Batteries for Electric Cars

A case study in industrial strategy

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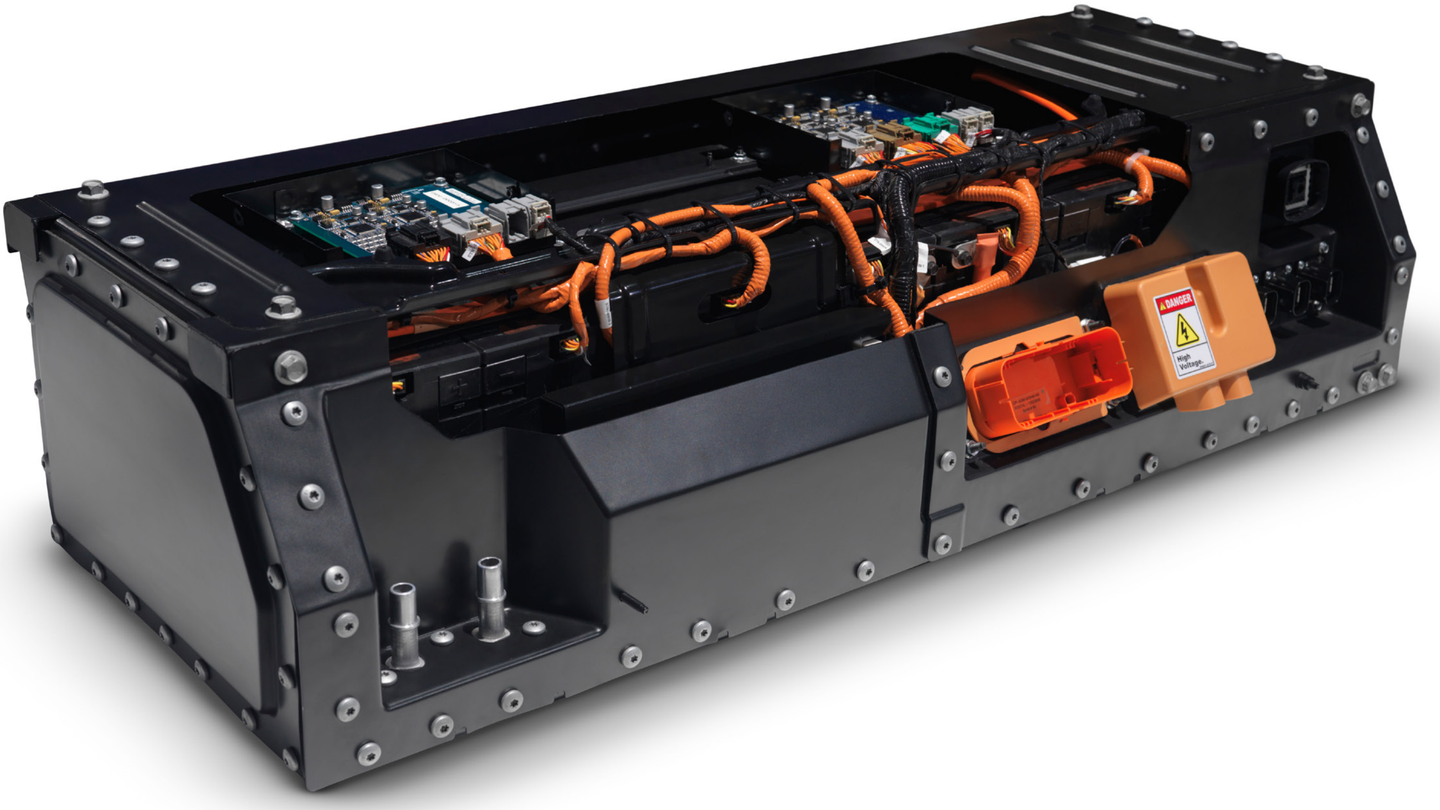

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About the Author

Sir Geoffrey Owen is Head of Industrial Policy at Policy Exchange. The larger part of his career has been spent at the *Financial Times*, where he was Deputy Editor from 1973 to 1980 and Editor from 1981 to 1990. He was knighted in 1989.

Among his other achievements, he is a Visiting Professor of Practice at the LSE, and he is the author of three books - *The rise and fall of great companies: Courtaulds and the reshaping of the man-made fibres industry*, *Industry in the USA* and *From Empire to Europe: the decline and revival of British industry since the second world war*. He is the co-author, with Michael Hopkins, of *Science, the State, and the City: Britain's struggle to succeed in biotechnology*.

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Executive Summary

When Theresa May became Prime Minister in 2016, she announced her intention to launch a "proper industrial strategy". Since then, a number of sectoral schemes have been introduced, including support for advanced technologies where, in the government's view, British firms should be able to improve their competitive position. This paper looks at batteries, principally batteries for electric cars, which was one of the first sectors to receive funding from the government's newly established Industrial Strategy Challenge Fund. The purpose of the paper is to examine the rationale for the battery programme and its implications for industrial strategy.

The choice of the battery sector as an early target was influenced by several considerations:

- the need to accelerate the shift to electric cars as part of the drive to reduce CO2 emissions
- the belief that, thanks to the strength of the UK's academic science in electrochemistry and related disciplines, British firms were well placed to win a bigger share of the growing market for energy storage
- the need to ensure that, as the UK-based car assemblers decide how and where to make electric cars, they have access to a viable battery supply chain within the UK.

This last factor is of particular importance for the UK, where the motor industry is not only an important employer and exporter, but also largely foreign-owned. The government fears that, unless the UK battery sector is substantially strengthened, the car manufacturers may choose to make their electric cars elsewhere, and perhaps even move all their operations outside the UK.

The £246m support programme for batteries, known as the Faraday Challenge, is designed to make the UK a more attractive location for investment by British and non-British manufacturers of batteries and battery materials. The funding package has three parts:

- £78m for academic research, to be coordinated by a new research institute, the Faraday Institution
- £88m for close-to-market innovation, handled by the government's innovation agency, Innovate UK
- £80m to support the construction of a battery development facility in the Midlands.

The most critical element in the battery supply chain is the cell. Most electric cars now on the market use batteries based on lithium-ion cells, a technology that was first commercialised in Japan in the early 1990s.

The supply of lithium-ion cells for car batteries is currently dominated by Japanese, Korean and Chinese companies. The architects of the Faraday Challenge hope that, as a result of the battery support programme now under way, one of these big Asian suppliers may decide to build a cell factory in the UK. This, they think, will make it more likely that the car assemblers will produce electric cars here, and thus reduce the disinvestment risk.

As an early indication of what the government means by industrial strategy and how it will be implemented, the Faraday Challenge has a special importance. While energy storage is clearly an important technology and there is a case for more spending on research in this field, the battery programme raises several questions which merit closer scrutiny.

First, if the future for electric cars is as bright as many forecasters expect, it is not clear why the necessary investment in batteries cannot be financed by the private sector. Second, the battery business is global, and it is not obvious that the UK needs to be represented in all phases of the battery supply chain. While an investment from one of the big Asian cell makers would be welcome, the presence or absence of cell-making capacity in the UK is unlikely to have a decisive influence on where the UK-based assemblers make electric cars. Third, the government needs to provide more detail on how the success of the battery programme will be evaluated.

Some of these issues are relevant to other sectors which may be included in the industrial strategy. In picking technologies to be supported, the government needs to show why an injection of public funds is necessary; it also needs to make a realistic assessment of the UK's strengths and weaknesses in the chosen sector. Any support programme should be organised in a way that encourages competition from new entrants; there are dangers in a single national programme in which established companies may have a preponderant influence. Finally, the objectives of the programme should be set out clearly in advance, and progress measured against them. Support should be terminated if inadequate progress has not been made.

The Return of Industrial Policy

Industrial policy, defined in this paper as intervention by government to support particular companies, sectors or technologies, has had a chequered history in the UK. The Labour governments of the 1960s and 1970s intervened directly in several industries, hoping to create "national champions" through subsidies and preferential procurement, and by encouraging mergers. Most of these interventions were unsuccessful, leading to a long period in which, under both Labour and Conservative governments, selective industrial policy was largely off the agenda.

This began to change in the closing years of the Blair-Brown Labour government (1997-2010), in response to the recession that followed the world financial crisis. Several initiatives were launched at that time; one was the creation of the Automotive Council, a joint government-industry body charged with developing a strategy for the British motor industry. The Conservative/Liberal Democrat coalition which took office in 2010 went further in the same direction; by then the case for an active industrial policy was broadly accepted across the political spectrum.

When Theresa May became Prime Minister in 2016, after the EU referendum and David Cameron's resignation, she made it clear that what she called "a proper industrial strategy" would have a high priority in her administration; the industry department was renamed Department for Business, Energy and Industrial Strategy (BEIS). The strategy would involve, along with broad policies aimed at improving the business environment, partnerships between government and business in particular industries and technologies where, with government support, UK-based firms should be able to improve their competitive position in world markets.

One of the targets, as it had been under the coalition government, was the motor industry. This industry had been in a state of near-collapse in the early 1980s, but had subsequently staged a partial recovery, thanks largely to inward investment. Three Japanese companies, Nissan, Toyota and Honda, built assembly plants in the UK, mainly to serve the European market. The old "national champion", British Leyland, was broken up; part of its business, Jaguar Land Rover (JLR), is now owned by Tata of India, another part, the Mini, by BMW of Germany. The most recent change of ownership was the sale by General Motors, the American company, of its two assembly plants at Ellesmere Port and Luton to PSA of France. The other big US manufacturer, Ford, no longer assembles vehicles in the UK, but is a large producer of engines, most of which are exported; it also has a development centre at Dunton in Essex, responsible for the design of small cars.

As a result of these changes, an industry that had seemed doomed to decline is now widely seen as a British success story. Yet it has some weaknesses, not least the hollowing-out of the supply chain, a consequence of the wave of closures among component makers that took place in the 1970s and 1980s; the big UK-based car assemblers rely for more than half of their components on non-British, mainly European, suppliers. There is also the ever-present risk that the foreign-owned car makers might divert their investments away from the UK. That risk has been magnified by the Brexit vote; exit from the European Union could disrupt supply arrangements and make exporting to the Continent more difficult.

A particular challenge, which forms the subject of this paper, is the need for the industry to adjust to a fundamental change in technology: the shift from petrol and diesel engines to battery-powered cars. While there are many uncertainties about the speed of the transition, most forecasters think that by 2025 at least 20 per cent of all cars sold in developed countries will be wholly or partly electric.[1] The shift has been driven partly by concern over global warming – the need to curb carbon dioxide emissions – but it also has an industrial policy dimension. Governments in car-producing countries like the UK want to ensure that the replacement of internal combustion engines by batteries does not weaken the domestic motor industry and lead to a loss of employment.

The pacesetter in electrification has been China, which, thanks to government subsidies and other incentives, is already the biggest market for electric cars and a leading manufacturer of car batteries. Successive US governments have funded research in battery-related science, as well as subsidising the purchase of electric cars. The European Union is working on plans to correct weaknesses in the European battery supply chain; some EU officials have proposed an Airbus-type consortium of leading European companies to invest in advanced battery production.

This is the context in which Theresa May's government, in July 2017, announced a £246m programme of support for the UK battery sector; much of the funding will come from the government's newly established Industrial Strategy Challenge Fund. The purpose of the programme, according to Greg Clark, Business Secretary, is to ensure that the UK "leads the world in the design, development and manufacture of electric batteries".[2]

The battery programme, known as the Faraday Challenge, is targeted not just at electric cars but also at the broader field of energy storage, supporting technologies that will allow electricity coming from intermittent energy sources, such as wind and sun, to be stored in the grid. In the short term, however, the focus is on electric cars, where the need to strengthen the UK's competitive position is seen to be urgent. This paper deals only with batteries for vehicles.

The purpose of the paper is to examine the rationale for the Faraday programme, to look at the organisation that has been put in place to implement it, and to consider whether the goals of the programme

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[1] It is important to note that "partly electric" covers a wide range of technologies, including those featuring only lightly assisted internal combustion engines, requiring very small batteries.

[2] Department of Business, Energy and Industrial Strategy, Press Release July 24, 2017. Batteries had previously been identified by the government as one of six areas on which the Industrial Strategy Challenge Fund would focus over the next four years; the others were healthcare and medicine, robotics and artificial intelligence, self-driving vehicles, manufacturing and materials of the future, and satellites and space technology.

are realistic. It will also discuss the wider implications of the battery programme for industrial strategy.

The paper looks first at the international background: the growing sales of electric cars; recent developments in battery technology; and the efforts being made by governments in the US and Europe to strengthen their battery sectors. The next section assesses the Faraday programme. The paper concludes with some general comments about the role of government in promoting the exploitation of new technologies.

The Shift to Electric Cars

In the pioneering days of the world motor industry, towards the end of the 19th century and the beginning of the 20th, electric cars were competing on level terms with petrol- and steam-driven cars, and it was not obvious at that stage which technology would be best. Steam proved to be impractical for personal vehicles, partly because of long-start-up times. Electric cars were clean and quiet, but limited in how far they could travel before the battery needed to be recharged. As the performance of petrol-powered cars improved, notably through the invention in 1912 of the self-starter (removing the need to crank the vehicle by hand), electric cars lost ground. By 1920 the electric car as a commercial product was "nearly dead".[3] For most of the 20th century battery-driven vehicles were largely confined to specialist uses such as milk delivery floats in the UK or off-road applications such as forklift trucks.

It was not until the 1960s that interest in electric cars began to revive. The stimulus was the need to reduce pollution, especially in big cities where smog, generated partly by coal burning but partly also by exhaust fumes from cars and trucks, was damaging public health. Several countries, including the US and the UK, passed Clean Air Acts, and subsequent legislation imposed restrictions aimed at forcing manufacturers to make their cars cleaner. In the US an influential agency was the California Air Resources Board (CARB), which set emission standards for vehicles sold in the state.

Government regulation of air quality prompted a flurry of activity in electric cars. Ford in the UK developed a small city car, the Comuta, but its maximum speed was 40 miles per hour, and it could travel for only 40 miles before the battery had to be recharged. The excitement soon faded and the car was never put into production. Thereafter, regulatory pressure focused on reducing emissions from conventional engines; a widely used emission control device was the platinum-based catalytic converter, which converts gases coming out of the exhaust into less toxic gases.

The oil crisis of the mid-1970s gave a stronger fillip to the development of electric cars. The Arab oil embargo and the quadrupling of world oil prices prompted strenuous efforts by the oil importing countries to curb petrol consumption. The US imposed a mandatory speed limit for cars, initially set at 55 mph, and introduced the Corporate Average Fuel Economy (CAFE) standards, whereby manufacturers had to ensure that the average fuel consumption of its cars did not exceed a maximum level. The US government also authorised the Department of Energy to support research into alternatives to the internal combustion engine; much of this research was carried out at the Argonne National Laboratory, which was to

[3] Michael Brian Schiffer, *Taking charge: the electric automobile in America*, Smithsonian Books, Washington, 1994.

become an international leader in battery research.

The fall in the oil price in the mid-1980s took some of the urgency away from fuel economy, but there was still concern in industrial countries both about air quality and about over-dependence on oil supplies from the Middle East. The most stringent rules were imposed by the California Board, leading in 1990 to the zero emissions directive; the board ruled that by 1998, 2 per cent of all vehicles sold in the state must be emission-free, rising to 5 per cent in 2001 and 10 per cent in 2003.

At the time of the directive General Motors was working on a new approach to electric cars (an earlier venture, the Electrovette, had been abandoned in the early 1980s), and the technology was given an unexpected boost by enthusiastic support from GM's chairman, Roger Smith.[4] At the Los Angeles auto show in 1990 Smith announced that the company would go ahead with an entirely new electric car, built from the ground up; the Electrovette had been a converted version of an existing petrol-driven car.

Launched with great fanfare in 1996, GM's electric car, first called Impact and later renamed EV1, was presented as the first in a line of high-technology vehicles that the company would introduce over the next few years. Ironically, the launch came just a few weeks after the California Board had softened the zero emissions directive, a decision that infuriated environmental groups. This was in response to energetic lobbying from the car manufacturers (including GM) and the oil industry. Their argument was that, in view of the time needed to develop, produce and sell zero-emission cars in the required numbers, the 2 per cent target for 1998 was unrealistic, and that the directive as it stood would impose unacceptable costs on the industry.[5]

GM did go ahead with the EV1, and despite its high price – and the fact that the battery had to be recharged after 70-90 miles – it attracted a small but enthusiastic band of customers. However, production was on a very small scale; it was more a demonstration vehicle than a serious entry into the mass market, and it never made a profit. In 2002 the company brought production to an end. One historian has suggested, "in view of the highly restricted availability of the car and its overall lack of promotion, we are justified in concluding that GM was not interested in whether the EV1 achieved commercial success".[6]

The EV1 had been leased rather than sold, and the company's decision not merely to recall all the leased cars but to have them crushed provoked furious protests from customers (including celebrities such as Mel Gibson) who had grown to love the car.[7] It was a public relations debacle for GM, but the episode confirmed the industry's view that, at least in the medium term, demand for electric cars was unlikely to be large enough or profitable enough to justify a major investment.

Yet the furore over GM's handling of EV1 highlighted another factor which was to become a powerful influence on the world motor industry: the growing strength of the environmental movement.

This movement was given new impetus by a different sort of pollution, not visible like smog, but one that came to be seen as posing a threat to the future of humanity. [8] This was the phenomenon known as global warming,

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[4] Michael Shnayerson, The car that could: the inside story of GM's revolutionary electric vehicle, (Random House, New York, 1996).

[5] Seth Fletcher, *Bottled lightning: superbatteries, electric cars and the new lithium economy*, Hill and Wang, New York, 2011, 82.

[6] Schiffer, *Taking charge*, vi

[7] A much-praised documentary film, *Who killed the electric car?* was a scathing attack, not just on GM, but also on the oil industry and the state regulators.

[8] Fletcher, *Bottled lightning*, 23

or climate change. The average temperature of the earth's climate system had been rising over the past century, and many (though not all) scientists believed that if this trend continued, the impact could be catastrophic. There was also a growing consensus that global warming was largely caused by man-made carbon dioxide emissions. Several countries began to phase out coal-fired power stations and to subsidise investment in renewable energy. Another target was the motor industry. Forcing car makers to develop low- or zero-emission vehicles – and providing financial inducements to encourage consumers to buy them – was seen as essential to the fight against global warming.

The first big car manufacturer to respond to these pressures was Toyota, which in 1997 launched the Prius, the world's first mass-produced hybrid car.[9] Powered partly by a battery and partly by a conventional engine, the hybrid car was a way of reducing CO2 emissions without seriously affecting performance (Table 1). Although the Prius was more expensive than conventional cars of similar size, it attracted support from environmentally conscious consumers and helped to establish Toyota as the "greenest" of the car makers.

The reaction in the rest of the industry was sceptical. There was no rush to follow Toyota's lead. What came next, however, was potentially a more serious challenge for the established vehicle manufacturers.

In 2003 two Silicon Valley entrepreneurs, Martin Eberhard and Mark Tarpenning, formed a new company, Tesla Motors, to manufacture fully electric cars for the luxury end of the market. This venture attracted the attention of another entrepreneur, Elon Musk, who had made a considerable fortune from his earlier investments[10], and now wanted, according to his biographer, "to do something meaningful with his life". He apparently shared the conviction of the Tesla founders that the US must end its addiction

Table 1: Principal electric car types

Hybrid electric vehicle (HEV)

The hybrid vehicle is powered both by petrol (or diesel) and by a battery. The electric energy is generated by the car's braking system to recharge the battery; the car starts off using the electric motor, and the petrol engine cuts in as load or speed increases. Full hybrids use the electric motor to drive the wheels, with the petrol engine acting as an on-board generator. Mild hybrids do not have an exclusive electric-only means of propulsion, and need less battery power than full hybrids.

Plug-in hybrid electric vehicle (PHEV)

These vehicles have a battery that can be recharged both through regenerative braking and by plugging into an external charging outlet. Toyota introduced a plug-in version of the Prius in 2012.

Battery electric vehicle (BEV or EV)

Fully electric vehicles are powered entirely by the battery and do not have a petrol or diesel engine.

[9] A second hybrid car, the Honda Insight, was launched in Japan in 1999.

[10] One of these investments was PayPal, which was sold to EBay in 2002 for $1.5bn. Before joining Tesla, Musk's interest in interplanetary travel had led him to start Space Exploration (SpaceX), a rocket-launcher business.

to oil; he wanted "to change the energy equation of the country".[11]

Musk joined Tesla in 2004 and became the company's chief executive, chief publicist and a hugely successful fund-raiser. As a disrupter of an established industry, Musk came to be compared with Steve Jobs of Apple.

The first Tesla model, the Roadster (based on a body designed by Lotus, the British sports car manufacturer), was launched in 2008, and received admiring reviews. One writer described it as "Low-slung and sleek… by far the sexiest electric car anyone had ever seen".[12] Production of the Roadster was discontinued in 2011, to be followed by the Tesla S in 2012 and the Tesla X, a sports utility vehicle, in 2015, Both these models were aimed at the high end of the market, but by then the company was working on a lower-priced model for the mass market, the Tesla 3, to be launched in 2017.

These Tesla cars used batteries based on lithium-ion cells supplied by Panasonic of Japan, which later agreed to invest alongside Tesla in a huge battery factory – the so-called gigafactory – in Nevada; it was designed to produce, when fully operational in 2020, 35GWh of battery capacity.[13] The Nevada project was expected to cost around $5bn, part of which was covered by federal and state grants and loans.

The combination of Toyota's success with the Prius and the competitive threat from Tesla – reinforced by increasingly onerous low-emission targets imposed by governments – compelled even the most reluctant manufacturers to take electric cars more seriously. Within a few years of the launch of the first Tesla car, other companies had launched electric or partly electric cars, led by Nissan's all-electric Leaf, launched in 2010, and General Motors' Chevrolet Volt, a plug-in hybrid launched in the same year. Two early European entrants were the Renault Zoe and the BMW i3, both launched in 2013.

In addition to imposing strict limits on emissions, governments in most of the industrial countries introduced subsidies to stimulate the purchase of electric cars, altered the vehicle tax regime to benefit electric cars, and provided funds for the construction of charging stations. In some of them, including the US, there was also direct financial support for manufacturers of electric cars and batteries. Tesla received a $465m loan from the Department of Energy in 2010; it was repaid in 2013, nine years early.[14]

In terms of government intervention, the most aggressive country was China. From the mid-1990s onwards the government introduced a range of subsidies aimed at boosting demand for electric cars and encouraging manufacturers to invest in the new technology. These measures were prompted in part by environmental concerns, but there was also an industrial policy objective. In the 1980s and 1990s the motor industry had been one of the principal targets of Chinese industrial policy, but although the industry grew rapidly in those years, it remained dependent on foreign investment and foreign technology; attempts by Chinese car makers to establish their brands overseas had been unsuccessful. The government-induced shift to electric cars gave China a second chance to become a world leader in this industry.[15]

In 2016 China accounted for about 45 per cent of total world sales of

[11] Ashlee Vance, Elon Musk, *How the millionaire CEO of SpaceX and Tesla is reshaping our future*, HarperCollins 2015.

[12] Seth Fletcher, *Bottled lightning: superbatteries, electric cars and the new lithium economy*, Hill and Wand 2011, 64

[13] One gigawatt-hour equals one billion watt-hours. Tesla's factory, when announced, was far larger than existing lithium-ion battery plants, but other companies, mainly in Asia but also more recently in Europe, are building or planning to build similar-sized plants. As defined by Benchmark Mineral Intelligence, a consultancy, plants with a capacity above 1GWh are classified as megafactories.

[14] The 2010 loan had been provided under the Advanced Technology Vehicle Programme, which had been signed into law by President George W. Bush in 2008.

[15] In 2010 a leading Chinese car maker, Geely, bought Volvo Cars, and is now expanding that company's range of electric cars. In 2018 Geely bought a substantial minority stake in Daimler.

electric cars, compared with 29 per cent in Europe and 21 per cent in the US. But as Table 2 shows, electric cars in that year accounted for a tiny share of the market in most countries.[16] At present there are just over 3m electric cars in circulation in the world, and this is forecast to rise to 5m by the end of 2018.[17] The International Energy Agency has estimated that the numbers could rise to between 9m and 20m in 2020 and between 40m and 70m in 2030.[18]

The wide range of these estimates reflects the many uncertainties that surround the future of electric cars: how soon the cost gap between electric and conventional cars will be eliminated; whether enough charging facilities will be built; concern over the availability and price of key raw materials, especially cobalt and nickel; how far governments will continue to subsidise the purchase of electric cars; and what the true level of consumer demand will be when subsidies are removed. Nevertheless, all the world's major car manufacturers have by now taken the view that they cannot afford not to be in the electric car business.

To make electric cars these companies need access to a reliable supply chain, providing the materials, components and systems that electrification requires. For conventional cars the supply chain is well established; some of the major components, usually including the engine, are made by the car manufacturers themselves, while others are bought from long-established specialist suppliers. The supply chain for electric cars is much less well developed, especially in Europe and the US.

For reasons to be discussed in the next section, the dominant producers of lithium-ion car batteries – the most widely used battery type in today's electric cars – are companies based in Asia, principally Japan, South Korea and China. China, in particular, is investing on a very large scale in lithium-ion battery capacity. These Asian companies supply almost all the cells used in the electric cars currently being manufactured in Europe and the US.

The future of battery technology – and the extent to which Asian companies will continue to dominate the battery market – has become a matter of burning interest to governments in the US and Europe, and to car manufacturers. Strenuous efforts are being made, with government support, to develop new battery chemistries which will not only make electric cars cheaper, but also make the Western motor industry less dependent on Asian suppliers.

The next section describes the evolution of battery technology, and shows how Asian producers achieved the dominance that they now enjoy.

Table 2: Sales of electric cars in 2016

	Total sales	Market share (%)
China	336,000	1.37
US	159,586	0.91
UK	37,912	1.41
France	29,507	1.46
Japan	24,851	0.59
Germany	24,622	0.73

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[16] An exception was Norway where, thanks to exceptionally generous consumer incentives, the market share of electric cars in 2016 was 29 per cent.

[17] Figures from EV Volumes.com.

[18] International Energy Agency, *Global EV outlook 2017: two million and counting*

Battery Technology: the Rise of Asian Producers

The rechargeable or secondary battery is one that can be charged, discharged and recharged many times, as opposed to the primary battery which can be used only once. It is made up of one or more electrochemical cells; each cell contains a positive electrode (cathode) and a negative electrode (anode), together with an electrolyte which controls the flow of electrically charged atoms, or ions, across the battery. The choice of materials for the electrodes largely determines the performance of the battery – how much energy it can store, and how long it lasts before needing to be recharged.

The most common type of rechargeable battery is the lead acid battery, which uses lead for the electrodes and sulfuric acid for the electrolyte. These were the batteries used to drive the early electric cars. Although batteries were soon displaced as a source of power by the internal combustion engine, lead acid batteries were used for other functions - starting, lighting and ignition – and the motor industry continues to be the largest outlet for this type of battery.

From the early 20th century onwards, inventors and entrepreneurs tried to improve the performance of rechargeable batteries by testing different materials for the electrodes.[19] Thomas Edison in the US patented the nickel iron battery, which was more rugged than lead acid, but had disadvantages, including a tendency to corrode and inferior performance at low temperatures. More successful was the nickel cadmium battery which used metallic cadmium for the negative electrode. It performs better at low temperatures than lead acid and requires less maintenance, but it is more expensive; cadmium is also a toxic material, and the disposal of used batteries causes environmental problems.

None of these batteries were well suited as a source of power in cars. An apparent breakthrough was made by Ford in the 1960s, when it announced a battery with a sulphur cathode and a sodium anode. It was a light-weight battery which could store more energy than lead acid, but because it had to operate at high temperatures it was practical only for stationary storage in electric power stations.[20]

When General Motors began work on the EV1 in the 1980s, it used a modified version of the lead-acid battery, but a better alternative soon emerged in the form of the nickel-metal-hydride battery, which had been invented by an American scientist, Stanford Ovshinsky.[21] Although GM abandoned the EV1, Ovshinky's technology was used by other car makers,

[19] This section draws on R. M. Dell and D. A. J. Rand, *Understanding batteries*, Royal Society of Chemistry, 2001.

[20] Steve Levine, *The powerhouse: inside the invention of a battery to save the world*, Viking 2015, 19-20.

[21] Ovshinsky's company, Energy Conversion Devices, had previously won a development contract from the US Advanced Battery Consortium, set up by the Big Three US car companies to sponsor research into batteries. GM took an equity stake in Energy Conversion Devices; the shares were later sold to Texaco.

including Toyota and Honda, for the hybrid cars that were launched in the 1990s. Nickel-metal-hydride batteries for the Toyota Prius were made by Matsushita, a large Japanese electronics company.[22]

Other scientists had been working on lithium as an electrode material. Lithium is the lightest metal in the periodic table, and thus attractive for lightweight batteries It also has higher energy storage potential than other materials. But it is also unstable and cannot be used with an aqueous electrolyte. A major advance was made by Stanley Whittingham, a British-born, Oxford-educated chemist who did his post-doctoral fellowship at Stanford in the US before joining Exxon, the oil company, in 1972; Exxon was then exploring alternative sources of energy that might reduce its dependence on oil.

Whittingham showed how an electrode could be made from a layered material, one that could store lithium ions within sheets of titanium sulphide – a technique known as intercalation[23]; this made it possible for a lithium-based battery to work at room temperature. Exxon put Whittingham's battery into production with a titanium sulphide cathode, a metallic lithium anode and an organic electrolyte, but there were safety problems – a tendency for the cell to ignite when the battery was overcharged – and Exxon abandoned the project.[24]

The use of lithium was taken further by an American physicist, John Goodenough, who was to become one of the most celebrated figures in the history of the rechargeable battery. After service in the Second World War, Goodenough worked first at the University of Chicago and then at MIT's Lincoln Laboratory. In 1976, when interest in battery technology was reviving as a result of the Middle East oil crisis, he was recruited by Oxford University to be professor of inorganic chemistry. Building on Whittingham's work, Goodenough saw that a higher voltage could be obtained if lithium was intercalated into a metal oxide rather than the titanium sulphide that Whittingham had used. After testing numerous metals, he found that cobalt was the most suitable metal for this purpose. The outcome was the lithium-cobalt-oxide cathode, which was patented in 1979.[25]

Goodenough's laboratory had links to the UK Atomic Energy Authority, a government agency which, though primarily concerned with nuclear technology, was also researching non-nuclear sources of energy, including advanced battery chemistries with lithium and sodium materials. The AEA was given the responsibility for licensing the Goodenough patent. The first licensing agreement was signed in 1990 with Sony.

Japanese companies at that time were the world leaders in consumer electronics, and it was that industry, not cars, which provided the market for Goodenough's battery. Japanese consumer electronics manufacturers had used primary (non-rechargeable) mercury-based batteries, but mercury is a toxic product, and as the volume of production increased mercury contamination arising from discarded batteries posed a health hazard.

Sony's researchers, led by Yoshio Nishi, worked on the development and scale-up of a lithium-ion battery, using Goodenough's cathode in conjunction with a hard carbon anode. Further advances were made

[22] Matsushita was sued by Ovshinsky for patent infringement; the suit was settled in 2004.

[23] "Titanium disulphide has a layered crystal structure and the lithium ions insert themselves between the layers. The reaction takes place when titanium disulphide is made the positive electrode in a cell which uses a solution of a lithium salt as the electrolyte", Dell and Rand, *Understanding batteries*,144

[24] LeVine, The powerhouse 20-21

[25] Fletcher, *Bottled lightning*, 41-44

by Akira Yoshino at Asahi Kasei, a chemical company; he described the benefits of using lower temperature carbons such as petroleum coke for the anode.[26] Yoshino's invention was patented in 1985 and a practical prototype was produced in the following year.

At the academic level, Europe was not far behind Japan in battery science. An important contribution came from Bruno Scrosati at the University of Rome; he showed how the use of two intercalation electrodes with different voltages could overcome the safety problems with the metallic lithium anode. Another leading researcher was Rachid Yamazi at CNRS (the French National Centre for Scientific Research); he worked on the intercalation of lithium into graphite as an alternative material for use in lithium batteries. Neither of these advances was exploited commercially by European companies.

Meanwhile, Sony continued to work on improvements to the technology. (The company had become more dependent on its own laboratories, as a result of the break-up of its long-standing technology partnership with Ever Ready, the largest battery maker in the US.[27]) In 1991 Sony launched a camcorder – a device that combines a video camera and a videocassette recorder - based on lithium-ion technology. This was the world's first mass-produced lithium-ion battery. It marked a turning-point in the history of the rechargeable battery, and a shift in the balance of power in the world battery industry.

During this period, demand for portable electronic devices such as video cameras, mobile phones and small computers was expanding rapidly, and there was a rush by Japanese electronics firms into lithium-ion. Several of them were members of large, vertically integrated groups making batteries and other components in their own factories as well as the finished products. This permitted close coordination between the designers of the battery and the designers of the electronic devices. The US electronics industry was organised differently, with manufacturers having an arm's length relationship with their battery suppliers; this has been seen as one of the reasons why US battery makers such as Duracell and Energiser (the successor company to Ever Ready) did not make a major commitment to lithium-ion.[28]

The challenge to Japanese leadership in advanced batteries came, not from the US or Europe, but from South Korea, where the consumer electronics industry had grown rapidly in the 1980s and 1990s. As in Japan, the principal Korean battery suppliers were vertically integrated groups which made a wide range of electronic components and equipment. Out of these groups emerged three big cell suppliers - Samsung SDI, LG Chem and SK Innovation – and by the early 2000s they were catching up with Panasonic (which changed its name from Matsushita in 2008) and the other Japanese companies. In 2009 Japan and South Korea held an estimated 80 per cent share of global production of advanced lithium-ion batteries, with China holding 12 per cent.[29]

Having mastered the production of lithium-ion batteries for consumer electronics, Japanese and Korean companies were well placed to compete

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[26] George E. Blomgren, "The development and future of lithium ion batteries", *Journal of the Electrochemical Society*, 164 (1), A5019-A5025 (2017).

[27] Ever Ready was a subsidiary of Union Carbide, a chemical company, which faced a financial crisis in 1984 after a disastrous explosion at its Bhopal plant in India. It was forced to divest all its consumer businesses, including batteries, and Sony bought full control of the joint venture.

[28] Ralph J. Brodd, *Factors affecting US production decisions: why are there no volume lithium-ion battery manufacturers in the United States?* Advanced Technology Program, Working Paper 05-01, June 2005

[29] Marcy Lowe, Saori Tokuoko, Tali Trigg and Gary Gereffi, *Lithium-ion batteries for electric vehicles: the US value chain*, Center on Globalisation, Governance and Competitiveness, Duke University, October 2010

in the emerging market for car batteries. However, it was not obvious at the start that lithium-ion was the most appropriate technology for cars, which needed larger, more powerful and more robust batteries. As noted earlier, Toyota chose nickel-metal-hydride for the Prius, and its example was followed by several Japanese and Western car manufacturers. Nissan, Toyota's principal Japanese rival, opted for a fully electric car based on lithium-ion, but it did so through a partnership with a Japanese electronics company, NEC, rather than relying on outside suppliers. This joint venture, Automotive Energy Supply Corporation (AESC), made batteries for Nissan's first electric car, the Leaf, which was launched in 2010.

Economies of scale are crucial in the production of cells, and as the cell producers gained more experience with lithium-ion, reducing cost and improving quality, most electronics companies and later most car manufacturers withdrew from in-house production of batteries. Sony, for example, sold its battery business in 2016 to Murata, which planned to use Sony's technology to enlarge its share of the electric car market.[30] In 2017 Nissan and NEC sold AESC, their battery partnership, to a Chinese group, GSR Capital. There was also consolidation among cell producers; in 2009 Panasonic merged with Sanyo, making it the largest Japanese lithium-ion cell producer.

Catching up fast in cell production were the Chinese producers, spurred on by the growth of the domestic market for electric cars and by financial support from the government. By 2023, according to forecasts made by Benchmark Mineral Intelligence, China will account for 48 per cent of

Table 3: The lithium-ion automotive battery supply chain

1. Mining and processing of raw materials – lithium, copper, cobalt, nickel, graphite
2. Development and production of materials for the cathode, anode, electrolyte and separator
3. Manufacture of cells
4. Design and production of battery packs
5. Production of electric cars and commercial vehicles
6. Battery recycling

Note: Lithium-ion cells are converted into modules, which are then assembled into the battery pack. The pack forms part of the battery management system, which is linked to the electric motor, power electronics, and other components. While cells can be transported over long distances, the battery pack is too heavy to be shipped in that way. Hence most large electric car makers keep the design and production of battery packs under their own control and locate those functions close to where the cars are assembled. There are also independent designers and manufacturers of battery packs, whose customers include specialist vehicle makers that are too small to justify in-house pack production.

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[30] Kana Inagaki, "Sony sells battery business to Murata", *Financial Times*, July 28 2016.

the world's lithium-ion megafactory capacity, compared with 23 per cent in Europe and 16 per cent in North America. The biggest of the Chinese firms are BYD and CATL. The former is unusual in also being a leading car manufacturer; the US investor, Warren Buffett, has an equity stake in this company. CATL has the most ambitious plans for expansion, with capacity objectives which, if fulfilled, will take it well beyond the Tesla/Panasonic operation in the US.[31] Both Chinese companies are benefiting from the government's insistence that foreign companies which are making electric cars in China should use only Chinese-made batteries.

What has emerged over the last few years is a complex supply chain for lithium-ion automotive batteries (Table 3), a key part of which, the manufacture of cells, is dominated by Asian companies. Asian producers are also the leaders in battery materials, although they do not dominate that segment to the same extent. In cathode materials, for example, Umicore in Belgium is a major supplier, and other European companies, including BASF in Germany and UK-based Johnson Matthey, are actively investing in this field. (BASF has a partnership with Toda Kogyo, a Japanese producer of cathode materials.) There are also numerous start-up firms, in the US and Europe, some of which are developing new battery materials.

How far this structure will change as the volume of electric car production increases is uncertain. Much will depend on decisions taken by the big car manufacturers on how to organise their battery supply. BYD and Tesla (through its partnership with Panasonic) are unusual in making batteries in-house. Most other car makers source their cells from Asian producers, either importing them from Asia or buying them from the plants which the Asian companies have built in the West. LG Chem, for example, has a plant in Michigan which supplies GM and other US customers. All three Korean cell makers are building cell factories in Eastern Europe – Samsung SDI and SK Innovation in Hungary, LG Chem in Poland - to serve European car makers.

As the next section will show, there is concern among Western car manufacturers – and to some extent also their governments - about their dependence for a vital component on distant suppliers over whom they have no control. A complicating factor for these companies, as they develop their

Table 4: Principal lithium-ion cell variants

- Lithium Cobalt Oxide (LCO)
- Lithium Nickel Cobalt Aluminium Oxide (NCA)
- Lithium Iron Phosphate (LFP)
- Lithium Manganese Oxide Spinel (LMO)
- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Titanate Oxide (LTO)*

*LTO, an anode material, is an alternative to using graphite, offering lower energy density but longer cycle life; it is also more durable at higher charge/discharge rates.

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[31] CATL is also expanding internationally. In 2017 it formed a partnership with Valmet Automotive, a Finnish contract vehicle manufacturer.

strategies for electric cars, is the uncertain future of lithium-ion technology.

This technology - invented in the late 1970s and first commercialised in the early 1990s – is more than twenty years old. Over this period scientists have worked on improvements, and several variants are now in use (Table 4). In the US, for example, the Argonne National Laboratory developed the nickel manganese cobalt oxide cathode (NMC), which offers advantages in speed of acceleration and time between charges.[32] This technology has been licensed to two Asian companies, LG Chem in Korea and Toda Kogyo in Japan, as well as BASF in Germany and GM and Envia in the US.

Thanks to these improvements, the performance of the lithium-ion battery has steadily improved since the early 1990s, and most experts believe that the rate of improvement will be maintained. But cars powered by lithium-ion are still some way from matching petrol-driven vehicles in cost and driving range. Several alternatives to lithium-ion are being pursued, mostly involving new materials for the electrodes, such as lithium-sulphur, sodium-ion and lithium-air. Another active research area is the solid state battery; based on a solid rather than a liquid electrolyte, this technology is expected to have advantages over lithium-ion in higher energy density, quicker charging times and improved safety.

Western car makers are keenly interested in these new technologies, which could overcome the disadvantages of current battery types and help to stimulate demand for electric cars. At the same time, governments concerned about the future of their domestic motor industries are supporting research which they hope will lead to a breakthrough in battery technology and give their car makers a competitive advantage.

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[32] Steve Levine, *The powerhouse* 45-48

Battery Strategies in the US and Europe

The US

With the launch of the first Tesla model in 2008, followed in 2010 by the Chevrolet Volt, the shift to electric cars in the US appeared to be gaining momentum. Yet at that time, as a later report remarked, "The United States faced the prospect of entering the age of electrified transportation without a significant domestic advanced battery manufacturing industry. Virtually all lithium-ion cells, widely expected to be a core technology for electric cars and trucks of the future, were made in Asia. Even though there were many promising US start-ups with innovative lithium-ion battery technology for cars, few could raise funds to build factories in America".[33]

These comments were contained in a report published by the US National Research Council, based on presentations made at a conference on batteries that had been held in Michigan in 2010. The conference was attended by representatives from the Department of Energy, the battery industry and the car manufacturers as well as members of Congress. The focus was on how the US could close the technology gap in batteries with Asian producers.

In a keynote speech at the start of the conference one of the two Michigan senators, Debbie Stabenow, said that the last thing the US needed was "to go from a dependence on foreign oil to a dependence on foreign technology". Building the next generation of energy-efficient vehicles, she said, "is do-or-die for all of the automakers, for the state of Michigan, and for America". The other Michigan senator, Carl Levin said that attitudes towards cooperation between government and industry had shifted dramatically in recent years. Policy makers now understood that US companies were at a competitive disadvantage because they were competing not just with other companies but with other governments that supported their domestic industries. "The question no longer is about whether government should be teaming up with industry", Senator Levin said. "The question is about what we need to do, how we do it, and with what timeline".

Although President Obama had not specifically endorsed industrial policy, his approach to the US manufacturing sector, and to the motor industry in particular, was in line with the sentiments expressed by the Michigan senators. After entering the White House in 2009 the President's immediate priority was economic recovery, and that was the purpose of the American Recovery and Reinvestment Act (ARRA) of 2009. But the Act also contained measures designed to promote investment in electric cars,

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[33] National Research Council, *Building the US battery industry for electric drive vehicles: progress, challenges and opportunities*, Summary of a symposium, National Academies Press 2012.

including direct financial support for battery manufacturers. "If we want to reduce our dependence on oil", the President said, "put Americans back to work and reassert our manufacturing sector as one of the greatest in the world, we must produce the advanced, efficient vehicles of the future".[34]

The Obama Administration was not the first to take an interest in electric cars. In 1976, following the Middle East oil embargo, Congress authorised the Department of Energy to fund research into electric and hybrid vehicle technologies. Several hundred electric demonstration vehicles were produced over the next few years, but that programme was cancelled by President Reagan in 1981.[35] Under President Clinton, the Department of Energy supported the US Advanced Battery Consortium, set up by the Big Three car makers to finance battery research. President Clinton also allocated $1.5bn to the Partnership for a New Generation of Vehicles, a public-private agency which aimed to increase vehicle fuel efficiency through new technologies. This was replaced under the Bush Administration with FreedomCar, which funded research on fuel cell technology as well as lithium-ion.

Thus President Obama, when he entered office in 2009, was able to build on a substantial research base in battery technology, and there were government programmes in place to support commercialisation. But the battery supply chain in the US was still weak; companies such as Tesla and General Motors which had launched or were about to launch electric cars were dependent on Asian cell technology.

Before the election, there had been some discussion between battery researchers and Obama's advisers about creating a government-backed consortium of battery makers to build an American lithium-ion industry capable of competing with Asian producers; the model was Sematech, a consortium of semiconductor makers which had been set up in 1987 to counter Japanese competition.[36] That idea was not pursued after the election. Instead, the government introduced a support package through which battery makers and material suppliers could apply for funds.

As part of the American Recovery and Reinvestment Act, the government provided $2.4bn in stimulus funding to support the establishment of lithium-ion battery facilities in the US. The Act also allocated $400m to a recently created agency within the Department of Energy, known as ARPA-E, whose mission was to fund "transformational" research in the energy field.[37] Obama subsequently launched other initiatives to make electric cars more affordable, including an increase in the tax credit for buyers of electric cars.

Among the recipients of ARRA grants were several entrepreneurial, early-stage firms. The largest of them was A123 Systems, which had been formed in 2001 by scientists at the Massachusetts Institute of Technology. It was funded at the start by government grants but later attracted capital from venture capitalists; this was a period of investor enthusiasm for clean energy firms of all types, and A123 was regarded as a likely star.[38] It competed unsuccessfully against LG Chem to supply batteries for the GM Volt, but that did not prevent it from launching a successful Initial Public Offering in 2009; it was the biggest IPO on NASDAQ in that year. However, the technology may have been

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[34] White House 2009.

[35] Bill Canis, *Battery manufacturing for hybrid and electric vehicles: policy issues*, Congressional Research Service, April 3, 2013.

[36] LeVine, *The powerhouse*, 129-131.

[37] ARPA-E (the Advanced Research Projects Agency-Energy) was modelled on DARPA (the Defence Advanced Research Projects Agency), a Defence Department agency which had developed several innovative technologies relevant to the needs of the US military. ARPA-E was founded in 2007 under the Bush Administration, but it received its first tranche of Federal funds through ARRA.

[38] Fletcher, *Bottled lightning*, 137-143.

pushed ahead too quickly, and A123 was unable to win enough business to keep its Michigan factory fully occupied. The company was taken over in 2012 by Wanxiang, a Chinese automotive parts supplier; the A123 plant is now believed to be operating profitably under Chinese ownership.

A123 was not the only well-regarded entrepreneurial firm to run into financial problems. Envia Systems, founded in 2007, was based on technology licensed from Argonne, and its progress was sufficiently impressive to attract support, not only from ARPA-E but also, more importantly, from General Motors. GM took an equity stake in Envia, and the two companies worked closely together, but the supply contract which Envia had expected did not materialise, principally because the performance of Envia's cathode material fell short of what it had promised.[39]

A123 and Envia were exceptional in the scale of their ambitions, but the record of other US battery start-ups has generally been disappointing. This is partly due to the well-known difficulty, not confined to energy, of commercialising new materials that are radically different from those in current use.[40] But the battery sector, as a recent study has pointed out, has some distinctive characteristics which make it hard for start-ups to grow into profitable businesses.[41] These include high initial capital costs, intellectual property barriers and long timelines to success. Moreover, the biggest battery applications (consumer electronics and electric cars) have highly competitive, commoditized markets with low operating margins; the original equipment makers put intense pressure on battery suppliers for lower prices.

For these reasons the sector has not been attractive to venture capitalists; many of those that invested in battery start-ups during the short-lived clean energy boom of the early 2000s lost money. An interesting alternative to the traditional venture capital model is Volta Energy Technologies, a Chicago-based investment firm closely linked to the Argonne National Laboratory; its chief executive, Jeffrey Chamberlain, had played a central role in developing and licensing Argonne's new cathode material (NMC). The two founding shareholders are Albemarle, the largest US supplier of lithium, and Exelon, a big electrical utility.[42] Unlike venture capitalists, they are strategic investors and under no pressure to exit their holdings within 5-10 years; they are also deeply involved in, and knowledgeable about, energy storage.

Whether the Volta model will succeed where venture capital has failed remains to be seen, but it seems that battery technology – unlike, say, computer software - does not lend itself to the relatively short time horizons of the typical venture capital firm. Meanwhile start-up and early-stage firms will continue to obtain support from federal and state agencies. ARPA-E, part of the Department of Energy, has a portfolio of battery-related firms, some of which are working on new chemistries that could supersede lithium-ion. One promising firm, which received an ARPA-E grant of $3.2m in 2012, is Sila Nanotechnologies, which is developing silicon anodes that could increase the energy density of lithium-ion batteries by 20-40 per cent; it was founded in 2011 by battery engineers from Tesla and a materials scientist from Georgia Tech.

However, the future of ARPA-E itself has looked less secure since the

[39] The Envia story is told in Levine, *The powerhouse.*

[40] The slow progress in commercialising graphene, invented in the UK in 2004 and hailed as a wonder material, illustrates this phenomenon.

[41] Eve D. Hanson, Samir Mayekar and Vinayak P. Dravid, *Applying insights from the pharma model to battery commercialisation*, Materials Research Society, Energy and Sustainability, Vol 4 September 2017

[42] Henry Sanderson, "Volta Energy joins the fray in battle for battery technologies", *Financial Times*, January 11, 2018.

election of Donald Trump.[43] In the budget proposals which he sent to Congress in 2017, he recommended the abolition of ARPA-E on the grounds that the programme was wasteful and provided funds for firms that were capable of raising finance on commercial terms. This was in line with the view of free-market think tanks such as the Heritage Foundation and the Cato Institute, which had been consistently critical of energy subsidies; they argued that the Department of Energy should focus on basic research and not be involved in commercialisation. Although Congress rejected the President's proposal and ARPA-E survived, the political environment for battery firms (and for energy research more generally) is much less favourable than it was under Obama.

How much did Obama achieve in batteries and electric cars? On one measure – the number of electric cars in circulation – his policies clearly failed. In his 2011 State of the Union address the President said he wanted the US to be the first country in the world to have 1m electric vehicles on the road by 2015; the actual figure at the end of that year was about 600,000. (By the end of 2017 the number had reached 757,000.) As for reducing the country's dependence on foreign technology, the two biggest cell factories in the US were based on technology from Japan (Panasonic) and South Korea (LG Chem).

On the other hand, the US has Tesla, a uniquely American phenomenon which has achieved an almost cult-like status and built a powerful brand. Even if, as Bernstein analysts suggest[44], Tesla will find it difficult to make an adequate profit from its newest model, the Model 3, and to achieve the necessary quality, the company's impact on the rest of the industry has been remarkable. Thanks in part to competition from Tesla, the Big Three manufacturers are now competing vigorously in the electric car market; General Motors has two models, the Chevrolet Volt and Bolt (the latter launched in 2016), among the six best-selling electric cars. Moreover, despite the disappointments at A123 and Envia, there is a large amount of entrepreneurial activity in the battery sector, as firms search both for improvements in lithium-ion and for new battery chemistries.

Underpinning this activity is the government's commitment to the funding of scientific research, conducted in national laboratories and in universities. The quality of American research has been an important factor in stimulating foreign investment. For example, the German chemical company BASF licensed NMC technology from Argonne and then built a cathode materials factory in Ohio; the factory began production in 2012. LG Chem from Korea is also an Argonne licensee.[45]

The hope is that out of government-funded research will emerge a novel battery technology that goes beyond lithium-ion. To do this, one leading scientist has suggested, will require the discovery of three new materials – one each for cathode, anode and electrolyte – each of which performs five times better than the corresponding lithium-ion material and which are all electrochemically compatible with each other.[46] Achieving that goal may take a long time, just as it took some twenty years from the early development of lithium-based batteries in the 1970s to Sony's camcorder in 1991.

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[43] William B. Bonvillian, "ARPA-E on the chopping block", *American Interest*, March 30, 2017.

[44] "Electric revolution 2018: the resistance", *Bernstein Global View*, March 2019.

[45] US regulations require licensees of technology arising from research funded by the Department of Energy to manufacture in the US.

[46] George Crabtree, "The Joint Center for Energy Storage Research: a new paradigm for battery research and development", *AIP Conference proceedings 1652, 112* (2015)

American experience in batteries shows that, even for a country as well-endowed as the US, with its high-quality universities, substantial government support for research, an entrepreneurial culture and a well-developed venture capital industry, there is no easy way of building an advanced battery sector against entrenched Asian competition. It is clear that in the lithium-ion era the Asians are the big winners. What happens after lithium-ion remains an open question.

Europe

In Europe, as in the US, industrial policy has been as important as environmental concerns in driving government support for electric cars. In Germany, France and the UK (the last of which is discussed below), the motor industry is a large employer and exporter, and governments in all three countries want to ensure that the transition to electric cars does not damage their domestic car manufacturers.

What form the transition should take, and over what time scale, has been a contentious issue in Germany, which is by far the largest car-producing nation in Europe. With an annual output of nearly 6m cars (compared to slightly less than 2m each in France and the UK), the German motor industry is a huge contributor to the country's trade surplus. With 800,000 employees and powerful trade unions, it also wields considerable political influence. Faced with the shift from petrol and diesel to low-carbon technologies, the industry has used its lobbying power to slow down or block emission regulations which it regarded as premature.

Partly for this reason, government policy on emissions has until recently been softer in Germany than in other European countries, and the move towards electric cars has been slower. After the oil crisis of the mid-1970s, the government did support research into non-oil propulsion technologies, but the focus was mainly on hydrogen fuel cells. Even after the launch of the Toyota Prius in the 1990s there was little interest in hybrid cars or in the new battery technologies that were coming to the fore at that time.

As concern over global warming intensified, the German government recognised that fuel cell technology was too far from commercialisation to be of much help in combating climate change. The Integrated Energy and Climate Programme, adopted in 2007, included electric cars in its plan to meet Germany's emissions reduction targets. Yet subsequent legislation, influenced by the car makers, did not amount to a fully-fledged strategy for electric cars. As two US academics have written, "The main concern of automakers was to not cannibalise demand for conventional cars, while hedging against a technological trend toward EVs in the long term". According to this study, electric vehicle policy in Germany largely stagnated between 2010 and 2016.[47]

By that time, however, the German government had committed itself to stringent targets for reducing CO2 emissions, and these could only be met if the transport sector was substantially electrified. Policy-makers also recognised that, because of its earlier reluctance to invest in electric cars, the motor industry was in danger of missing out on an important

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[47] Jonas Meckling and Jonas Nahm, *When do states disrupt industries? Electric cars in Germany and the United States* MIT Center for Energy and Environmental Policy Research, WP 2017-006, March 2017.

technology. In April 2016 the government announced a €1bn programme which included subsidies to stimulate the sale of electric cars as well as support for the construction of 15,000 new charging stations.

Announcing the programme, Sigmar Gabriel, the economics minister, said he wanted to increase the number of electric cars on the roads from 50,000 to more than 500,000, although he did not specify a timescale.[48] The aim was to secure the future of the German motor industry and to ensure that the next generation of car batteries was manufactured in Germany. Mr Gabriel compared the new policy to the creation of Airbus, the pan-European aerospace group which had been set up at a time when the world market for large civil airliners was dominated by Boeing. Germany's car industry was in a similar situation, the Minister said, with battery technology for the cars of the future increasingly being developed outside Europe.

Mr Gabriel also threw in some harsh criticism of the German car makers for their past opposition to government policy on CO2 emissions. Too often they had used "influence, lobbying and threats of job losses" to push back against government regulation.

Whether or not these criticisms had any impact, the last few years have seen a more positive attitude towards electric cars; one auto analyst, Max Warburton of Bernstein, has described the change as a "capitulation". The fall in sales of diesel cars, following the Volkswagen emissions scandal in 2015, has been another factor in spurring investment in electric cars.

Despite continuing anxiety about the strength of consumer demand – and about how profitable the investment will be – the three German manufacturers have recently announced ambitious expansion plans. Volkswagen says that by 2025 it will be offering 50 pure electric vehicles and 80 electrified models. By that time BMW expects electric vehicles and plug-in hybrids to account for 15-25 per cent of its sales. The launch of Daimler's new range of electric cars, sold under the EQ brand name, will start in 2019 with a mid-sized sports utility vehicle, followed by a stream of models which will include a direct competitor to the Tesla 3.

Will this be enough to preserve Germany's leading position in the world motor industry? An unresolved issue is the sourcing of batteries. At present German-built electric cars use cells imported from Korea or Japan, but for reasons of cost and security of supply the industry would probably prefer a local source, either in Germany or in a nearby European country.

As noted earlier, three Korean companies, Samsung SDI, LG Chem and SK Innovation, are building cell plants in Eastern Europe. There have also been moves to set up European-owned cell-making plants. In 2017 a group of German companies and research institutions formed a consortium, known as TerraE, to plan the construction of a large-scale lithium-ion cell factory. One of the prime movers is BMZ, a German manufacturer of battery packs which has facilities in China and the US as well as Germany and Poland. Participants in the first phase, involving the development of manufacturing processes, include Umicore, the battery materials supplier, as well as engineering groups such as Siemens and ThyssenKrupp. The project has received a grant of €5.5m from the Federal Ministry of Education and Research (BMBF).[49]

[48] Guy Chazan and Patrick McGee, "Germany seeks lead in electric car race" , *Financial Times*, April 27, 2016

[49] TerraE press release, December 14, 2017

Another new entrant is Northvolt in Sweden. Set up by an ex-Tesla executive, Peter Carlsson, Northvolt plans to build a high-volume cell manufacturing plant at Skelleftea, situated in a mining area in northern Sweden. The factory is scheduled to start production in 2020, and there will also be an R & D centre in Vasteras in central Sweden. Carlsson has secured a number of powerful investors, including ABB, the engineering group, and Vattenfall, a Swedish energy company; the European Investment Bank has also approved a €52.5m loan facility for the project. The plant at Skelleftea will be an integrated operation, making electrodes on site as well as the cells. The site was chosen partly because of its easy access to low-cost hydro-electric power; the company believes that its costs will be lower than at the Korean-owned plants in Eastern Europe.

These two projects, if they are carried through, will provide German car makers with a nearby source of cells. But physical proximity is not the only issue. Just as German car makers control the technology that goes into internal combustion engines, so in the long run they may need to have control over battery technology. Will that mean making their own cells? In 2008 Daimler formed a joint cell-making venture, known as Li-Tec, with Evonik, a chemical company, but production was halted in 2014 because costs were too high. Bosch, the largest German component maker, has been actively considering in-house cell production. In 2013 it formed a partnership, known as Lithium Energy and Power, with two Japanese companies, GS Yuasa and Mitsubishi; two years later it acquired a US battery start-up, Seeo, which had made a promising advance in solid-state battery technology. However, in February 2018 Bosch announced that it had decided not to set up its own cell-making operation.[50] It would continue to supply key components of the electric power train, including the electric motor, power electronics and battery systems, but it would buy in the cells. "For Bosch", a spokesman said, "it is important to have a technical understanding of cells. We don't need to make them ourselves." The Japanese alliance would be dissolved and Seeo would be sold.

In explaining the decision, Bosch said it had become clear that investing in the commercialisation of cell technologies was too risky. For a competitive cell manufacturing operation the initial investment would be some 20 billion euros, and there would be operating costs running into billions. "Given dynamic external market factors that can only be predicted with difficulty, it is unclear whether this investment would pay off for Bosch, and when, in the interest of the company as a whole, such a risky investment cannot be justified".

While the strategy of a component maker does not necessarily coincide with that of car makers, it seems that for the present the prevailing view in Germany is that cell-making is best left to specialist manufacturers. The car companies will take a close interest in battery technology and may develop their own intellectual property in batteries, but are unlikely to invest in cell production.

Some of the same issues arise in France, which, like Germany, has a strong, nationally owned motor industry, including two of Europe's leading

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[50] Bosch press release February 28, 2018

car makers, Renault and PSA, as well as several large component makers. Over the last decade the French government has been more active than its German counterpart in promoting the shift to electric cars. France is now the largest European market for electric cars, and this partly reflects the supportive measures put in place by successive governments over the past decade.[51]

An environment conference held in 2007 paved the way for a raft of measures, including the launch of a demonstrator fund for low-carbon vehicles and increased funds for R & D. This was followed by a low-carbon plan which set a target of 2m zero- or low-carbon vehicles to be on the road by 2020. A "bonus-malus" system was introduced whereby subsidies were provided for buyers of low-emission vehicles and tax penalties imposed on other vehicles. Funding was also provided for charging stations, and central and regional government agencies were instructed to buy low-emission vehicles.

France's two big car manufacturers adopted different approaches to electric cars. PSA started with hybrid technology, with the first models launched in 2010; these cars used nickel-metal-hydride batteries, imported from Sanyo in Japan. Renault, which is now part of an alliance with Nissan and Mitsubishi Motors, followed Nissan in moving directly into fully electric cars. The Renault Zoe, launched in 2012, is currently the best-selling electric car in Germany as well as France. The Zoe uses cells supplied by the Korean company LG Chem, but the Renault alliance has been taking a close interest in advanced battery technology; it recently acquired a stake in an American start-up, Ionic Materials, which is working on a new approach to solid state batteries.

The largest French battery maker is Saft, which has been owned since 2016 by Total, the oil company. It has a small lithium-ion battery plant at Nersac in southwestern France, but this company has focused mainly on defence, space and aviation applications rather than the high-volume automotive market. However, in February 2018 Saft announced the formation of a partnership with other European companies – including Solvay in Belgium and Manz and Siemens in Germany – to work on the development of advanced batteries which would address all market segments, including electric vehicles.[52]

The weakness of the European battery supply chain has been a matter of concern to the European Commission. In October 2017 the Commission convened a conference to discuss how to build a European cell manufacturing industry.[53] Maros Sefcovic, the Commission vice-president in charge of energy, said that Europe was in danger of being left behind in the battery race. The sight of electric taxis on the streets of Brussels made by BYD, the Chinese company, had reinforced his view that Europe needed to move quickly.[54] "Let's step up the game because this is going very fast".

Using the same example as Sigmar Gabriel had done in Germany, Mr Sefcovic proposed an Airbus-type consortium for batteries. "In the 1960s we had a lot of smaller (aircraft) companies with cutting edge technologies but what they missed was the scale. We needed the Germans, the French and other Europeans to get together and to develop what today is a marvellous plane".

The outcome of the October conference was an agreement to set up

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[51] Eike W. Schamp, *The formation of a new technological trajectory of electric propulsion in the French automobile industry*, German Development Institute, Discussion Paper 12/14 (2014).

[52] Saft press release February 22, 2018

[53] Rochelle Toplensky and Peter Campbell, "Brussels wants Airbus-style consortium to lead battery revolution", *Financial Times* October 3, 2017.

[54] BYD won the Brussels taxi contract in 2014, beating rival bids from Nissan and Renault.

several working parties, which would pave the way for what Mr Sefcovic described as "a comprehensive roadmap for an EU battery alliance". At a subsequent meeting, in February, 2018, Mr Sefcovic spoke of the need for between ten and twenty giga-factories in different parts of Europe, with the Commission acting as system integrator or facilitator.[55]

The UK Battery Sector

The UK has an honourable place in the history of the lithium-ion battery, thanks to the work of John Goodenough and his team at Oxford University in the 1970s. Several of the scientists who worked with Goodenough, such as Peter Bruce, now Wolfson Professor of Materials at Oxford, went on to build successful academic careers and are internationally respected researchers in the battery field.[56]

Up to now, however, the UK's record in converting this academic strength into profitable battery-related businesses has been less impressive. In the case of lithium-ion, part of the reason was the lack of a dynamic domestic battery industry. As noted earlier, the Goodenough patent was taken up by Sony, and the technology came to be widely used by Japanese and later Korean manufacturers of portable electronic devices. That market was slow to develop in the UK.

The Goodenough laboratory in Oxford had links to the UK Atomic Energy Authority, which had received a grant from the European Commission for energy research; part of that funding was used to support a student in the Goodenough group. The AEA owned the intellectual property arising from this work, and since it had an in-house patent department, it was the appropriate body to handle the licensing of the Goodenough patent.

In the 1980s, as government support for nuclear technology was running down, the AEA's status was changed to that of a trading fund, providing consultancy and contract research for other companies. It continued to work on batteries, and when the AEA was privatised in 1996 the battery business formed part of the successor company, AEA Technology.

The AEA's lithium-ion technology was the basis for a joint venture formed in 1997 with two Japanese companies, the Japan Storage Battery Company (later part of GS Yuasa) and Mitsubishi Materials, a supplier of battery materials. The Japanese firms, which together held 45 per cent of the shares, were interested in using AEA's technology to develop their own industrial lithium-ion cells (for applications outside consumer electronics) and battery materials. The company, known as AGM Batteries, was based at Thurso in Scotland, not far from an AEA nuclear facility at Dounreay.

In 2005 the Japanese companies, having achieved their goals, withdrew from the joint venture. By that time AEA Technology was running into financial problems, partly because of heavy pension liabilities inherited from the period of government ownership. Over the next few years several of its businesses, including batteries, were sold.[57] After several changes of ownership, the cell-making facility at Thurso, now owned by AMTE Power and still known as AGM Batteries, continues to exist, as do some other ex-AEA battery activities.[58] Under its current management AGM concentrates

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[55] Speech by Maros Sefcovic, European Commision, February 23, 2018.

[56] Peter Bruce is also director of the UK SUPERGEN Energy Storage Hub, set up by the EPSRC in 2013 to bring together energy storage researchers from several universities as well as industrial partners.

[57] What remained in AEA Technology after these disposals went into administration in 2012.

[58] A separate business on the Thurso site, Denchi Power (formerly ABSL Power Solutions), is a battery pack and charger company, mainly for military applications. ABSL also had a space battery operation, based at Culham in Oxfordshire, which is now owned by EnerSys, a US battery manufacturer.

on using its factory to help other companies move their technologies from laboratory scale to early-stage production, thus increasing the value of UK-owned battery-related intellectual property.

Several ex-AEA scientists and managers went on to occupy senior positions in newly formed British battery companies, forming part of a sector that was benefiting from increased support from government. The Labour governments which held office between 1997 and 2010 took a number of steps aimed at "decarbonising" the economy, including financial incentives to stimulate the sale of hybrid and electric cars, and increased funding for research. In 2007 the government's innovation agency, the Technology Strategy Board (later renamed Innovate UK) launched the Low Carbon Vehicles Innovation Platform to accelerate the drive for cleaner vehicles.

These measures were taken further by the Conservative/Liberal Democrat coalition which took office in 2010. In 2013, working with the Automotive Council[59], the government provided half the funding for the Advanced Propulsion Centre, whose mission was to support the development of the next generation of low-carbon technologies.

At the university level the Engineering and Physical Sciences Research Council (EPSRC) has been giving a higher priority to energy storage. Among the beneficiaries were universities such as Oxford, Cambridge and Imperial College London, which were strong in electrochemistry and materials science. The University of Warwick also became a prominent player, thanks to the work of the recently created Warwick Manufacturing Group (WMG). This group, whose expertise was in manufacturing engineering rather than basic science, had been established in 1980 by an entrepreneurial Indian-born academic, Kumar (now Lord) Bhattacharyya, whose ambition was to reinvigorate British manufacturing through closer links between academia and business. With support from the government, WMG established an Energy Innovation Centre to work on the development of new battery materials.[60]

Among the early-stage firms formed during this period was Nexeon, set up in Milton Park, near Oxford, to develop silicon-based anode materials based on the work of Professor Mino Green at Imperial College. Green was a co-founder of the company, along with Paul Atherton, a private investor, and Rob Neat, who had run AEA Technology's battery business[61]; several other ex-AEA scientists joined the company, including Bill Macklin as chief technology officer. Initial funding for Nexeon came from Imperial College's technology transfer arm, Imperial Innovations (now Touchstone), and later funding rounds brought in institutional investors, including Invesco.

Oxis Energy, which is developing lithium-sulfur technology, has attracted some strategic investors, including Samsung from South Korea, Umicore from Belgium, and the Aerotec Fund, owed by CODEMIG of Brazil. Oxis is engaged in discussions with CODEMIG (which is owned by the state of Minas Gerais) to build a battery plant in Brazil; the plan is to exploit the large lithium deposits in Minas Gerais, and to collaborate on the use of pure graphene in the make-up of lithium-sulfur technology.

Other early-stage firms include Faradion, which is working on sodium-

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[59] The Automotive Council, a joint industry–government body, had been founded in 2009 to review the future strategy of the British motor industry.

[60] WMG was chosen in 2015 to lead a £14m consortium to create a new automotive battery pack manufacturing research centre. This project, called AMPLIFYII (Automated Module-to-Pack Pilot Line for Industrial Innovation), included a number of Original Equipment Manufacturers – Jaguar Land Rover, JCB and Ariel, a specialist sports car manufacturer – as well as well as designers of battery packs such as Delta Motorsport, Potenza and Vayon Group; there were also university-based partners, including the Department of Engineering Science at Oxford.

[61] Rob Neal died in 2008 and was succeeded as chief executive by Scott Brown, who had previously worked for Cambridge Display Technologies.

ion technology[62], and Ilika, which was spun out in 2004 from the school of chemistry at Southampton University. Ilika's strategy at the start was based on contract research, using its high throughput techniques to discover and optimise new materials. More recently, it has developed its own solid state battery technology, which it licenses out to cell manufacturers and original equipment manufacturers. Ilika has worked closely with Toyota on solid state batteries.

A much larger new entrant is Johnson Matthey, one of the world's leading suppliers of catalytic converters to the motor industry. As the shift to electric cars gathered pace, Johnson Matthey took the logical step of diversifying into batteries, and it did so by means of acquisitions. In 2012 it bought Axeon, the largest UK manufacturer of battery packs, and this was followed by two acquisitions outside the UK: a battery materials plant in China, bought from the US company, A123, and the energy storage business of Clariant, the Swiss chemical group. Johnson Matthey is planning a major expansion of its cathode materials business, although the location for this investment has not been disclosed.

Johnson Matthey is a global company, but its head office is in the UK as is the bulk of its research and development, and it could become a major player in the UK battery sector. Most other firms in the sector are small or medium-sized. Among the players in battery management are companies with a motor industry background such as Cosworth; engineering consultancies such as Ricardo; and pack manufacturers such as Williams Advanced Engineering, McLaren Advanced Technologies and Hyperdrive.

Thus the last few years have seen increasing activity by UK-based firms in different parts of the battery supply chain, thanks in part to government support. But the future growth of battery manufacturing in the UK depends crucially on decisions taken by the big car assemblers, over which the government has only limited influence. Will they make electric cars in the UK, and if so will they source their batteries here?

The first move on this front came from Nissan, which announced in 2009 that, through its joint venture, AESC, it would build a lithium-ion battery plant in Sunderland, close to its existing car assembly factory. Two years later Nissan confirmed that it would assemble its first electric car, the Leaf, in Sunderland. The technology and some of the materials for the battery plant came from Japan; it is an assembler of cells, modules and packs, rather than a fully-fledged cell manufacturer, and it is not linked to a UK-based battery supply chain. In 2012 one of Nissan's Japanese material suppliers, Mitsubishi Chemical, opened an electrolyte plant at Stockton-on-Tees, not far from Sunderland, to supply Nissan and other European customers. That plant was mothballed in 2016 because of lack of demand, but the company recently announced that it would restart production in 2018.

The other two Japanese assemblers, Honda and Toyota, have not so far followed Nissan's lead. The next move came in 2012, when Jaguar Land Rover unveiled its first electric car, the Jaguar I-PACE. Launched in March 2018, this car is manufactured in Graz, Austria, by Magna Steyr, a contract

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[62] Faradion's chief executive (and co-founder) is Chris Wright, who had been the director responsible for non-nuclear businesses in AEA Technology.

vehicle manufacturer. The battery pack is designed by Jaguar Land Rover, but production is handled by LG Chem's new battery factory in Poland; the packs are shipped from Poland to the assembly plant in Graz. Another UK assembler, BMW, announced in 2017 that it would build an all-electric version of the Mini at its Cowley plant; production is due to start in 2019, with batteries and electric motors imported from BMW's factories in Germany.[63]

An intriguing new entrant into electric cars is Dyson, the manufacturer of cordless vacuum cleaners and other household appliances. This company, founded and run by Sir James Dyson, one of the UK's most successful entrepreneurs, has been investing substantially in battery research in recent years. In 2015 it caused something of a surprise when it bought Sakti3, a spin- out from the University of Michigan which claimed to have made a major advance in solid-state battery technology. Although Dyson subsequently returned some patents to the university, the company is continuing to work with the Sakti3 team in creating new intellectual property in energy storage; Dyson says it currently has 94 Sakti3 patents and patents pending to protect these developments. In 2017 Sir James announced that the company would spend £2bn on developing an electric car, to be launched in 2020; he said it would not be aimed at the mass market. The company has released no details about the battery technology that its electric cars will use.[64]

At present, large-scale production of lithium-ion automotive batteries in the UK is confined to the Nissan plant in Sunderland. In 2017 the future of this operation was thrown into some doubt when Nissan and NEC decided to sell AESC, their joint battery company. The new Chinese owner, GSR Capital, which now controls the ex-AESC battery plants in the US and Japan as well as the UK, is likely to expand the Sunderland facility and look for additional European customers. Nissan will have a long-term contract with the new owners, but will be free to buy cells from other suppliers.

For the British government, eager to strengthen the battery supply chain, the creation of new cell-making capacity in the UK is a highly desirable objective. The most obvious source of such an investment would be one of the big Asian cell producers; if that were to happen, the government believes that it would increase the attractions of the UK as a location for making electric cars, and stimulate investment in other parts of the supply chain. This line of thought forms part of the rationale for the Faraday Challenge, which is described in the next section.

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[63] Peter Campbell, BMW to build electric Mini in UK, Financial Times, July 25, 2017.

[64] Peter Campbell and Michael Pooler, "Daring manoeuvre reflects Dyson's tech clout", *Financial Times* February 15, 2018.

The Faraday Challenge

In April 2017 the Business Secretary, Greg Clark, announced that the newly established Industrial Strategy Challenge Fund would focus in the next four years on six key areas: healthcare and medicine; robotics and artificial intelligence; batteries for clean and flexible energy storage; self-driving vehicles; manufacturing and materials of the future; and satellites and space technology.

Mr Clark did not explain why these areas had been selected, except to say that the government had worked with businesses and academics "to identify core industrial challenges, where research and innovation can help unlock markets and industries of the future in which the UK can become world-leading".[65]

The inclusion of batteries in the first batch of recipients was based on the belief that energy storage, both for transportation and for the grid, was a technology of growing economic importance – most importantly as a means of reducing carbon dioxide emissions – and one in which British firms should be able to establish a strong competitive position. Another factor, at least as important in the government's thinking, was concern over the future of the British motor industry.

Earlier governments had recognised that if the UK's car manufacturers were to keep pace with their international competitors, they needed to move faster to develop low-carbon technologies. A government-sponsored report in 2009 had noted that, following the drastic decline in the motor industry's spending on R & D, car makers were in a weak position to meet the low-carbon challenge. As the importance of alternative power trains (including hybrid and electric vehicles) increased, the UK would find it harder to maintain its position in the global automotive industry. "The main developments in this space", the report said, "are currently being done in Japan, Germany, France and the USA. We have little evidence that a growing 'low carbon vehicle' competence is developing in the UK".[66]

Shortly after this report was published a joint government-industry body, the Automotive Council, was established to work out a strategy for the motor industry. As noted in the last section, discussions between the Council and the government led in 2013 to the creation of the Advanced Propulsion Centre, charged with supporting the development of low-carbon technologies.

The creation by Mrs May's government of the Industrial Challenge Strategy Challenge Fund, coming at a time when the shift to electric cars appeared to be accelerating, provided an opportunity for the industry to press for more government-support for battery technology. The Automotive

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[65] Press Release, Department for Business, Energy and Industrial Strategy, April 21, 2017.

[66] Matthias Holweg, with Philip Davies and Dmitry Podpolny, "The competitive status of the UK automotive industry", commissioned by the New Automotive Innovation and Growth Team (NAIGT), 2009, 66-67. The NAIGT had been set up by the Labour government to "to identify and agree a strategic view of the innovation and growth challenges" facing the sector.

Council began lobbying to this end in the summer of 2016.

At the same time, Peter Bruce and his colleagues in Oxford University's Department of Materials were working on a proposal to the government for an expansion of battery-related research. They believed that the technology of energy storage was evolving in a way which could create opportunities for British business, as well as contributing to the government's programme for "decarbonising" the economy. What was needed, in their view, was an increase in government support for the basic scientific research that could unlock the door to advances in storage techniques, but delivered in a different way. They argued that the research needed to be focused on specific targets, carried out at scale and leveraging the strength of the UK science base outside as well as within energy storage. To achieve that, a new organisation was necessary.

After discussions with Mrs May's advisers in Downing Street, the government brought in Sir Mark Walport, the chief scientific adviser. His view was that the Oxford-led proposal should be combined with that of the Automotive Council. The outcome was a joint paper put to Sir Mark by Peter Bruce, representing the academic community, and Graham Hoare, a senior Ford executive, on behalf of the Automotive Council.

In his recommendations to the government Sir Mark noted that the UK had world class expertise in battery-related disciplines, including electrochemistry and materials science, which could help to solve short- and long-term challenges in electrical storage in automotive and other areas. "A well-coordinated national research programme", he said, "would send a strong signal to the automotive industry that the UK Government is serious about getting ahead of the game in battery R & D and has an industry-focused strategic vision".[67]

Such a programme, according to Sir Mark, would make the UK a more attractive investment location for foreign battery and battery material suppliers. A key objective, he suggested, would be to secure an investment from one of the big cell suppliers such as Samsung, LG Chem and Panasonic. This would encourage UK car makers to locate their battery production in the UK, helping to "anchor their vehicle assembly operations here and reduce disinvestment risks".

Central to Sir Mark's recommendations was the concept of close linkage between the three phases of the product development process: scientific research; innovation, which he described as "market- and product-driven problem solving, often leading to proof of concept"; and scale-up, defined as manufacturing-driven problem solving. In each of these areas there were existing agencies; the EPSRC was responsible for academic research, Innovate UK for close-to-market innovation, and the Advanced Propulsion Centre for scale-up.

On the research side a new institute would be set up to sponsor and manage "mission-driven" research in energy storage. Sir Mark said this would require the science community to work together in a new and different way - "as a synergistic strategic collective rather than a large number of small uncoordinated groups". The next stage, to be handled by

[67] Letter to the Business Secretary from Sir Mark Walport, published by the Department for Business, Energy and Industrial Strategy, March 3, 2017.

Innovate UK, would draw on the results of academic research, and on the output of industrial research laboratories, to demonstrate the feasibility of new technologies. For the third stage, moving from proof of concept to scale-up, Sir Mark commended the Automotive Council's proposal for creating a prototyping and pilot production facility, in which firms would test out new materials and new technologies before taking them through to commercialisation.

In accepting Sir Mark's proposals, Greg Clark said the government would make available £246m for the first four years of the Faraday Challenge - £78m for research, £88m for innovation, and £80m for scale-up. Over the next few months, the government moved quickly to put a new organisation in place and to launch the first of the competitions for funding under the three streams.

A new research institute, the Faraday Institution, was established to coordinate and manage the research programme. The founding members of this organisation are seven universities – Oxford, Cambridge, Southampton, Warwick, Newcastle, Imperial College and University College London – but the Faraday Institution itself will be independently managed, not controlled by the universities. A notable coup for the government was to recruit as chairman of the Faraday Institution Peter Littlewood, a distinguished physicist who, though British and a graduate of Cambridge University, had spent most of his career in the US. He had worked for several years in Bell Laboratories and later served as director of the Argonne National Laboratory.

The Faraday Institution's task was to invite bids for specific research projects from universities and their industrial partners, but these contracts would be different from the awards previously made by the EPSRC. They would be larger and more industry-focused; they would be monitored more rigorously by the project managers in the Faraday Institution; and they would be closed down or reshaped if insufficient progress was being made and the resources could be better used elsewhere.

The first four projects, announced in January, 2018, included one, led by Oxford University, which was focused on next-generation solid-state batteries. The other three were: a project on recycling and re-use, led by Birmingham University; a project on extending battery life, led by Cambridge; and a project led by Imperial College on battery system modelling, where the aim was to develop new software tools to understand and predict battery performance.

A separate competition for innovation-related proposals was handled by Innovate UK. Among the winners were several early-stage firms, including Nexeon, Oxis Energy and Faradion, as well as Johnson Matthey (to work on a recycling supply chain for lithium-ion batteries) and AGM Batteries (to establish a battery cell supply chain for low-volume vehicle manufacturers).

The largest single project was the prototyping and pilot production facility that had been advocated by the Automotive Council. The winning consortium was a Midlands-based group that included WMG at Warwick

University, which already had smaller testing facilities in place.[68] (The unsuccessful bidder was the Advanced Manufacturing Research Centre at Sheffield University.) The new facility, to be known as the National Battery Manufacturing Development Facility, is expected to open in early 2020. Its functions, as set out in the request for bids, include "the capability to simultaneously trial and prove-out initial production runs of advanced battery components and assemblies".

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[68] WMG is a part of a consortium led by Coventry and Warwickshire Local Enterprise Partnership.

Assessment

As an early indication of what the government means by industrial strategy, the Faraday Challenge deserves close scrutiny, all the more so if it serves as a model for support programmes in other sectors. There has so far been little public debate about the programme, perhaps because Brexit has crowded out other topics, or because there is general support, in business and in Parliament, for the government's industrial strategy. Four key questions need to be addressed:

- What is the rationale for the programme?
- Are the objectives realistic?
- Is the organisation that has been set up to implement the programme likely to be effective?
- How will the success of the programme be evaluated?

On the first question, part of the justification for the programme is that energy storage is an important technology that will generate big commercial opportunities, and that UK-based firms, thanks to the UK's strength in the underlying science, should be well placed to exploit them.

There is a good case for energy storage to be given a higher priority in state-funded scientific research, but the government has not explained why, if the potential rewards are so attractive, commercialisation cannot be left to the private sector. As shown earlier in this paper, many British firms are competing in various parts of the battery supply chain, and it is not obvious that they are held back by lack of capital from commercial sources. Moreover, in basing the programme in part on the strength of UK academic science, the government might have provided more detail about the contribution which British laboratories have made to advances in battery research. While the work of John Goodenough and his colleagues on the lithium-ion battery is justly celebrated, no other major breakthroughs have so far emerged from UK academic research. Some quantification of the UK's performance perhaps through patents and citations, would have been useful.

Another part of the rationale is the need to ensure that the UK's car manufacturers, as they decide how and where to make electric cars, have access to a viable battery supply chain in the UK. The government believes that the supply chain should include one or more high-volume cell-making factories, and desirably this will involve an investment in the UK by one of the big Asian cell producers. The issue here is whether the absence of cell-making capacity will make the UK a less attractive base for making electric cars and increase the risk that the car assemblers might shift their investment to other countries.

While there are disagreements within the industry on this point, it is not certain that UK-based manufacturers of electric cars will be at a disadvantage if they have to import cells from, say, one of the Korean-owned plants that are being built in Eastern Europe, or from one of the factories which are being planned in Germany and Sweden. Cells – unlike battery packs – can be shipped over long distances, as is happening now with imports from Asia.

Since all the major car assemblers are foreign-owned, the government is understandably concerned about the risk that they might divert their investment in electric cars away from the UK, and perhaps even leave the UK altogether. But it does not follow that, to keep them here, the UK needs to be represented in all phases of the battery supply chain. Other factors – including the UK's future trading relationship with the EU – are likely to have more influence on the industry's investment decisions than the presence or absence of cell-making capacity.

As for the overall objectives of the programme, these have been pitched by government at an ambitious level. Greg Clark has said that the government wants to ensure that the UK "leads the world in the design, development and manufacture of batteries for the electrification of vehicles".[69] Given the strength of international competition and the current state of the UK battery sector, that hope seems unrealistic. Asian companies have a twenty-year lead in current battery technology, and they are spending heavily on research and development to stay ahead.

An element of optimism in government announcements is not unusual, and should not necessarily be regarded as a sign of wishful thinking. But there have been some exaggerated claims about British prowess in several of the documents associated with the government's industrial strategy, and this may create a misleading impression of the UK's strengths and weaknesses. The foreword to the document setting out the Automotive Sector Deal includes the following: "For decades, the UK's automotive industry has powered our economy forward. Today, automotive firms from around the world choose to set up shop here, citing our history of excellence".[70] A more balanced judgement would be that the industry has recovered well from the dark days of the 1970s and 1980s, but the recovery is still fragile.

In the case of batteries, an upbeat message about future opportunities should at least acknowledge the obstacles that stand in the way. A larger British presence in the market for car batteries may well be desirable, but world leadership is not an attainable goal.

Of the new organisations that have been set up to implement the programme, the Faraday Institution is a potentially valuable addition to the UK's scientific capability, concentrating on "user-inspired" research rather than the basic research which will continue to be funded by the research councils.[71] It could play a similar role in the UK to that of Argonne in the US, becoming in effect a national energy laboratory. To fulfil this role the institution may in future need a laboratory of its own, although this is likely to be opposed by the universities.

[69] Department for Business, Energy and Industrial Strategy, Press Release, April 21, 2017.

[70] Department for Business, Energy and Industrial Strategy, Automotive Sector Deal, January 10, 2018.

[71] The Faraday Institution has its headquarters in the Harwell Science and Innovation campus, the old home of the Atomic Energy Authority.

As noted earlier, the government has emphasised the importance of the three-way linkage between basic research, innovation and scale-up. This has been described as a novel approach which no other country has followed, and one which will "drive a significant change in the way the UK turns world-leading research into market-ready technology".[72] How significant the change will be should become clear over the next few years as the research programmes that are now getting started near completion. But it is important that the focus on "user-inspired" research does not skew the research effort too far in the direction of improving existing technologies. The main thrust of publicly supported research, as is often stressed by US innovation scholars, should be to push out the technological frontiers.[73]

The most controversial element in the first phase of the Faraday Challenge is the battery development facility that is to be built in the Midlands. While existing UK-based battery firms (including early-stage firms) are likely to be the principal users of this facility, the architects of the programme believe that foreign cell makers may wish to use it to test their new materials and new technologies; this could lead, over time, to direct investment in the UK. Yet, as far as the leading Asian companies are concerned, it seems doubtful whether the skills and capabilities at the new facility will be sufficiently different from what they have at home to affect their decision as to whether or not to invest in the UK.

This is not to say that an investment from a Panasonic or an LG Chem would not be welcome, all the more so if it was closely linked to the UK's research base. But that would be a commercial decision that cannot be directly influenced by government. There has been no suggestion that the government would offer a financial inducement to a potential cell-making investor, but the government hopes that the other measures which it is taking to stimulate the battery sector will make the UK more attractive to non-British manufacturers.

A more general question about the Midlands project is whether it will have the capacity to handle all the various materials and technologies that may come forward in the next few years. Difficult choices will have to be made as to which processes to focus on and which equipment to install.

Finally, the government needs to set out more clearly how and when the success of the programme will be evaluated. What needs to have happened after the first four years to justify continued funding? It would be unreasonable to expect all the research programmes that are now getting under way to have achieved concrete results by then, but the government will want to satisfy itself (and the taxpayer) that at the end of the four-year period the battery sector has been strengthened and that a viable supply chain for car batteries has been, or is close to being, established. There is also the important question of whether the government intends to phase out state support after the initial objectives have been achieved.

[72] Department for Business, Energy and Industrial Strategy, Automotive Sector Deal

[73] David C, Mowery, Richard R. Nelson, and Ben R. Martin, "Technology policy and global warming", *Research Policy 39* (2010), 1011-1023

Governments, Markets and the Private Sector

The battery programme, and the other sector-based schemes which form part of the industrial strategy, raise some familiar questions about the role of government in the economy. Can governments turn weak industries into strong ones? How far can government intervention supplement market-based competition as a spur to innovation?

The conventional justification for government intervention is the existence of market failure. This is the notion that in some circumstances markets on their own will not produce the social and economic outcomes which governments think are necessary. An example of market failure which is accepted by most economists relates to basic scientific research. Research that has no obvious or immediate commercial application will not attract investment from the private sector, even though in the long term some of that research may be of great value to private firms. This is a funding gap which has to be filled by government.

It is at the next stage of the innovation process where the case for intervention becomes more controversial. To justify support for firms seeking to bring novel products to the market, the government has to be sure that the risks associated with investment in that particular technology are too great to be borne by the private sector on its own, or that investment by profit-making companies will not be sufficient to achieve the government's objectives. But the reluctance of private-sector companies to invest on the scale desired by government may simply reflect their judgement that the investment will not yield an adequate return. Past experience of selective intervention suggests that the use of government funds to override the judgement of the market can often lead to expensive disappointments.

Intervention at the sectoral level can only be justified if the benefits outweigh the costs, and that calculation is not easy to make. As two UK government economists have pointed out, policy-makers can possess only a fraction of the information available to market participants, so that any decision to intervene will be rough and ready. "Not only is there a risk of miscalculating the effect of policy measures on their chosen target, or even of choosing the wrong target altogether, but distortions may be created elsewhere in the economy." [74]

Too often in the past industrial policy has been seen as a weapon in a competitive struggle with other countries. An extreme example was Concorde, where the government hoped that the development of a supersonic airliner would enable the UK to regain the lead in large civil

[74] John Barber and Geoff White, "Current policy practice and problems from a UK perspective", in Partha Dasgupta and Paul Stoneman (eds), *Economic policy and technological performance* (Cambridge 1987)

[75] P. D. Henderson, "Two British errors: their probable size and some possible lessons", *Oxford Economic Papers* 29/2 July 1977.

airliners that had been lost to the US; the outcome was a massive waste of taxpayers' money.[75] There has also been a tendency to believe that the UK needs to be represented in certain technologies deemed to be "strategic", and that if the private sector is reluctant to invest in those technologies, the government should step in to fill the gap. One example was the attempt in the 1970s to create a UK-based competitor in the US-dominated semiconductor industry.[76]

As long as capital and technology can move freely across borders companies will locate their laboratories and their factories in countries which offer the most conducive environment for their particular activity. This does not mean that governments should subsidise foreign companies to invest in their country. Subsidies may have a temporary effect, but companies will only continue to invest in that country if it makes economic sense – that is, without subsidies – to do so.

If a government wants to encourage investment in high-growth, technology-based industries, the main focus should be on broad, non-sectoral policies: support for high-quality academic research, ensuring an adequate supply of well-trained scientists, engineers and technicians, and developing a financial system that allows young firms to attract the capital they need. The government must also ensure that the domestic market is open to foreign trade and foreign investment.

Moving from non-selective policies of this sort to sectoral strategies, as the present UK government is doing with its industrial strategy, is risky. To increase the chances of success, the government should bear in mind the following points.

First, the objectives of any sectoral intervention should be based on a realistic assessment of the UK's strengths and weaknesses in the relevant technology, and of the international competition which British firms will face.

Second, sectoral intervention should not be seen as a quick fix, allowing a country to catch up with its foreign competitors in some favoured technology within the space of a few years. Energy storage is an area where the process of turning scientific advances into commercial products has often taken many years. In the case of lithium-ion batteries there were numerous false starts, and many apparently promising discoveries that led nowhere.[77] There is no reason to suppose that this pattern will not be repeated in the "beyond lithium" space that researchers around the world are now exploring.

Third, any support scheme that the government introduces must be designed in a way that encourages new entrants, and avoids capture by industrial lobbies. In a technology like energy storage, where no one can predict which lines of research will prove to be most productive, multiple sources of invention and innovation are essential. Entrepreneurial discovery is as likely to bring about the next breakthrough in battery technology as a coordinated development programme led by a government-backed consortium of established companies.

Fourth, the government should build into any support scheme a rigorous process of evaluation against the objectives that were set at the start, and

[76] Geoffrey Owen, *From Empire to Europe*, HarperCollins (1999) 172-173

[77] George Crabtree, Elizabeth Kocs and Lynn Trahey, "The energy-storage frontier: lithium-ion batteries and beyond", *MRS Bulletin* 40, December 2015.

be ready to terminate the scheme if it is not successful. The scheme should be seen as temporary rather than open-ended, with a strong preference for government funding to be replaced by private sector finance as soon as it is practicable to do so. Industrial strategy should not be used as a continuing source of state funding for favoured sectors, in the hope that one day they will become world leaders.

A revolution is under way in the motor industry the shift from petrol and diesel to electric cars – and the British Government wants to ensure that the UK is well equipped to handle the transition. The £246m battery support programme, announced last year as part of the industrial strategy, is intended to promote the development of a battery supply chain, making it more likely that the car assemblers will make their electric cars in the UK.

The Government's concern over the future of the motor industry is understandable, but there are several questions about the battery programme which have not been fully answered. Why is public money needed to support a technology which should be highly attractive to the private sector? Is it necessary for the UK to be represented in all phases of the battery supply chain? How realistic is to think that the UK can lead the world in developing batteries for electric cars?

These are among the questions discussed in this wide-ranging report, which puts the UK battery programme in the context of the world battery industry. The findings have important implications, not just for batteries, but for the industrial strategy as a whole. For example, the Government must be clear when funding will be withdrawn if evidence of progress is not forthcoming.

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Policy Exchange
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Westminster
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