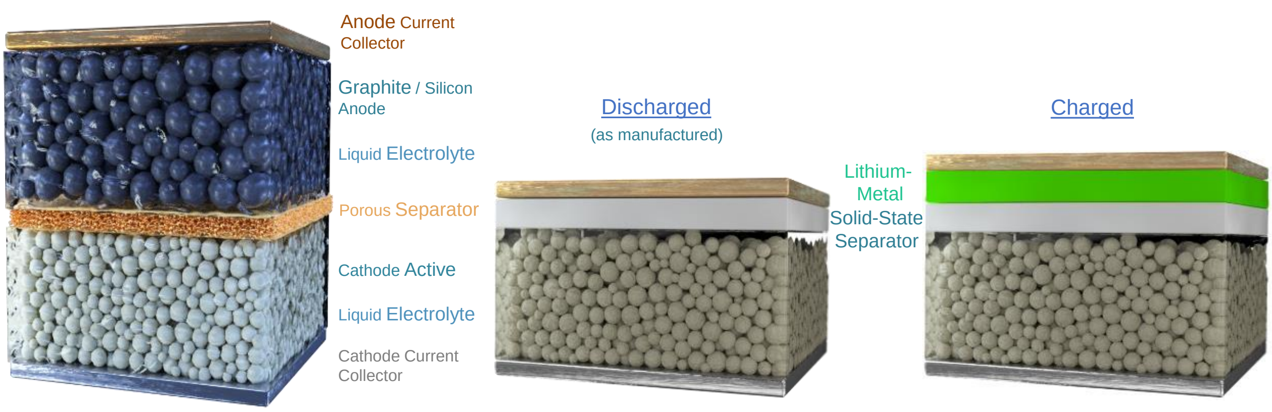
A solid-state battery replaces the liquid or polymer gel electrolyte in a lithium-ion battery cell with a solid material, usually a ceramic such as Ohara's LICGC or a glass. Solid-state batteries typically have higher energy densities than conventional li-ion batteries, resulting in smaller and lighter batteries. Using a solid electrolyte also makes the batteries safer because liquid electrolytes are more flammable. Improving safety helps with the energy density of the overall system, because less protection is needed for solid-state formats. Depending on the composition of the electrolyte, the batteries can also have faster charge times (Ilika is aiming for 10 minutes, which is six times faster than conventional lithium-ion technology and QuantumScape has demonstrated 15 minutes charge time), hold charge for longer and endure many more charge/discharge cycles than conventional lithium-ion batteries. Eliminating the liquid electrolyte also makes it possible to recycle the materials in spent cells using established metal extraction techniques.

Many prominent automotive manufacturers and their suppliers, though apparently not Tesla, are investing in solid-state technology because they believe solid-state batteries will play a big role in electric vehicles over time since the increased energy density reduces the overall weight of the battery, solving the range anxiety issue. Faster charge times and improved safety are also important.

However, the technology remains substantially more expensive than conventional lithium-ion batteries at present because it is not being manufactured at scale. Given the challenges this presents, it seems unlikely that solid-state technology will make a big inroad into the automotive sector at least until 2025. For example, in April 2021 BMW noted that it will develop solid-state battery technology suitable for use in road cars by the end of the decade, with a demonstrator vehicle due before 2025. BNEF estimates that solid-state and conventional lithium-ion technology will not reach price parity until 2033/34, although QuantumScape believes that it will be able to manufacture solid-state batteries that are substantially less expensive than conventional ones well before that (see below). However, once the manufacturing processes have been established, Bloomberg NEF believes that the adoption of solid-state technology will help drive down the cost of EV battery packs.

Continental and Volkswagen backing QuantumScape

Exhibit 11: QuantumScape's anode-less structure potentially delivers high-energy densities and fast charging



Source: QuantumScape

Solid-state battery start-up **QuantumScape (QS:US)** completed its initial public offering (IPO) in November 2020. Trading since has been very volatile. Investors prior to the IPO included Bill Gates, German automotive supplier **Continental (CON:ETR)** and **Volkswagen (VOW:GE)**, which has invested in QuantumScape since 2012. As of Q121, the company had around $1.5bn to commercialise its batteries and scale up production. Management expects that this will be sufficient to take the company to the start of mass production, which is scheduled for 2024/25. The patented ceramic that QuantumScape has developed for the electrolyte, which also acts as a separator, means that cells do not need a hosted anode of silicon or carbon. This eliminates the anode manufacturing step. Instead, an anode of metallic lithium is formed on the current collector when the cell is charged. The company claims that this construction, which dispenses with a bulky carbon or silicon anode, gives an energy density of over 400Wh/kg. In addition, the electrolyte/separator used is resistant to dendrite formation at room temperature, supporting fast charge times and an extended cycle life. Test data from single-layer pouch cells published in December 2020 indicates that a QuantumScape battery could be charged to 80% of its capacity in 15 minutes while capacity remains at 80% or above after 1,000 charge/discharge cycles and that the cells can operate at temperatures as low as -30 degrees Celsius. While the data is promising, so far the company has only provided data for four-layer cells of 70mm by 85mm. Further development work will be needed to convert the four-layer cells into cells with dozens of layers and then prepare these for mass production. To listen to an interview with QuantumScape's CEO Jagdeep Singh, please click here.

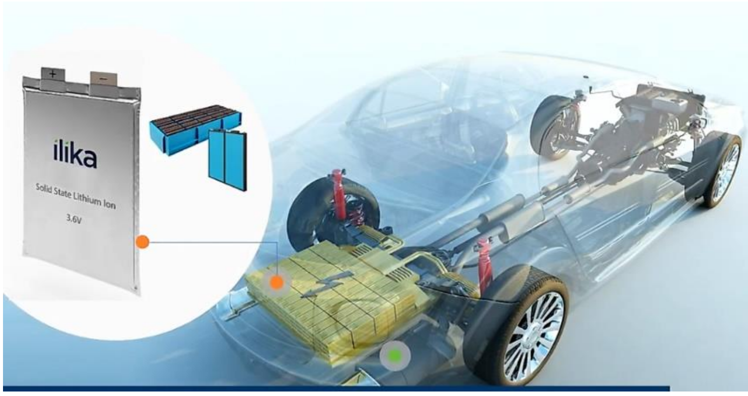
Volkswagen is assisting QuantumScape with scaling for production at its first facility. The car manufacturer will then have the right to become the first purchaser of the batteries. In March 2021 QuantumScape announced it had met the technical milestone required for Volkswagen to invest an additional US$100m.The two companies have agreed that they will select the location of their joint-venture 1GWh solid-state battery pilot-line facility, which will probably be in Salzgitter, Germany, by the end of 2021. QuantumScape and Volkswagen intend to expand production capacity by a further

20GWh at the same location, which QuantumScape estimates will enable the production of cells that will be 15–20% less expensive than conventional lithium-ion cells because of the lack of an anode manufacturing line. QuantumScape is targeting commercial production by 2024/25, ramping up to 91GWh of capacity by 2028, which it estimates is equivalent to around 910,000 EVs.

Ilika is working with Honda, Jaguar, Land Rover and McLaren

AIM-listed **Ilika**'s **(IKA:LN)** batteries use a patented ceramic electrolyte to boost energy density and charging time. In September 2019 the company opened a pre-pilot facility for the development and initial production of large-format solid-state batteries for EVs. The capacity was needed to support Ilika's portfolio of industrial collaboration programmes with Honda, Jaguar, Land Rover, McLaren and Ricardo and was partially funded from the £5m granted to Ilika through the UK government's Faraday Battery Challenge. Currently the line output is 1kWh per week and while Ilika is still working on performance enhancements, it has shipped samples to automotive partners for evaluation. Ilika has plans to scale this to 10kWh per week by 2022/23. In addition to scaling-up its own facility, Ilika has signed a framework agreement with the publicly funded UK Battery Industrialisation Centre (UKBIC), which will give access to full-scale production equipment. This level of output is sufficient to support the first commercial launches of large-format cells, which are likely to be for household appliances and for mule and multiple vehicle test validation. For larger volumes to support mass market adoption, Ilika intends to form a JV or licence to a manufacturing partner from 2026. To listen to an interview with Ilika's CEO, Graeme Purdy, please click here.

Exhibit 12: Ilika's solid state battery for electric vehicles (please click for video)



Source: Ilika

BMW, Ford and Hyundai have invested in Solid Power

Automotive manufacturers BMW, Ford and Hyundai, battery manufacturers A123 Systems and Samsung and chemicals company Solvay have all invested in Solid Power, a Colorado-based developer of solid-state batteries. The company is expected to list on Nasdaq during Q421 under the ticker symbol SLDP, via a merger with a special purpose acquisition company which values the combined entity at about $1.2bn. Solid Power's batteries use an inorganic sulphide solid electrolyte and metallic lithium, which has a capacity 10 times greater than conventional graphite, as anodes. In October 2020 Solid Power announced the production and delivery of multi-layer 20Ah cells, which were manufactured using lithium-ion industry standard processes and automated equipment on its MWh-scale roll-to-roll pilot manufacturing line. The cells have an energy density of 330Wh/kg, which the company states is higher than conventional lithium-ion batteries, with a roadmap to surpass 400Wh/kg by 2022. This generation of cells is being manufactured to validate large-format cell production processes. The company anticipates entering the formal automotive qualification process in early 2022 with even larger-capacity all-solid-state battery cells with a view to having a viable solid-state battery for cars by 2026.

Hyundai, Nissan, Mitsubishi, and Renault have stakes in Ionic Materials

Massachusetts-based start-up Ionic Materials develops and supplies polymer electrolyte material, lithium metal anodes, sulphur cathodes and liquid electrolytes. It is working with A123 Systems on a solid-state battery combining its advanced ionically conductive polymer with A123's next-generation NMC/graphite lithium-ion chemistry. In February 2018 Ionic Materials secured $65m in a Series C funding round from investors that included carmakers Hyundai, Nissan, Mitsubishi and Renault, Sun Microsystems co-founder Bill Joy and A123 Systems.

BlueSolutions has solid-state batteries in commercial operation

BlueSolutions, which was acquired by French holding company **Bolloré (BOL:FP)** in March 2020, already has solid-state batteries in commercial operation. Its lithium metal polymer (LMP) solid-state batteries have been deployed in EVs since 2011 including car-sharing services in France and the United States and electric buses for Bolloré (BlueBus) and Daimler (eCitaro), cumulatively travelling over 300m kilometres. In July 2020 BlueSolutions and Daimler signed a three-year battery supply contract with a two-year extension option. Annual production capacity currently totals 500MWh, though the group notes this could be increased to 1.5GWh as the market grows. However, the technology is based on a solid polymer electrolyte manufactured elsewhere in the group that does not conduct lithium ions as well as liquid electrolytes. This means that the internal operating temperature of the battery is 60–80 degrees Celsius, so if the battery is left unplugged, it will take time for it to reach operating temperature before it can be used, making it unsuitable for passenger vehicles. In addition, the polymer electrolyte cannot be used with high-performance cathode materials, which adversely affects energy density, and it is very susceptible to dendrite formation at high rates of power. This means that the batteries do not accept fast charging and are prone to shorting, resulting in around 30 new eCitario buses being taken out of service earlier this year.

Major battery manufacturers and a lithium producer entering the market

Toyota (7203:JP) is investing ¥1.5tn ($13.9bn) in its battery business. The carmaker has announced that it will present a prototype SUV powered by solid-state batteries later in 2021, with the vehicles being commercially available by the middle of the decade. It claims that this new SUV will be fully charged from flat in 10 minutes and have a range of 500km. Toyota is developing the battery jointly with Panasonic and still needs to improve cycle life and reduce manufacturing costs before the technology is a commercial option.

In March 2020 **Samsung (005930:KS)** announced that it had developed a solid-state battery cell with a silver-carbon (Ag-C) anode, which it claimed removed the problems with dendrite formation. The cell had an energy density of up to 900Wh/l, which it estimated would give a range of up to 800km, and had a cycle life of over 1,000 charges. In May 2021 the company stated that it intended to produce prototype all-solid-state battery cells by 2025 and initiate mass production in 2027.

In April 2021 China's major lithium producer **Ganfeng Lithium (002460:SHE)** announced plans to build a lithium metal plant with a production capacity of 7kt per year to produce materials for solid-state battery anodes. It is currently building a 3GWh production line for its semi-solid-state battery products. In April 2019 Ganfeng signed a memorandum of understanding with Volkswagen to secure supplies for the carmaker's electric car plans for the next 10 years. The battery modules have an energy density of just over 200Wh/kg.

Reducing the charge time and weight of a complete battery system

In addition to modifying the chemistry inside battery cells, EV battery manufacturers are looking at modifying the way the cells are integrated into battery packs to reduce the charge time and weight of the complete system.

Exhibit 13: LION LIGHT battery pack

Source: Lion SMART

Battery system development specialist LION Smart (part of **Lion E-Mobility (LMI:GR)** has developed a novel concept for integrating cylindrical battery cells, which enables extremely high energy and packing densities. The battery cells and electronics are completely immersed in a high-tech fluid which gives optimum heat exchange, ultra-fast charging (15 minutes at present, which may come down pending further development work), and ensures effective and even temperature control of the battery. Each cell is monitored by a single-cell battery monitoring system and is individually fused. Since the cooling medium also acts as an extinguishing agent in the event of thermal runaway, the battery is also inherently safer. In June 2021, LION Smart announced that the final tests on the LIGHT battery and its subsystems integrated into test vehicles that were carried out as part of a joint development project with one of the world's leading tier one suppliers to the automotive sector had completed successfully. Both companies are currently in constructive talks regarding further cooperation.

In February 2021, LION Smart announced that it was working with a consortium of companies, consisting of Evonik, product development consultant Forward Engineering, developer and manufacturer of plastics moulding materials Lorenz Kunststofftechnik, and Vestaro, a specialist in composites for the automotive industry, which had collectively developed a brand-independent, cost-effective battery concept for electric vehicles. The weight of the battery was reduced by around 10%, partly by using new glass-fibre-reinforced epoxy sheet moulding compound based on Evonik's VESTALITE epoxy hardener and designing a housing with a bottom plate made of aluminium. To listen to an interview with Lion E-Mobility's Ian Mukherjee, please click here.

AIM-listed Trackwise Designs **(TWD:LN)** has developed a proprietary, proven technology, IHT, for manufacturing extremely long, flexible circuits that can replace conventional wiring harnesses. This disruptive technology is applicable to many industries including EVs, medical devices and aerospace. Trackwise has already manufactured prototypes for customers in each of these sectors and received its first series production order from an EV manufacturer in September 2020. IHT has been shown to support weight savings of up to 75% compared to conventional wiring harnesses.

Beyond lithium-ion

Looking beyond lithium-ion chemistry altogether, researchers are investigating alternative technologies that potentially offer substantially higher energy densities. Some of these alternatives eliminate the need to use lithium, the extraction of which brings its own environmental challenges, or cobalt, much of which is sourced from the Congo under conditions that have elicited condemnation from Amnesty International for violating human rights. There is some debate as to whether there is sufficient quantities of these materials available globally to meet demand if EVs are widely adopted. Moreover, lithium and cobalt are both toxic and can negatively affect the environment when they are extracted as well as when they are disposed of. As automotive companies look to improve their environmental credentials, the way in which battery materials are extracted and recycled becomes an important consideration.

Running on air: Metal-air cells

Metal-air battery cells use an anode made from a pure metal such as zinc, aluminium, magnesium or lithium and an external cathode exposed to the oxygen in the atmosphere. Lithium-air technology has the highest theoretical energy density, 5,000–11,000Wh/kg, aluminium 1,900–3,900Wh/kg and zinc 900Wh/kg. This high energy density makes the technology very attractive, but developing a practical rechargeable battery for EVs is challenging because of the lack of suitable cathode catalysts and stability issues when the cells are being charged quickly and with high currents, which limit battery lifetime. Recently listed **Phinergy (PNRG:TLV)** has developed a metal-air battery system that it claims can charge fully in less than five minutes and has a lifespan of thousands of working hours, but the details are sketchy. Our research suggests that drivers would not be able to recharge the batteries at home but would need to swap out discharged batteries with ones that had been replenished with fresh electrolyte. In March 2021 Phinergy formed a JV with state-run oil marketing company Indian Oil Corporation to manufacture aluminium-air systems in India and recycle used aluminium with the intention of reaching commercial production of the car energy system by 2024. The JV has signed letters of intent with Indian automotive manufacturers Maruti Suzuki India and Ashok Leyland. In January 2021 Bangalore-based Mahindra Electric announced that it was testing out Phinergy's batteries on its Treo three-wheeled vehicle. **Zinc8 Energy Solutions (ZAIR:CNSX)** is also working on metal-air batteries, but for stationary energy storage systems, not EVs.

Lithium-sulphur cells cut out cobalt

Lithium-sulphur (Li-S) battery chemistry has a theoretical energy density of 2,700Wh/kg, which is five times greater than lithium-ion. It is also inherently safer because the lithium and sulphur react to form polysulphide compounds, so there are no lithium ions shuttling from one side of the cell to the other during charge/discharge cycles and the highly reactive lithium anode is passivated with sulphide materials during operation. From an environmental perspective, the cells do not include cobalt and the sulphur used is produced during the recycling of oil refinement by-products so is readily available and relatively inexpensive. Li-S technology is therefore regarded as a promising alternative to lithium-ion for the future. Li-S cells from privately owned Sion Power were used in 2014 by Airbus Defence and Space to power its Zephyr 7 high-altitude pseudo-satellite, which set a world record for continuous flight. OXIS Energy had made thousands of its patented Li-S battery cells before going into administration in May 2021.

Graphene beneficial for Li-S chemistry as well as conventional lithium-ion

Start-up NexTech Batteries has produced several full-scale pouch format Li-S cell prototypes with energy densities of 410Wh/kg. These use its proprietary cathode and electrolyte materials. The patented novel nanoparticulate cathode active material combines the sulphur with graphene nanoplatelets from Directa Plus. The two companies have a supply agreement and strategic R&D agreement under which Directa will supply graphene nanoplatelets on an exclusive basis (with regards to lithium batteries) for up to five years, starting with 300kg of nanoplatelets in 2021. In addition, the two companies will jointly develop new specific grades of graphene nanoplatelets for a next generation of Li-S batteries. NexTech is in the process of scaling up its production unit in order to meet increasing demand from customers for its batteries. In June 2021 NexTech established a subsidiary with the initial objective of evaluating the feasibility of producing cathode active materials in Italy using Directa Plus's nanoplatelets for the manufacture of Li-S batteries across Europe to accelerate the technology's commercialisation. NexTech has a strategic partnership with emerging EV manufacturer Mullen Technologies, which is to merge with **Net Element (NETE:US)**.

Sodium-related chemistries potentially address issues with lithium availability

Sodium and lithium are neighbours in the periodic table of elements, so share similar characteristics. Research into sodium-ion battery chemistries did not take off until around 2012 following concerns about the availability of lithium, so development is still at a relatively early stage. UK-based Faradion, one of the holdings in **Mercia Asset Management**'s **(MERC:LN)** portfolio, is developing and commercialising sodium-ion pouch cells based on its proprietary layered metal-oxide cathode and commercial hard carbon anode. Faradion claims that its prototype cells deliver energy density of 150–160Wh/kg and notes that the chemistry is safer than lithium-ion. Nail penetration of sodium-ion cells at full charge shows no flames or evidence of ignition. Faradion calculates its technology will cost 30% less than lithium-ion. The technology has been demonstrated on an electric bicycle. In 2020 the company received an order for batteries for use in stationary energy storage systems in Australia and announced a partnership with a heavy goods vehicle fleet services provider in India. French start-up Tiamat Energy has produced 10,000 sodium-ion battery cells, which it has used to power two e-scooters. It claims a charging time of around five minutes and a cycle life of over 5,000 cycles.

Rather than try to modify lithium-ion chemistry to accommodate sodium ions, UK start-up LiNaEnergy is reworking operationally proven sodium/nickel battery chemistry from the 1980s in a solid-state format. LiNa successfully completed the proof-of-concept phase in November 2019. The project included an evaluation of processes for mass production of the cells. This phase is being followed by an 18-month project to demonstrate a prototype of the cell in real-world conditions. LiNa is constructing a prototype stack and developing all the manufacturing processes required. The stack will be operated in a commercial installation. The £1m project is also funding LiNa's commercial preparations for market launch and assisting the company to strengthen relationships with key suppliers and end users.

Organic batteries environmentally sound, but at an early stage

Organic materials, that is ones based on carbon, hydrogen and oxygen, are a promising alternative to using inorganic metals. From a green perspective, the materials can be derived from bio-mass and combusted at the end of their useful life. However, the organic battery field is still in its early stages and there is much room for improvement with regards to energy density, life cycle time and stability.

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