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PRODUCING THE ELECTRIC CAR

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1. Introduction

Many factors have been of importance in the growing market share of electric cars, but the contribution of design and production strategies has been somewhat neglected compared with the attention given to incentives for consumers, regulatory interventions, and the provision of public charge infrastructures. Pre-COVID 19 forecasts of electric vehicle production anticipated rapid expansion: in the EU for example T&E (2019) expected about 25% of annual output (or about 4 million cars and vans) for all types of electric vehicle by 2025. By 2021 forecasts were for even stronger growth, along with stronger regulatory pressures to phase out internal combustion engines. An open question is the extent to which the adoption of battery electric powertrain marks a decisive shift in the structure and economics of the automotive industry. This chapter explores that question as it relates to manufacturing, and in so doing demonstrates there are multiple approaches to electrification of automobility in a complex balance between continuity and radical change.

2. ICE and EV compared

Before considering battery electric vehicles (BEVs), it is worthwhile to provide a brief account of traditional car manufacturing, especially for petrol and diesel internal combustion engines (ICEs). There are similarities and differences that matter when the transition to mass manufacture is contemplated, and which help to explain why the diversity of BEV manufacturing approaches remains. In this, the account considers the powertrain as a functional system.

ICEs comprise an engine and exhaust, clutch and gearbox, transmission, and fuel system in which liquid hydrocarbon fuel is converted into rotational energy delivered to the wheels. The core is the engine block and cylinder head, that contain the pistons, conrods, valves, and crankshaft. Following decades of development and refinement, contemporary engines comprise multiple materials, manufacturing process steps, and many components. A great many ancillary parts are necessary for the system to function, ranging from radiators and the cooling sub-system, to diagnostic sensors and electronic ignition. Most parts are usually sourced by the vehicle manufacturer from a long-

established supply chain, with in-house operations confined to some casting, machining of blocks and cylinder heads, and assembly of the engine. With a few exceptions, engines are a strategic competence. Many vehicle manufacturers also make their own gearboxes or automatic transmissions. In the final assembly of the car, a key step is the 'marriage point' where the powertrain sub-assembly (usually including the radiator, gearbox and often the front driveshafts) is fixed into the car bodyshell from below.

In practice there is a diversity of design configurations for the ICE powertrain. There may be 2, 3, 4, 5, 6, 8 or even 12 cylinders; in in-line, V, W, or horizontally opposed configurations. The engine size can range from a mere 50cc to over 5,000cc. The gearbox can have 3,4,5,6 or more speeds, or be automatic in a variety of formats including continuously variable transmission, and DSG (dual clutch) systems. A typical engine 'family' is produced in very high volume and can then be applied across a range of models over a protracted period.

Importantly, a contemporary ICE is capable of over 180,000km of travel and, on one fuel tank, has a range of at least 300km (and typically nearer 600km). It can be refuelled in minutes via a widely available infrastructure. The engine is designed to last for the lifetime of the car but can also be remanufactured and reinstalled at reasonable cost. Despite the many moving parts, an ICE is generally reliable within a defined maintenance regime that includes changing oils, filters, etc. as necessary.

It is against this benchmark that the design and manufacture of battery powertrain needs to be considered. The ICE system is deeply embedded, with a robust supply chain of readily sourced materials and components and is very low cost. There is a huge infrastructure to support and maintain ICEs in use, and consumer definitions of automobility have been constructed around the performance parameters of the ICE.

The BEV powertrain comprises the battery pack (itself comprised of cells that are built up into modules), the cooling system (some are air cooled), a motor (sometimes hub motors or one motor per axle) and a transmission system that will usually incorporate regenerative braking that can supply additional charge to the battery. Some vehicle manufacturers are developing their own manufacturing capability for battery packs, but many still obtain them from an independent supplier or are engaged in joint initiatives. Compared with ICEs, the supply chain is far more limited for battery packs, cells, and even the key materials that are mostly used in those packs (e.g. lithium, cobalt, manganese). In their initial commercial applications from around 2011, battery packs and the associated powertrain components were much more expensive and heavier than the equivalent ICE, while also compromised in performance. Moreover, Life Cycle Analysis shows that BEV powertrains have a higher ecological burden in production compared with ICEs despite the overall advantage in lower CO₂ emissions (Hawkins et al., 2012; T&E, 2020). T&E (2020) use an estimate of 86 kgCO₂e/kWh to calculate the expected burden from battery pack manufacturing. As a rule of thumb, in a typical ICE vehicle the in-use phase accounts for 85% of total GHG emissions, with only 15% for manufacturing and recycling. In comparison, early BEVs such as the BMW i3 incurred around 65% of total GHG emissions in manufacturing (Wells, 2019).

In the battery electric powertrain approximately 60-70% of the total weight is for the high voltage battery pack itself. The transmission system comprises up to 20% of total weight, while the remainder is accounted for by the HVAC and cooling systems, high voltage cables, high voltage junction box, AC-DC converter(s), and the onboard charger system.

Importantly, the technology for BEVs has not stabilised around a design. There are multiple competing chemistries and morphologies (or form factors), reflecting in part that the BEV powertrain has not to date been competitive with ICE on key consumer expectations over cost, range, and speed of refuelling. Thermal management is critical, particularly in high-performance applications, as battery packs lose efficiency at high or low temperatures, and thermal mismanagement can result in battery failure. Each choice over chemistry, cell type, module design, cooling strategy, and pack design (including the pack container) has implications for cost and performance, and for manufacturing techniques.

There are also three competing (incompatible) charge point designs: CCS, CHAdeMO, and Tesla. AC and DC designs run at various charging rates up to 400kW. Some cars such as the Nissan Leaf have an on-board converter to allow the charge to be delivered via a domestic electricity supply. There is no uniform, agreed charge infrastructure and charge points can operate at various rates and under various corporate or public controls, with a bewildering array of prices. This results in wasteful duplication and exclusionary strategies, and confusion for consumers when compared with the ICE system. The lack of standardisation also has an impact on manufacturing cost.

As of 2021 the dominant choice has been some form of Lithium Ion battery pack for pure BEVs, but even here there is a lack of consistency from one model generation to the next, as is shown with the Nissan Leaf. The first-generation model came with a 24kWh capacity battery, later upgraded to 30 kWh. The second-generation model has a 40kWh battery, or an optional 62kWh. Considerable attention has been afforded to increasing the power density and reducing the cost of battery packs, both with changes in chemistries and with learning in manufacturing operations. One consequence is that manufacturing operations are also undergoing rapid developmental changes.

3. The EV supply chain: vertical integration and production strategies

A key constraint on BEV output to date has been with the supply chain, from key raw materials right through to complete battery packs and motors. For vehicle manufacturers then, an important decision is how far to initiate vertical integration or other strategies to secure supplies. Shortages of supply were evident for several vehicle manufacturers ahead of the COVID-19 pandemic at the end of 2019, when planned production expansion could not be met. Production shortages relate to two aspects: the core materials; and the cells and modules needed for fully-assembled battery packs. However, there is also a concern for vehicle manufacturers of the narrowness of the supply chain, and hence a desire to avoid dependence upon a single supplier.

Up to the start of 2020 the available installed capacity to produce battery packs was most concentrated in China, following strong policy support for BEVs and an initial advantage with lithium supplies and production of Li-Ion batteries for diverse uses. With impending EU regulations on CO₂ emissions coming into force over 2020-21 the automotive industry and suppliers have sought to expand capacity with a surge of investment (T&E, 2019). Vehicle manufacturers that had already suffered supply shortages of battery packs and key materials in 2019 and early 2020 included Jaguar Land Rover (iPACE), Audi (e-tron), Kia (Niro), and Hyundai (Ioniq), while battery suppliers themselves suffered shortages of cobalt, zinc and copper (Evarts, 2019). These shortages may have contributed to maintaining the price of battery packs above the 'target' figure of US\$100 per kWh capacity, and to constraining the market share of BEVs. The surge of 'gigafactory' investment in Europe from 2020 onwards to produce battery packs for BEVs has already led to concerns that there may be over-capacity by 2030 unless market demand expands in line. In the EU this has resulted in calls to follow the UK proposals to phase out pure ICEs by 2030, and even hybrids by 2035.

A range of supply chain strategies is possible from outright vertical integration to 'battery as a service' models. It is notable that the Tesla factory in the US is in partnership with Panasonic, illustrating that the equity involvement of a vehicle manufacturer with supplier is usually the option chosen, though Tesla in 2020 was reportedly interested in manufacturing battery cells itself. A preferred emergent approach is multi-sourcing from 3 or 4 partners in which the vehicle manufacturer has a small investment in a bid to guarantee future supplies. The example of Mercedes is illustrative. According to Hempel (2020), Mercedes purchases cells but undertakes assembly of modules and packs. The company has purchased cells from SK Innovation and LG Chem (both from South Korea), as well as CATL (China), and in 2020 extended the supply base to include Farasis Energy (China) in which Mercedes took a small shareholding. The preferred system is then to co-locate battery assembly with vehicle assembly. A further illustration of close manufacturer-supplier ties is that CATL is expected to build a battery factory at Erfurt, Germany to supply Mercedes – potentially with fully-assembled battery packs using their proprietary 'Cell-To-Pack' technology that obviates the need for the intermediary stage of building modules. The more that the entire production of cars becomes BEVs, the more likely it is that vehicle manufacturers will prefer vertical integration to assure supplies.

In response to the growing demand, the need for physical proximity, and manufacturers' preference for multiple suppliers there has been a surge of new entrants into the battery pack supply chain (Berman, 2020; Randal, 2020b). They typically comprise joint ventures by two or more interested parties and include Northvolt (Sweden and elsewhere), BritishVolt (UK), and Verkor and Saft (France). An important consideration in locational strategies is the need to reduce CO₂ emissions from the energy-intensive production process. A feature of the Tesla Gigafactory 1 in Nevada is the large solar panel farm alongside the factory, thereby making a contribution to reducing the carbon emissions cost of production.

Battery assembly capacity is usually measured in terms of the annual GWh of cell storage a facility can produce. T&E (2019) estimate that by 2023 there will be at least 16 large-scale battery factories, with a combined capacity of 131GWh in the EU. By 2030 there could be more than 1,000GWh of capacity in the EU (including the UK). The translation of this output into a given number of cars

depends upon the specifications of the cars and batteries concerned. As a guide, Randal (2020a) states that the Tesla Gigafactory 1 in Nevada can produce 13 million cells per day @ 17Wh per cell. This means the factory produces battery cells with a total capacity of 221MWh per day or 80GWh per annum. Daily output is approximately equivalent to 3,000 Model 3 battery packs (at say 60 kWh capacity or 3,000 cells per car).

Hence a plant producing 80GWh per annum can support the assembly of 3,000 cars per day at typical prevailing averages for battery installations, if the estimations for Tesla are correct. Details on the investment cost are unclear but estimates usually are for US\$4.5 to US\$5.0 billion for the case of Gigafactory 1. Tesla originally claimed that 5,000 jobs would be created. In summary, the investment and manpower costs of cell and battery pack manufacture are an order of magnitude higher than is usually the case for an ICE plant, albeit with higher levels of vertical integration. Competition by national and regional governments to attract battery manufacturing sites is evident in the US, the EU and elsewhere. There is probably scope for much higher levels of automation.

In 2019 European Commission recently approved US\$3.5 billion in funding to support the European Battery Alliance across multiple Member States, companies, universities and other key actors in projects ranging from raw material extraction to end-of-life battery pack recycling (Scott, 2020). In Germany, by mid-2020 the government had committed to spend over US\$3bn on bringing battery production to the market, alongside major investments by VW Group, Mercedes, and BMW into new electric vehicle models.

According to the World Economic Forum (2019), global annual revenues from battery production could reach US\$300bn by 2030, with a requirement for over US\$440bn in cumulative investment to reach an estimated 2,600GWh capacity by that date. Over 60% of output is expected to go to the automotive industry.

With the emergence of BEV powertrain, attention has focussed on the supply of cobalt, which is used on the cathodes of the battery pack, and is both limited in absolute supply and geopolitically constrained. Chinese companies control about 66% of global refined cobalt production (Sanderson, 2019). Estimates of automotive demand vary, but one source (www.bgr.bund.de) suggests total demand growth (all applications) from 120,000t (2017) to 225,000t (2026) largely driven by BEVs. Here the concern is with artisanal mining in the Democratic Republic of the Congo (DRC) where uncertain environmental practices and the employment of children has prompted a search for mechanisms to assure the provenance of supplies. The DRC supplies about 60-70% of global cobalt, of which some 30% is thought to be from unregulated artisanal mines (Sanderson, 2019). Output from the artisanal mines is sold to intermediary traders, mostly Chinese, who then sell on to the major producers and exporters. There are resultant concerns over the presence of third parties, the use of child labour, the environmental burdens of mining, and the lack of traceability. However, future growth in BEV output cannot be met using existing Li Ion chemistries without recourse to supplies from the DRC. Vehicle manufacturers are keen to avoid reputational risk to their brands, as has already occurred to producers of mobile telephones. In consequence, there is ongoing research

into the use of technologies such as blockchain to provide supply chain traceability (Hastig and Sodhi, 2020).

In the EU, investment is dominated by the German chemicals company BASF which has invested in cathode materials precursor plant in Harjavalta, Finland, and a cathode materials plant in Schwarzheide, Germany (due to come on stream in 2022 with capacity for about 400,000 BEVs per annum). A notable feature of the BASF investment in Finland is the relationship with the Russian metal specialist Nornickel, as this facility will also be the location for recycling battery packs.

While most attention for BEVs has been on cobalt, copper and zinc, there are also concerns over the rare earth metals used in electromagnetic motors and regenerative braking systems (Fishman et al., 2018). Supplies of metals such as neodymium, praseodymium and dysprosium could constitute real constraints on the expansion of BEV production (Nansai et al., 2015; Pavel et al., 2017) although research into alternatives in some applications is promising.

4. EV manufacturing: battery packs

The focus of R&D efforts to date has been on reducing the cost of manufacturing, by a combination of changes to chemistry (low cobalt cathodes in the so-called MNC 811 ration) and to process innovations. In comparison, thinking about themes beyond ‘design for manufacturing’ to embrace design for recycling has attracted rather less attention. The battery pack is of prime importance when it comes to BEV manufacturing due to its share of the total BEV cost and physical structure. For example, in a Tesla Model X, the battery pack alone accounts for nearly 65% of the vehicle’s weight. In similar vein, the battery pack and related items account for well over half the cost of the vehicle. On a like-for-like basis, BEVs up to 2020 were in the region of 50% to 90% more expensive in retail list price terms than ICE equivalents. BEVs typically comprise over 30% by weight of non-ferrous metals, compared with under 10% for traditional ICE vehicles (Klemola, 2016).

Table 1 below gives a comparison of the proportion of total costs in manufacturing between a typical ICE and a BEV.

Category	ICE	BEV
Battery pack	0	43
Vehicle structure	10	7
Vehicle body	17	13
Transmission / engine	23	14
Other equipment	33	19
Other items	17	10

(Source: Author estimates)

In the EU regulatory provisions under the Ecodesign Directive (2009/125/EC) and Extended Producer Responsibility (under the Batteries Directive (2006/66/EC)) regulations establish a framework for setting mandatory ecodesign requirements for energy-related products sold on the EU market and apply to battery pack design.

Issues of durability, repairability and recyclability standards are of some contention as they apply to battery pack design. Benefits in terms of battery pack manufacturing (such as modular designs) may conflict with dismantling or concepts like the right to repair. Beyond this, a likely future concern is the diversity of design solutions compared with the simple 'standard' battery designs for AA, AAA, and other small batteries that make replacement easy and low cost for consumers. Tesla has reportedly under development a low-cost battery able to last for a million miles (Shirouzu and Lienert, 2020), but it is not clear whether this battery will also enable easier repair and recycling.

Battery pack manufacturing usually has three main steps: production of the individual cells, production of the modules by joining of cells, and production of the pack by joining of the modules, along with items such as the cooling system. Cells may be prismatic containers, prismatic pouches, or cylindrical and are typically produced by independent suppliers. Vehicle manufacturers typically like to have control over the final assembly of the battery pack. However, the situation is very fluid due to the immature character of the battery supply chain.

Mass manufacture of battery packs is still under-developed, in part because of the design changes noted above. Typical process steps are outlined below, but in almost all there is scope for further innovation to reduce costs and improve quality. For example, CATL is reportedly working on a system that eliminates the need to pack cells into modules prior to assembly of the battery pack, and to increase levels of automation, thereby reducing cost and complexity. This so-called 'cell to pack' approach utilises very large prismatic cells, resulting in many fewer connections and circuits, and higher levels of automation. As an indicator of the rate of development, T&E (2019) use an estimate of 86kgCO₂e/kWh (of installed capacity in the car) carbon emissions in production when calculating the future energy demand from BEVs but also note that by 2030 the rate could be as low as 40 kgCO₂e/kWh.

According to Heimes et al. (2019) there are multiple process steps in battery pack manufacture, depending upon details such as cell design and chemistry, and most steps have potential development routes to reduce costs, increase production speed, and enhance quality. While the BEV powertrain has few moving parts, production and assembly of the battery pack requires multiple precision process steps. A key overall aim is to change batch processes into flow processes, and thereafter to match the flow capacity of each stage to remove bottlenecks or idle capacity.

Following Heimes et al. (2019) cell manufacturing has three process steps: electrode manufacturing, cell assembly, and cell finishing. Each cell comprises two electrodes (anode and cathode), kept apart by a separator, and a liquid electrolyte that allows ions to move across the cell. Electrode assembly is a specialist area, and with the cathodes one of the most significant in terms of costs. Changes to the

ratio of nickel, manganese, and cobalt (NMC) can reduce costs, but at the risk of reduced thermal control and other performance aspects such as energy density. Hence, cathodes started at NMC1,1,1 and are increasingly NMC 6,2,2 or NMC8,1,1.

There are several stages in electrode manufacturing: Mixing the electrode ingredients into a slurry; coating of the copper (for the anode) or aluminium (for the cathode) foil rolls; drying the rolls (an energy-intensive process); calendaring or pressure rolling of the coils to a uniform thickness; slitting of the wide electrode roll into narrower strips that are re-wound into new coils; and finally vacuum drying of the coils (between 12 and 30 hours). The coils can then be sent to the cell assembly process, followed by cell finishing.

Cell assembly for pouch cells requires an initial stage of separation of the individual cathode and anode sheets from the coils, and the insertion of separation sheets. Electrodes are then stacked using a diversity of techniques and the stacked cells are welded at tabs along the edge prior to insertion into a deep-drawn foil pouch, which can subsequently be sealed. Assembly of the pouch cell is finished by filling with electrolyte under a vacuum. This stage is usually repeated several times to ensure the pouch is properly filled before it is sealed.

The process is different for cylinder or prismatic cells. In these cases, the first cell assembly stage is winding of the electrode foil around a mandrel (prismatic cells) or central core (cylinder cells). Winding is followed by packaging of the cell contents into a container or housing, which is then welded shut. Electrolyte is inserted via a valve (prismatic cells) or dosing needle (cylinder cells) before final sealing.

Cell finishing involves an initial stage where the battery cell is charged and discharged under a specified cycle and precise voltage and current curves. This process crystal structure of the graphite on the anode side. Thereafter, cells are moved onto the de-gassing stage. In the case of pouch cells, the charging process generates gas into a 'gas bag' that must be removed, and the pouch sealed again. The final process is aging and testing, a form of quality assurance process during which under high temperatures and normal temperatures the cells are monitored to establish that performance is within expected parameters. Cells must be discharged to a specified level for transport.

Battery pack assembly is a function of the chosen system of cells, modules and series or parallel connectivity. For example (following Zwicker et al., 2020), the Tesla S roadster has 11 modules connected in series, with each module comprised of 9 sheets also connected in series, and each sheet comprised of cylindrical cells connected in parallel and providing 2.16Ah individual cell capacity. The Tesla Model S then has 7,104 cylindrical cells, 404 cells per module, and 16 modules in the finished battery pack. The battery pack has to withstand mechanical, thermal, electrical, and metallurgical stresses when in use in a vehicle, so the production process has to be designed to produce a pack accordingly. A key aspect of pack assembly therefore becomes one of joining (welding) the connections (termed bus-bars) required inside the pack.

At the battery pack level, a key target is an energy density of 140Wh/kg as this is a threshold for government subsidy in China (Rudisuela, 2020). Alternative chemistries such as Lithium Iron Phosphate (LFP) offer much reduced costs, but also much reduced performance (or a requirement for a much larger battery pack).

Innovations in the manufacturing process for electrodes or cells can further result in cost savings. As noted above the large LFP prismatic cells developed by CATL and, independently, by BYD (both in China) should yield cost savings. The approach is also being applied in NMC battery packs, for example by GM in partnership with LG Chem using large-format pouch cells, in a bid to retain a high level of performance while reducing costs. Such cells do, however, reduce design flexibility in terms of vehicle packaging.

5. BEV production, distribution, and retail strategies

There is a close relationship between the production strategies for cars, and the associated distribution and retailing strategies. BEVs may offer opportunities for innovative approaches to the market, provided the production strategies are appropriate.

In the raft of new models coming through in the early 2020s for the EU it is notable that the market is dominated by cross-over SUVs in the medium size ranges. SUVs have emerged as a segment between the traditional 4x4 or off-road vehicles and medium-sized family cars (saloons, hatchback and estate body styles) that formed the bulk of the market until recently. These so-called 'crossover' vehicles lack true off-road capability but have the styling cues, and physical attributes of traditional SUVs. The attraction of electrifying the powertrain of the crossover vehicles is due to the popularity of the segment in recent years, but also arises because these larger vehicles can accommodate larger battery packs and command higher prices in the market to allow cost recovery (Markard et al., 2020). Again, the nascent character of the battery supply chain and the use of BEVs means vehicle manufacturers do not all share the same approach to vehicle design and thence to marketing, distribution, and retail strategies.

Building battery packs into large, heavy cars is an inefficient and wasteful solution for mobility. The Tesla S, for example, is about 2,200kg and more than 50% of that mass is attributable to the powertrain. These vehicles are also expensive. The 2020 Audi e-tron has a UK retail price of over £70,000 for example. New BEV models coming to the market have tended to be medium or large SUV style vehicles.

There are consequences of the popularity of crossover vehicles and smaller SUVs as the most likely target for electrification in the segment (Taylor, 2020). Compared with smaller saloon and hatchback cars, these vehicles require more resources in manufacturing (especially larger battery packs) and result in higher carbon emissions in use. For example, the Nissan Leaf (midsize car) uses 21 kWh/100km which, in an EU electricity generation mix, approximates to 65 gCO₂eq/km. It is notable

that the IEA energy forecasting model uses a weighted average of 20.0 kWh/100km (Moro and Lonza, 2018). The Audi e-tron (SUV) is stated to require a combined cycle energy consumption of 26.6 kWh/100km, approximating to 120 gCO₂eq/km on an EU average energy mix. The BMW i3, with a weight-saving but expensive carbon fibre body structure, achieves 14.0 kWh/100km.

Early pioneers such as TH!NK explored the potential of combining radical product innovations with new marketing strategies and business models (Wells and Nieuwenhuis, 1999). The TH!NK City Bee had a purpose-designed body with steel floorpan and plastic body panels to create a two-seat car. Battery packs were sourced externally (from Saft). The production line was very compact (circa 100m) and factory capacity was low (5,000 units per annum). The intention was to 'clone' factories to new locations as the market expanded. Despite changes of ownership, and unlike Tesla, TH!NK lacked the depth of finance capital necessary to underwrite the cashflow costs of production expansion. In 2020 a new company emerged in the UK, called Arrival, that does have the financial support needed (via US investment funds) to pursue an aggressive 'microfactory' strategy to produce electric buses. In 2021, Arrival also announced plans to produce battery electric cars for UBER, initially to serve their fleet in London.

The application of battery packs to create BEVs has attracted a host of new entrants alongside Tesla. Experimentation in terms of design and manufacturing systems has been paralleled by experimentation in business models and routes to market. There have been plenty of casualties among the new entrants, including Dyson which announced a BEV project in 2016 but abandoned the plan in 2019 (Leggett, 2019).

The following models are all available on the market as of mid-2020, and give an indication of the diverse strategies under use during this phase of uncertain market expansion.

- **FIAT 500e.** This is an adaption of a conventional ICE design, and therefore more compromised than purpose-designed cars. Under previous CEO Marchionne, FIAT was opposed to the introduction of BEVs. The 500e represented a relatively low-cost means of market entry in the product segment where FIAT was competitive.
- **Tesla Model S.** The car is built around the battery, with the emphasis on range and acceleration. The Model S has a conventional all-steel body and a traditional manufacturing strategy using Tesla batteries, being produced in a former Toyota factory in California. Tesla has a proprietary dedicated charge infrastructure and uses direct sales (bypassing franchised dealerships). Software updates can be provided through the mobile telecommunications network.
- **Nissan Leaf.** This is a purpose-designed car that is largely conventional apart from the powertrain, built in high volume (e.g. in Sunderland, UK) with dedicated battery factory alongside. The emphasis on cost results in limited range.
- **BMW i3.** This is a purpose-designed car of unusual proportions and features that employs a carbon fibre reinforced plastic body (cfrp). The logic of this expensive solution is that a lightweight vehicle will require a significantly smaller battery pack and, at prevailing pack costs, might be lower total cost as a result. However, this solution also required a pioneering

step into high volume cfrp body manufacturing in which BMW made direct investments in the supply chain to secure supplies, adopt low-carbon energy sources, and control material quality.

- **Renault Zoe.** The first-generation Zoe was unusual in that it was designed for a battery swap concept (as originally intended by Better Place). While the strategy never materialised, it did mean that the battery pack was readily replaceable, unlike many other designs, and this enabled Renault to pursue battery leasing offers to consumers. Hence the buyer of a Zoe could separately lease the battery pack, thereby reducing initial purchase costs.
- **NIO ES6 and ES8.** NIO is a Chinese start-up BEV manufacturing which, with these models, has vertically integrated the battery swap concept for which the cars are designed (see below).
- **VW ID.** With the ID concept VW has a purpose-design architecture (termed MEB) able to be adapted to several brands and model designs, somewhat similar to the GM 'skateboard' concept promoted by designer Chris Borrioni Bird (Borrioni-Bird et al., 2010). An interesting feature of this design is that VW is offering the concept to other manufacturers in a form of 'Intel inside' strategy. The US company concerned (O'Kane, 2020) was reportedly in negotiation with VW to follow this idea, marking almost a return to the 'coachbuilding' era of vehicle assembly in the early 1900s. VW also has a major strategic partnership with Ford that will allow shared BEV platforms. In parallel, VW in Germany is experimenting with an agency model of sales and distribution rather than the usual franchised dealership. One reason may be that in the agency model, VW retains ownership of the car via its own finance provision, and this in turn may help ensure battery packs return to VW at the end of life stage.

6. Lifecycle management and end of life battery packs

In contrast to traditional ICE vehicles, concerns over production and supply chain management do not end with the assembly of the finished vehicle, but extend deep into the in-use and end-of-life phases. Battery packs have the potential to become a source of long-term revenue (if the manufacturer retains ownership) or of repeated sales, and ultimately as a source of materials to build future battery packs. With future possibilities around remanufacturing of discrete modules or cells, and retained ownership, then 'production' ceases to be a one-off event in the life cycle and becomes a series of interventions to support pack longevity.

BEVs are thus seen as a means to capture new in-use revenue streams, with two areas of potential importance: Vehicle-to-grid (V2G) and second life. With V2G owners can in theory sell the electricity provided by their car to a local or national grid. There are several ways to achieve V2G, but the essence of the benefit is that the owner can earn extra revenue by selling to the grid at times of peak demand, and charge the vehicle at times of low demand. In addition, V2G can allow excess domestic solar electricity to be supplied to the grid, and allow grid operators and electricity production companies the opportunity to reduce demand peaks and the resultant capacity peaks. V2G offers an opportunity for vehicle manufacturers to extend their reach into domestic and commercial electricity management, thereby generating new revenue streams and valuable customer data (see e.g. Tesla Powerwall; Mercedes; Renault).

A somewhat neglected feature since the demise of Better Place is the concept of battery swap stations (Christensen et al., 2012). The current leading exponent is NIO, as noted above. According to Kane (2020) the first NIO swap station was opened in May 2018. By May 2020, the company had 131 stations and had completed 500,000 swaps on a fleet of 40,000 cars. All the cars can be charged conventionally, but the swap operation only takes 6 minutes. The strategy also means that NIO can retain ownership of the battery packs, and offer different capacity batteries, upgrade batteries, replace end-of-life batteries, and crucially can ensure that users are not stranded by technological change. In 2021 NIO announced their plans to expand in Europe, starting with Norway.

Manthey (2020) provides further details on this example. The 'battery as a service' model means that customers can purchase the car but still lease the battery. In turn, the purchase price is significantly lower and then customers pay a monthly fee for the battery. The same battery pack can be used in all three vehicles in the NIO range. This is an important step towards battery pack standardisation, something that the Chinese government has identified as a policy target that would enable greater customer choice of vehicles and lower costs.

Second life applications in theory arise because once the battery pack has ceased to be viable in an automotive application, it still has capacity for less demanding applications in energy storage. In the case of companies such as Tesla, battery packs are already in use in energy storage (e.g. in Victoria, Australia) in grid stabilisation. Back-up electricity supply can be useful for emergencies when the grid fails, for instances where demand is highly sporadic (e.g. football stadium in Amsterdam), and for remote applications dependent upon local renewable sources.

The rush into BEV production and use has rather neglected the end-of-life consequences of battery pack management (Skeete et al., 2020). Expired batteries represent a potential source of valuable materials but are also hazardous. In part arising from concerns over future security of supply, vehicle manufacturers or other suppliers in the forward BEV powertrain chain are therefore interested in recovery of end of life battery packs that will constitute an important future stock of materials (Fishman et al., 2018). Again, a diversity of strategies is evident from outright direct ownership of recycling facilities (e.g. VW), to established and emergent recycling specialists (e.g. Umicor).

7. Beyond the mainstream: Afreecar, non-cars, and related concepts

At average occupancy rates the resource consumption involved in existing battery electric vehicles is extravagant. The boom in e-bike sales (initially in China but now worldwide) is indicative of a far better application in that it is efficient, adaptable, and affordable. Similarly, there has been a rapid uptake of electric scooters, mostly through sharing schemes, in many urban areas. It is not readily apparent how far this sort of micro-mobility is additional to or displacing of traditional public transport or indeed cars, but there is likely to be some substitutional effect for both (Heineke et al., 2020).

The EU 'L category' of vehicles has also attracted the attention of manufacturers. These are four-wheel 'non-cars' characterised by low top speeds and limited range, and are derived from the long-established French category of 'voiture sans permis' that allowed drivers as young as 14 to use the vehicles. By comparison with the vehicles discussed above, the Renault Twizy (a two-seat L category vehicle) uses 5.8 kWh/100km. A clear example of design and production moving in this direction is the Citroen Ami, launched in 2020. This two-seat BEV is very compact (see <https://www.citroen.co.uk/about-citroen/concept-cars/citroen-ami-one-concept>) at 2.50m long, 1.50m wide and 1.50m high. It has a limited range of less than 90km, but can charge in 2 hours. The vehicle has a 6kW electric motor and 5.5kWh battery pack, and at launch was priced at €6,900. The symmetrical design approach means that multiple exterior components are inter-changeable, reducing manufacturing and maintenance costs.

As many cars are currently over-specified for their usual applications, there is surplus performance available. That is, contemporary cars can carry more people, have higher top speeds, and have greater acceleration than is used or needed. The resultant design redundancy has a price in resource consumption in manufacturing, and in energy consumption in use. Hence, the more that vehicle fleets of the future are of the Citroen Ami type, and the fewer are of the Audi e-tron type, the less need there will be for gigafactories, cobalt supplies, and so forth.

The combination of decentralised solar and other renewable electricity sources with BEVs opens up intriguing prospects for the future of manufacturing and use. BEV technology is adaptable to a very wide range of vehicle designs, and to many scales of output. As cell prices fall and as portable solar power becomes a distributed low-cost reality so the scope for reaching into isolated and rural communities also increases. A great example of the sort of development possible, outside of and radically different to the mainstream automotive industry is that of Afreecar (see <https://afreecar.org/>).

8. Conclusions

Thus far there is scant standardisation in battery pack design and production. Different solutions offer differing combinations of cost, complexity, and performance across multiple dimensions. Few BEVs have completed a full life cycle so far, and a 'natural' market winner has yet to emerge.

Ultimately, the production of the battery electric car may no longer be confined to the technologically complex, capital intensive and economically dominant enterprises that constitute the automotive industry of today. As batteries become a commodity, and as vehicle designs and configurations proliferate, and as the circular economy lifecycle comes to dominate over 'fire and forget' production, so the barriers to entry will disintegrate. The production of ICE vehicles has been through 120 years of refinement and economic exploitation. The production of battery electric vehicles has only just started on that adventure.

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