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# The Lithium Wars: From Kokkola to the Congo for the 500 Mile Battery

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**Abstract:** This paper presents an analysis and interpretation of the current state of play in the global value network of minerals mining, refining and transformation processes in the contemporary battery industry, which will power potentially crucial future industries for manufacture of electric vehicles (EVs) and solar-storage energy systems. The dark influence of the carbon lock-in landscape is gradually being mitigated under the challenge of achieving the "500 mile" battery charge, which would make a transformational difference in the replacement of renewably fuelled vehicles and storage systems, currently still predominantly driven by fossil fuels. The challenge has led to a "war" between manufacturers, miners and refiners, who have realised that the challenge has come alive while most have been vacillating. At an "individualist" rather than an "institutionalist" level, Elon Musk, for all his faults, deserves credit for "moving the market" in these two important industry sectors. This paper anatomises key events and processes stimulating change in this global economic activity through an "abductive" reasoning model and a qualitative "pattern recognition" methodology that proves valuable in achieving rational, probabilistic forecasts. Established incremental innovation characterises first responses in the "war" but research agencies like ARPA are active in funding research that may produce radical battery innovation in future.

**Keywords:** batteries; lithium; renewable energy; cobalt; gigafactories

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## 1. Introduction

It is noticeable, in the reports of corporate investment strategies, which include in some cases stories of strategic failures of corporate strategy, that a competitive battle has begun between the producers and consumers of the lithium ion batteries (LIBs) that fuel electric vehicles (EVs), solar tiles for roofing and solar-storage systems for households and small businesses. An implication of the potential broadening of demand for LIBs is indicated in the following, which pivots upon the experience of one of the few non-Asian LIB producers, Tesla. Putatively, household energy and stationary energy storage can be expected to emerge soon as convenient, installed domestic and smaller business services. These may be installed in combination with solar and/or thermal solutions. Since Tesla began delivering its early 7 kWh lithium ion domestic batteries in 2015 to US customers for USD 3000, the market soon became drained of available product by 2016. The expectation at that time was that a German competitor would likely ramp up to fill the gaps in the market. Panasonic, Samsung SDI and LG Chem lithium ion batteries were further expected to be affordable by 2020 [1].

The implications of this study are of primary importance for sustainable mobility consumers, i.e., the global population who will use renewable energy for mobility. Directly, it improves responses to market demand by manufacturers of electric and other renewable fuels, automotive assemblers and suppliers of batteries. In what follows, this study analyses the state of play in LIB technology and its likely successors; the production system, its main users and providers of the means of fuelling demand for batteries or other competitor fuel-cell technologies; and the substances over which the rivalrous competitions centred upon LIB and post-LIB technologies take place. Next, there follows an account of the manner in which users have, in some cases, bounced back from the results of large corporate strategy mistakes and benefitted from luck or 'prepared mind' opportunities [2] mining opportunities when faced with technical change. Finally, this study is interesting in analysing some theoretical issues of a geopolitical nature. These are occasioned by the "related variety" [3–11] expressed by the recombination of innovation elements and their economic geography. This is done by displaying the special interest influence of agglomeration effects, mining, metal processing and resource agglomeration and disagglomeration effects. This is our "twin-carb" model. The article finishes with a discussion and conclusions section tying together the preceding narrative.

## 2. The Nature and Substance(s) of the Contemporary "Lithium Wars"

The nature and substance involve struggles or "wars" between producers of raw materials and—currently—some manufacturers of batteries. These include some who were late and/or tried to guess future technologies too early (e.g., Toyota), suffering losses in battles against carbon, on the one hand, and LIB batteries, on the other hand, as the leading propulsive ingredients for the present. The contest for supremacy in the global market for battery-driven energy systems is stimulated by a simple fact of physical science. This is that electrical energy is difficult to store, especially in portable form. In 2018 the US Department of Energy reported future storage possibilities with USD 30 million in funding to support batteries capable of 10 h bulk storage solutions. Later this was anticipated to be followed up with research aimed at increasing bulk storage capacity up to 100 h. This programme of research was funded by the Energy Department's Advanced Projects Research Agency—Energy (ARPA-E) [3] office, whose sister agency funded the Internet. From the ARPA-E viewpoint, LIBs work efficiently and effectively for cheaper, lower range storage, but costs increase markedly beyond the 10 h range. This refers directly to the current capabilities of integrated wind and solar supply because that is the issue for "pattern recognition" of the perceived problem: how to facilitate mixing of batteries with lower cost but intermittent wind and solar energy. Thus, the energy policy community recognises that the resilient grid of the future, currently beyond the horizon, will depend on efficient and effective energy storage. Storage systems must provide grid stability where renewables are intermittent. They do this by providing backup power which can fail when calibration of intermittent energy flows predominates, as occurred with negative implications for firms, hospitals and other intensive industrial and domestic users with the UK regional grid outage in the summer of 2019, which shut down when confronted with having to balance integration of intermittent renewable resources.

So, not only is demand for LIB batteries and their successors increasing many times over because of deep structural shifts in the power mix of economy grids—it is also intensifying due to demand for bigger battery packs for already in-use applications from established technology developers; [12,13]). Thus, in the field of EVs, leading innovator Tesla is developing a battery pack to enable its EVs to cover 400 miles before a re-charge is required, according to the automotive company's most recent system updates. These have also hinted at Tesla's LIBs jointly produced with Panasonic, according to CEO announcements promising the 400 mile battery before long. This is likely to be dedicated to the upmarket Model S rather than the popular and cheaper Model 3, which is not sufficiently powerful to accommodate a LIB system of the necessary size. Meanwhile the Model X (SUV) is considered too large and heavy to deliver a charge sufficient to reach 400 miles. Tesla also competes against other auto-manufacturers by emphasising longer distances between charges while the others focus upon affordability. Experts in LIB market analysis are of the view that the current LIB chemistry is approaching its charging limits and that future gains are et best likely to be incremental until the end of this decade rather than breakthroughs. Thus the 500 mile EV is thought to be unlikely to be achieved until at least 2010 and, for the affordable mass-market EVs, until beyond 2030

As noted above, by 2020 battery systems for stationary storage were anticipated to be likely to have grown in demand as a key instrument used for load-balancing between customers and users. This was precisely the problem experienced in 2019 by the UK grid. Cairn Energy Research Advisors [14] expected market growth from a total of USD 6.7 billion in 2015 to USD 13.2 billion by 2020. This would be a historic change in the 150 year history of electricity power generation and grid management which had never previously factored in battery storage. Essentially, everything about the electricity industry was seen as in a process of change. Traditionally, generation fluctuated but within understood load variations. However, generation with renewables means generation became unpredictable while consumption became more responsive to price, related to user time or demand response requirements. Accordingly, buffering of flexible demand by using batteries has come to the fore (Figure 1).

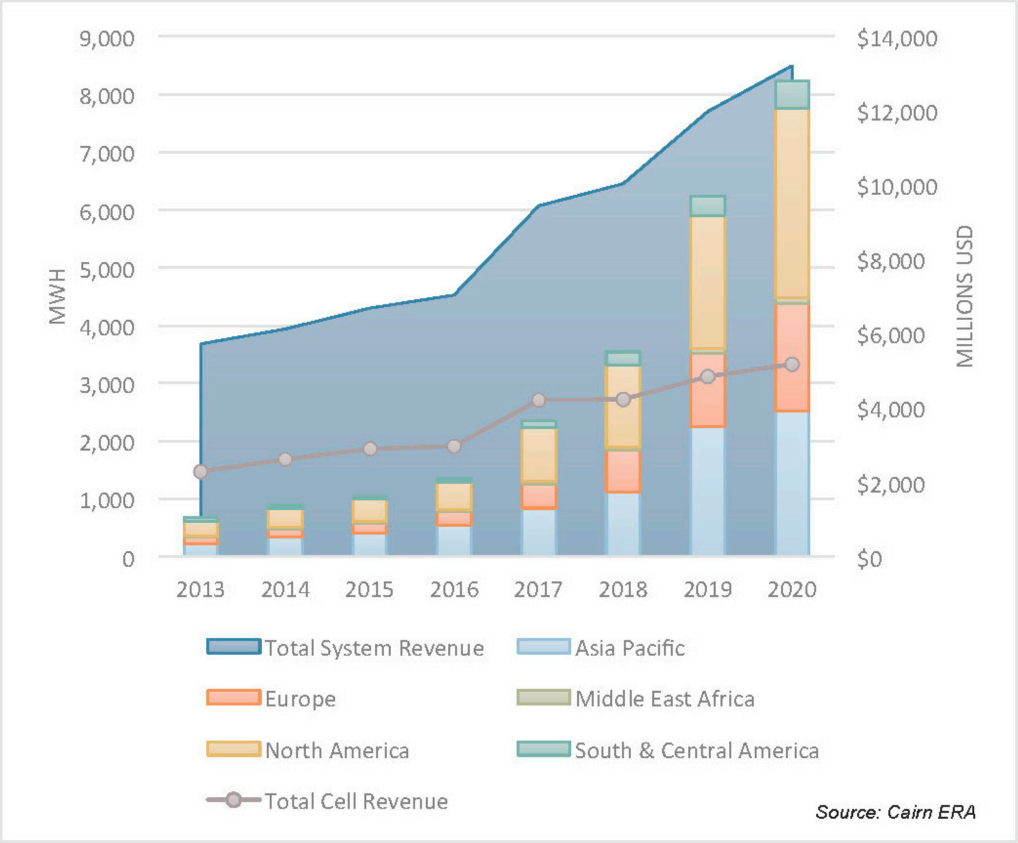

**Figure 1.** Global stationary storage battery energy capacity by region in MWH and cell and system revenue in millions of USD. Forecast: 2013–2020. Source: Cairn ERA.

### *Counter-Moves by Chinese and South-East Asian Rivals*

Accordingly, Contemporary Amperex Technology Co. Limited, acronym CATL, was founded in 2011 as a Chinese battery manufacturer and technology company specialising in the manufacturing of lithium-ion batteries for EVs, energy storage systems and battery management systems (BMSs). A complex (both non-linear and linear) sequence evolved like this:

1. In January 2017, CATL proposed to fashion a strategic alliance with Finland's Valmet Automotive based at Uusikaupunki. Valmet had assembled the Fisker EV and conventional sports cars (Boxter) for Porsche. The object here involved project management, engineering and battery pack supply for EVs and hybrid EVs.

2. CATL bought a 22% stake in Valmet. In 2019 Valmet Energy agreed to supply Umicore's Kokkola nearby cobalt refinery with a clean energy plant design. Belgian miner Umicore had bought Kokkola from US firm Freeport-McMoRan.

3. The Kokkola plant refines 10% of the world's lithium for LIBs, the rest being refined in China. In 2017 CATL accepted an offer from Swiss mining giant Glencore to supply "sustainable" Congo cobalt ore to the Umicore refinery in Ostrobothnia, Finland's "lithium province".

4. Pressure from German automotive firms, especially VW, caused CATL to build LIB facilities in Arnstadt, Thuringia (former East Germany). At the same time BMW reported a USD 4.7 billion arrangement for CATL to supply small-car LIBs [15–20].

5. CATL announced their annual 11.84 GWh of energy storage capacity in 2017. This meant CATL became the world's third largest provider of EV, hybrid EV (HEV) and plug-in hybrid EV (PHEV) batteries. The larger ones are Japan's Panasonic and China's BYD (see next para).

6. CATL aimed for 50 GWh global energy storage by 2020 and in 2019 CATL already reported that Tesla had arranged with them to supply cells for Gigafactory 3 in Shanghai and for expected future expansion elsewhere.

7. In 2019, Tesla also reported a battery supply deal with LG Chem (South Korea) for its Model 3 produced at Gigafactory 3 in Shanghai. This made it likely that LG Chem would ultimately split the Chinese order capacity for Tesla with CATL. CATL would supply Tesla Model 3 while LG Chem would supply Tesla Model Y (SUV) production

8. CATL is primarily using LiFePo (large-scale grid storage and buses) and nickel manganese cobalt (NMC) chemistries in prismatic cell formats. The implication of the Tesla order requires that suppliers branch into cylindrical cells, which Tesla has long pioneered for high-efficiency EV battery packs, unlike its competitors [20].

Moving on, we now turn to China's leading LIB producer Build Your Dreams (BYD). This firm was established in 1999 and, following ten years of R&D, has developed its own iron-phosphate-based lithium-ion (LiFePo) battery. All the main types of EV can be powered with LiFePo, which has a lifetime of over 10 years and a charge time of ten minutes to reach 50% battery capacity. BYD began by supplying mobile phone batteries to Nokia and Motorola, then, in 2003, the firm acquired Xi'an-based Qinchuan Motors, enabling BYD to expand from part and battery supplier to car marker. Ambitiously, BYD then acquired Ningbo-based SinoMOS Semiconductor in 2008 to consolidate its internal supply chain and speed-up its production of EVs [21–47]. Strategically the firm envisages production of nine million BYD EVs by 2025, overtaking the EV output of the rest of the world. However, BYD also plans to expand LIB production to control its own and other clients' market access [13]. By late 2019 BYD reported its plan for a new USD 1.5 billion 20 to 24 GWh battery gigafactory in Chongquin, Sechuan, to supply its own and other clients' EVs. This is to be BYD's second new battery gigafactory since the one in Qinghai, China's main raw lithium mines region (83%), opened in mid-2018. BYD focuses mostly on the production of prismatic LiFeP04 battery cells, which haver a longer life than most automotive industry nickel cobalt aluminium (NCA) and nickel manganese cobalt battery cells. BYD's total overall battery production capacity is intended to reach 100 GWh by 2030 as it ramps up its in-house EV production [13].

Regarding other Asian LIB competitors, on 5 December 2019, General Motors (GM) first reported partnership with South Korea's LG Chem to mass-produce LIBs for EVs. LG Chem makes LIBs for German firms VW (Audi) and Daimler (Mercedes-Benz). They intended to invest a total of USD 2.3 billion to build a new facility, to be located in Lordstown, Ohio as GM's "captive" gigafactory with more than 30 GWh capacity. New Chevrolet and EV trucks were mooted for 2021 but after a major trade union dispute over excluding former employees from the new EV plant, GM sold the factory to EV start-up Lordstown Motors (with Ohio state aids). GM's withdrawal was panicky due to Tesla's EV dominance and rising Asian and possible German competition [22–27] while LG promised to spend US 916 million in the replacement venture by 2023. In 2019 LG Chem also proposed to invest USD 424 million from 2020 in a new factory at Gumi, South Korea, for LIB cathode production to supply GM and VW by 2022. This new factory was anticipated to employ some 1000 domestic workers in South Korea. This would augment their two other cathode production factories, together with another one in China. In 2019, LG Chem, like Tesla (also dusting off its corporate child labour and corruption rules), agreed to purchase "controversial" Congo cobalt from Glencore, something Tesla was also planning due to global shortages [24,28–36]. In response to these moves, Toyota Motor Corporation and Panasonic set up a joint venture from 2020 to produce EV batteries. This reverses Toyota's hitherto expressed reluctance to own a LIB gigafactory because its strategic plans showed slow progress for the growth of mass-market LIB-driven EVs compared to hydrogen-driven ones. However, Tesla's and the other Asian LIB investments caused a rapid strategic reversal by Toyota. Now Japan and China will be made part of a new partnership to ramp-up LIB production 50-fold, aimed at increasing their EV market presence.

## 3. Illustrative Note on Methodology and the Pattern Recognition Question

The presentation of these narratives and empirical material is illustrative of the "pattern recognition" [11] approach developed in this kind of prefigurative study. This involves interrogation of claims made in qualitative and quantitative data. This involves drawing up a balanced schema of lines of inquiry to ascertain the deeper structures underlying "truth claims". Examples include "dark triad" psychological research, where underlying traits hidden by dissimulation may be exposed and explored. Thus, what may seem like "light" behavioural claims may be found to express "dark" behavioural drivers. A further example would be "green" claims not matched by actual practice ("greenwashing"). In qualitative research, the researcher is guided by structured propositions. For example, in psychological research, which is referenced in the paper, one approach to identifying "pathological" practice by entrepreneurs (and others) has three sub-frameworks: narcissism, Machiavellianism and psychopathy; "callousness" recently formed not a triad but a "dark tetrad" [1,37–39]. Each can be found from secondary research accounts, interviews and statements. A second framework counters these with fellowship, humanism and respectfulness. Bad employers or other actors can be interpreted from researching relevant documentation—denoting "dark entrepreneurship" and troublesome business outcomes. However, "light triad" aspects may also be found, which compensate for and moderate troublesome outcomes. This is called the "Socratic" method, which Kant also recognised in his reference to a "cosmopolitanism" that recognises humanity's imperfections as "crooked timber" with which humans necessarily work. Keeping the dark side in balance with interrogation also of the light side is an extremely powerful technique for critically locating respondents on the dark–light spectrum. This means gathering documentation, interviews and technical analyses to interpret "mentalities", attitudes and plans from reported speech. This is augmented by "snowballing" incrementally to "track and trace" lines of inquiry for hermeneutic analysis, inquiry and evidence of counter-factuals. It also involves contrasting the accuracy of "predictions", as is done on page 6. Elsewhere, we note Tesla's Machiavellianism regarding acquisition of Grohmann Automation, which leans more to the "dark" than "light" side (page 7). This means accessing early publication of "fugitive documentary material", early copies of consultants' reports, online reports by technically informed writers, company websites and academic research papers (though the last named now have often enormous gestation periods; this means their analyses can be well out-of-date by the time they are published, whereas triangulated instant reporting can be far more swiftly assessed). "Snowballing" means pursuing research leads, informed by "triad" "tetrad" or other types of interrogation schedule, until "saturation" of sources is reached (i.e., which can be a single "black swan" or recurring confirmations of the opposite). Qualitative research of such a type has thus become fashionable in the face of disappointments with the limitations of social science research based exclusively on quantitative analysis and modelling. Recent anxieties concerning this failing approach have been mounted by a new breed of "superforecasters" [44]. These involve focus group interaction utilising mixed research methods to assess probabilities of outcomes as part of interpreting deep structures of complex processes facilitated by "pattern recognition". In an exacting review, the authors single out Thomas Friedman of The New York Times for being an "exasperatingly evasive" forecaster, and point to the inaccuracy of most economists and other financial pundits. Accordingly, this approach, in turn, involves interrogating extrapolated claims based on next-to-zero future knowledge rather than appearing to claim prescience. Accordingly, quantitative forecasting has been considerably subject to claims of "bias", overdependence on "correlation" not explanation and failure to interrogate humans "anthropologically". So, echoing the tone of this contribution's graphic representations thus far, we propose to check the accuracy of the predictions in Figure 1 regarding expected growth in demand in MHW and USD, to the extent it is ascertainable, for 2020, or the nearest relevant date, from 2013. According to a report on the subject of global cumulative energy storage [12], the global sum for 2018–2020 was a "modest" 9 GW, rising to less than twice that (17 GW; also predicted) by 2020. This compares poorly with the CARE [14] forecast of 3.5 GWH that was the prediction for 2018, with 8.3 GWH being forecast for 2020. BloombergNEF's [12] near and present metrics are factually inaccurate over-statements whilst CARE's [14] forecasts are over-conservative under-statements. BloombergNEF's report [12] predicted 1095 GW by 2040, inviting a USD 662 billion investment from the market and still being quoted definitively by OilPrice.com the following year [42]. So, we need a tie-breaker, which is the IDTechEx report [25] which forecast 6.2 GWH deployed globally in 2018. However, as we referred to the BloombergNEF report as being guilty of "over-statement" forecasting (and CARE of understatement), our tie-breaker's 2018 estimate of 6.2 GWh in that year (GW for simplicity; in fact, Elon Musk's challenge to the South Australian government in 2017 was "100 MW (120 MWh) in 100 days") is comparable with BloombergNEF's forecast over 2019–2029 of an only 1.5 average annual GW increase, reaching 30 GW over the period. If so, IDTechEx is a greater over-estimator than BloombergNEF and CARE is still the under-estimator. Accordingly, BloombergNEF's assessment is taken here as the better forecasting guide. Even accounting for Musk's GW–GWh conversion only depresses CARE's forecast even more. However, unexpected events, such as coronavirus, may, of course, conceivably have a significant effect on investment and energy storage demand (China's shutdown was measured on 1 March 2020 as having measurably reduced global NOx pollution, hence global warming by some measure) which may bring CARE's low forecast back into the picture.

## 4. The Global Production Network for Mining, Refining and Processing LIB and Post-LIB Minerals

First, we can draw attention to "Kokkola", the Finnish town which appears in this contribution's title for the reason that it is one of Europe's few cobalt processing refineries and for lithium easily the largest. Kokkola is located in Finland's "lithium province" which is Europe's only serious source of raw lithium, thus making it important for processing as well as importing the raw material for LIBs. However, it is also important for hosting one of Europe's larger Cobalt refineries. It was a key metalworking district under the Swedish Empire. In combination, lithium and cobalt are critical to LIB manufacturing. A sign of this is the investment in LIB gigafactories in a Nordic Battery Belt from Mo-i-Rana in Norway through Skellefteå in northern Sweden to Vaasa in Finland's Ostrobothnia region (lithium province), where Valmet's EV assembly for Fisker and others has been conducted. However, the German EV market is planned as the real target of this output. The other refiners are Belgium, which mines no cobalt but refines 6.3 million tonnes (mt), France, which mines none but refines 119.0 mt, and Finland, which mines none but refines 11.187 mt of mainly imported ore. Cobalt is critical as a raw material, especially in LIBs, but with 55% of global ore supply originating from the politically unstable Democratic Republic of the Congo (DRC), its supply is vulnerable. Accordingly, due diligence issues are especially important, as prevailing international court cases testify. While China at 45.046 mt refines some 55% of global refined cobalt, it is mainly imported from Australia and Canada. Finally, official statistics include a strange alliance of Canada, Cuba and Norway (Glencore) as a kind of intercontinental alliance refining 9.044 mt, with Cuba mining but not refining its share [18]. Before moving on to Glencore (and other miners and refiners of note), we remain with Finland's exceptionalist cobalt-lithium niche.

Some indication of the sometimes-cutthroat manoeuvring for access to the inputs and outputs of the LIB supplier networks is given by the actions of Tesla's CEO Elon Musk to maintain his company's lead in superior rated cylindrical battery power-packs. A significant problem for innovating these in the joint Tesla–Panasonic plants at Reno, Nevada and Buffalo in the two "gigafactories" located there had been the process of sealing batteries into the cylindrical cells that power Tesla EVs, solar roofs and, conceivably, solar-storage systems. The key technology involves "separators" that keep LIBs safe for all domestic and industrial uses. Between a battery's anode and cathode is the permeable membrane which separates them. Accordingly, Tesla remained unsatisfied with Panasonic's supply of batteries and management weaknesses at Gigafactory 1, citing slow pace, high wastage and inconsistent quality. Thus, as noted previously, Tesla began negotiations with CATL to join LG Chem and Panasonic, the latter of whom were to become a third main supplier with Toyota to Tesla's Shanghai gigafactory. However, one of Tesla's main partnership problems involving Panasonic concerned the high battery wastage rate. An instance of this concerns Grohmann Automation, located in Rhineland, Germany. Tesla had detailed knowledge of quality, sometimes uniquely skilled, suppliers. The robotics manufacturer Grohmann produced robotics for separators used in production by Tesla at its gigafactory in Nevada. Tesla acquired Grohmann in 2017 as a single worldwide source for battery packs. This created friction over Panasonic's quality performance. Elon Musk instructed Grohmann to sever its supplier links with German vehicle assemblers, upsetting German manufacturers trying to catch up in the EV market. It also upset the unions and Grohmann himself, who resigned from what had become Tesla Grohmann Automation. Subsequently, Mercedes-Benz reported it was experiencing difficulties in meeting demand for batteries to install as part of the "intelligent" guidance for its EQC model owing to Tesla having acquired Grohmann. The latter had earlier been signed up by Mercedes-Benz to fulfil its manufacturing capacity build-up [13]. Further than this market "insurance" move by Tesla, industry reports [36,37] also noted the company was in talks with Glencore to negotiate a continuing contract to purchase cobalt from the DRC for its new gigafactory in Shanghai [36].

However, the Glencore agreement indicates that the metal will remain vital to Tesla's forthcoming anticipated expansion in China and Europe. As the world's largest cobalt miner, Glencore would clearly benefit from any rise in EV demand. The company made losses related to cobalt in the year prior to the agreement after prices collapsed in mid-2018 from over-supply. Subsequently, Glencore locked customers into new agreements in the EV supply chain. Accordingly, Glencore will supply BMW cobalt from mines in Australia and others in Morocco. Further battery materials will be sourced from Umicore (Belgium) and GEM (China) who have also agreed long-term contracts. Tesla's cobalt, as noted, will come from the "artisanal mineshafts" often employing child labour in the Democratic Republic of the Congo, known for fatalities and human-rights abuses being commonplace but where prices undercut and contribute to market fluctuations. BMW set up a three-year project in 2019 with Samsung SDI and the German government's development agency in Katanga province, southeast Congo, to improve working conditions at a single pilot mine. Tesla is also taking steps to ensure its suppliers resist contributing to corruption and potentially even child labour [13].

### *Mining Geographies and the Future of Batteries*

Regarding these, we may briefly outline the configurations in question. Freeport-McMoRan was once the world's largest refiner of cobalt. Today it is most well-known for molybdenum and became the largest copper producer in the world in 2007, moving its headquarters from New Orleans to Phoenix, Arizona. Its oil interest is in selling petroleum to the likes of US outlet Phillips 66, which accounts for some 7% of Freeport-McMoRan's profits. The corporation has been frequently implicated in legal cases involving corruption and pollution on a grand scale. Many miner/refiners have been mentioned, ordered as follows: Jinchuan Group (China), 7kt; Umicore (Finland but Belgian-owned), 6 kt; Nikkelverk

(Norway), 5 kt; Umicore (Belgium), Chambishi Metals (Zambia), Sumitomo (Japan), 3.6 kt; Sherritt (Canada), 3 kt; Ambatovy (Madagascar), Queensland Nickel (Australia) and Norilsk (Russia). Leading cobalt-only miners are Glencore, 2.7 kt; China Molybdenum, 1.6 kt; Fleurette (now Glencore), 0.8 kt; Vale, 0.6 kt; Gécamines (DRC), 0.4 kt [18]. Primary nickel mining and refining production is as follows. According to the International Nickel Study Group [31], global refined nickel production was 2.184 mt in 2018. The world's ten largest nickel producers of that year accounted for over 60% of this total. Vale (Brazil) was the second largest miner in the world and the leading nickel (244 kt) and iron miner. Next was Norilsk Nickel (Russia), which produced 244 kt, followed by Jinchuan (China) at 124 kt and Glencore (Swiss) at 124 kt, BHP Billiton (Australia) at 91 kt and Sumitomo (Japan) with 65 kt, Sherritt (Canada) at 63 kt, Eramet (France) at 55 kt, Anglo-American (UK) with 42 kt and Minara (Australia but wholly-owned by Glencore) with 39 kt. The authors of [23] conclude with the assumption that LIB technologies will be the prevalent battery technology for the foreseeable future. They envisage lithium demand rising from 87 kt in 2017 by 509 kt to a total of 672 kt by 2025, and cobalt rising from 41 kt to 117 kt in the same period purely for battery consumption. One innovation diversification process is already evident, for example with the development of the NMC 811 battery and related initiatives to reduce the use of cobalt in future batteries.

Here, more of the (Kokkola) account references the single Umicore plant in Kokkola, which, nevertheless, operates largely in a global innovation system (or supply chain for processing raw materials that may ultimately be used or obsolesced by innovators close to or actually at the "edge of innovation"). This has many global mining competitors, which are private firms buying and selling each other, as well as to each other. This is a complex international innovation system with much of the "system" buried in large corporates and their suppliers. So it is somewhat different from "localised industrial districts" or even "regional mono-cultural innovation systems", like Baden-Wuerttemberg, for example. One issue this research raises concerns the extent to which 4.0 industry evolves into a "dyadic" or "dualistic" system, with a few global corporate players servicing a "sporadic set" of innovative but also global sub-suppliers, where specialist 4.0 advanced knowledge exploitation may operate in localised lateral systems (e.g., university lab-to-innovative start-up) or singly in a vertical relationship in proximity or at a distance with a single global customer (e.g., the Tesla model has features like this, acquiring not only Grohmann but, for example, Canada's Maxwell Technologies in 'ultracapacitors'). So underlining the main thrust of this article means—possibly uniquely—that analysis must be interpreted—even individualistically—by use of "pattern recognition" of the preconditions for a global innovation system that may consist of different sporadic innovation system elements that may show some localisation, e.g., "academic knowledge translation", for battery innovation which, in turn, facilitates (e.g., the 500 mile battery) systemic EV innovation for competitive global advantage. This type has recently been observed in clean technology as a kind of global "supercluster" which is not really any kind of cluster due to its global "scattering" and "sporadic" and fluctuating supplier networks. Rather it has two (twin) "carburettors", if anything: one supplies globally-sourced raw materials and the other supplies LIBs to global EV manufacturers. In between are some distant innovative small firms experimenting with new raw materials for batteries or highly specialist singleton engineering firms like Grohmann (now Tesla Grohmann Automation) or Maxwell. Discussions of this twin-carb model type can be found particularly in [7,8,10,28].

According to Azevedo et al., authors of [1], there are five serious candidates for enhanced LIB technologies for the medium-term future of EV and solar storage. Cathode composition is the main differentiator among them.

1. Lithium cobalt oxide (LCO) has traditionally been the most widely-used cathode material in lithium batteries but is now being superseded due to cost, pollution and child labour exploitation. UK chemicals company Johnson Matthey has innovated with reduced cobalt in its enhanced lithium nickel oxide (eLNO) batteries, using higher levels of manganese, in order to halve cobalt costs. Mass-manufacture of 10,000 tonnes of battery

material per year will be conducted by Johnson Matthey in Poland. The German and Belgian competitors BASF and Umicore also have designs for lower-cobalt chemistries. Amongst these are Platinum Group Metals's and Oxis Energy's experiments to create lithium sulphur batteries [32]. However, first on McKinsey's list [1] of innovative pathways is lithium nickel oxide (LNO) but it is dismissed as more suitable for portable rather than EV electronics due to on its expensive reliance on cobalt [1].

2. Second is lithium nickel manganese cobalt, which has now advanced to the aforementioned NMC 811 battery, developed for EVs but applicable for solar storage, displaying the highest theoretical performance. Early batteries contained nickel, manganese and cobalt in equal amounts, but companies such as South Korea's SK Innovation (EVs and batteries for Hyundai) and LG Chem are building cathodes with 80% nickel and only 10% cobalt in the NMC 811.

3. Third is lithium nickel cobalt aluminium, also designed for EVs but alternatively usable for portable electronics because it depletes use of expensive cobalt and replaces it with aluminium. BASF of Germany is a main supplier to EV producers through its NCA product portfolio. NCA products are already marketed as automotive batteries. BASF launched its >90% nickel NCA grade product in 2017 in close collaboration with Tesla and gigafactory partner Panasonic.

4. Fourth is lithium iron phosphate (LFP), which has high power density and is applicable for small-grid, electric-bus and EV loads. CATL launched its solar-storage battery system in the US in 2019 based on LFP battery technology, augmenting its existing EV client list of BMW, Volkswagen, Ford and GM.

5. Fifth is lithium manganese oxide (LMO) installed in the popular Nissan Leaf EV because of its high reliability and relatively low cost. However, by 2020 Nissan Leaf (also VW ID 3 and BMW i3) models had lithium nickel manganese cobalt oxide batteries. For the VW 2020 model, the cells are NMC 811, reflecting improvements. Paradoxically, nickel has high power density but low stability without an alloy like manganese. Nickel is preferred over cobalt because of its lower cost, while small amounts of silicon at the anode contribute to enhanced energy density.

So, for now, the clearest conclusion to be drawn from this analysis is that cobalt is not the favourite mineral for future battery technology on cost, child labour and energy augmentation grounds and that nickel is, especially the NCM 811 innovation [26,27]. In order to pursue our qualitative "pattern recognition" research methodology in the space available, we now compare and contrast findings from two reports of comparable status and presence. The first is the report by Arthur D. Little [39], which produces three scenarios: first, present generation LIBs are given a medium rank of probability likelihood because diverse niches emerge and cost is less of a major constraint than performance. Second, a new LIB generation may emerge. This is ranked as having the highest probability likelihood because lithium-ion has reached its theoretical limits and EVs are a "pull" factor for innovation. The third scenario is that unforeseen battery technology breaks through, which is ranked as the lowest probability of likelihood because lithium is light, relatively safe and low cost. Even hydrogen fuel cells, a putative competitor, are only a long term threat. The expectation of the authors of the [39] report is that solid-state electrolytic batteries will gradually spread to the majority of applications, such as EVs and grid storage. Alternatives like flow (e.g., Foxconn) and zinc–air batteries will occupy only niche applications. The report uses the same five categories of LIB types as McKinsey, which may be thought reassuring. LCO is dismissed as inadequate for future EV and solar-storage use; LFP is near to the maximum energy performance but Chinese innovations in rotary ceramic kilns have cheapened and extended LFP life; nevertheless, superior technologies like hydrothermal methods are expected to maintain utility for high power applications in EVs, EV trucks and grid storage. NCA is thought to be good for increasing energy density and reducing cost. It is used by Tesla in cylindrical format from Panasonic while competitors use NCM. However, Tesla switched to NCM for energy storage applications and the authors of [34,39] see it is a possibility for future use in EVs. NCM, especially NCM

811, is expected to be chosen by all EV manufacturers (except Tesla) for the foreseeable future. LMO is considered comparably to LFP in terms of delivering high power and it is cheap but unstable, as indicated by Nissan's decision to discontinue installing LMO due to continued battery malfunctions. Accordingly, there is consensus on the present superiority of NCM 811 as the LIB of choice for both our main users in EVs and grid storage, except Tesla who may be capable of achieving a battery breakthrough. However, as noted, Tesla has moved partly to NCM for solar-storage applications [35,37,38].

Finally, we need to triangulate on the third battery forecast of the future, regarding the further advanced evolution of LIBs and the prospects for alternative battery technologies furthering the 500 mile charging range for EVs. The final report is unfair in post-dating the other two by two years but is interesting because it queries the lithium ion conventional wisdom to some extent. ARPA-E, the US Department of Energy's Advanced Research Projects Agency, funds each project. Regarding battery technology, we refer to the first five assessed for fair comparison though there are more "outsiders", some of which were merely skated over earlier; for example, in [32].

1. Accordingly, the first technology to be reviewed is sulphur flow batteries. Former researchers at Tesla created Form Energy in Somerville, Massachusetts. These batteries enable a seven-days-a-week backup capability, at least ten times cheaper than other rechargeables. Sulphur flow batteries have the lowest chemical cost of all rechargeable batteries but suffer from low efficiency. Form Energy is working with Lawrence Livermore Labs and Penn State University on new anode and cathode formulations, membranes and physical system designs to increase efficiency. United Technologies is also researching faults in sulphur flow membranes that hinder current efficiency. This clearly suggests the technology has breakthrough potential but is far from the market.

2. Electricity to Hydrogen involves the University of Tennessee breaking water into hydrogen and oxygen then using the hydrogen in fuel cells. However, such conversion is inefficient and prohibitively costly; it is ruled out due to feasibility and projected cost.

3. Zinc–bromine flow batteries are the specialty of Primus Power, Hayward, CA, who already manufacture these. ARPA-E is supporting research on separators to allow the entire electrolyte to be stored in a single tank instead of costly cells. It is a potential winner given its market status but high cost of running power. Other producers include RedFlow, Brisbane, Australia; Smart Energy, Shanghai, China; EnSync, Wisconsin; and ZBEST, Beijing, China.

4. Antora Energy of Fremont, CA, uses electricity to heat carbon blocks to2000 °C+. The carbon blocks are exposed to thermovoltaic panels to generate energy. With its ARPA-E grant, Antora will develop a "thermovoltaic heat engine" to double panel efficiency through new materials and "smart" system design.

Clearly, some proposals being funded by ARPA-E are over-complex and too elaborate for practical use. Physics dictates that every energy conversion involves losses. Accordingly, the efficiency of some of the systems being designed can be deemed questionable. However, the efforts made and possibly combined mean energy costs are probably on a downward curve with sulphur and zinc–bromine flow batteries and potential winners [4,15,19].

## 5. Conclusions

The initial implications and conclusions of this study are as follow. First, Tesla retains the lead from forward-thinking and strategy, causing many leading carbon-based auto-firms to fall behind (Mercedes, BMW, GM, Ford, Toyota and many others) the leader. Second, they are now trying to catch-up. Beneficiaries are, in particular, the cited Korean and Chinese LIB producers. Also, Tesla (again) is leading for early development of most competitive LIB technology. There are three further conclusions following our "pattern recognition" analysis of qualitatively assessing forecasts to determine which probabilities offer themselves as the least "outlandish". We began with portrayals of corporate investment strategies, which included in some cases stories of strategic failures of corporate strategy, in order to show that a competitive battle had at last begun. This is between the producers and consumers of lithium ion batteries that fuel electric vehicles, solar tiles for roofing and solar-storage systems for households and small businesses. The analysis of the dyadic twin-carb structure of a complex industry that looks simple on the outside but is rather convoluted and cross-sectoral, conglomerated and monopolistic, on the inside was enormously revealing. This also applies to the comparably dyadic structure of many of the battery-consuming end-users of the minerals, refinings and commodity factors that constitute quite revealing regional and local innovation systems, producing and consuming batteries for EVs and electricity storage systems—both major industries of the future. Many monopolists and exploitative firms were included in the preceding narrative. These ranged from those involved in the sometimes brutal histories of informal, "artisanal" mineworkers toiling—some as child labour—in the cobalt mines of once war-torn Katanga province in the Democratic Republic of the Congo, where Belgian imperialism contributed to the epithet "Darkest Africa", to repentant companies like Freeport-McMoRan, which were once bywords for conflict and corruption but divested much of their Congo and cobalt holdings, and finally to a still "entrepreneurial" but at least "sustainably" minded tycoon like Elon Musk, CEO of Tesla, a firm that seems single-handedly to be trying to destroy the world's global "carbon lock-in" [45].

When we examined the desire to promote sustainability through the generation of an innovative "green" landscape, despite some of the worst depredations of labour and environmental infractions by all kinds of players in the modern renewable energy industry, we found more scope for optimism. Our qualitative-abductive methodology yielded intelligent forecasting based on probabilities by interpretation of expert, sometimes fugitive, literature and documentation reporting expert analysis and specialist industrial journalism that was often up-to-date compared with the time lags that increasingly vitiate academic research results. From a plethora of documentary material we came to sensible conclusions on the following three findings. First, cobalt will soon be in retreat, though not yet because the EV and solar storage industries are at take-off stage. Cheaper and more powerful batteries are being produced and the lodestar is currently NCM 811, which even Tesla, the leading global EV and storage firm, has reluctantly turned to from NCA. This powered its pioneering EVs since its beginning and will particularly, for now, serve the Megapacks in energy storage systems it is about to build in California. For this author, the vignette of the deal between Tesla, the state authorities and Pacific Gas & Electricity was one of the most heart-warming to discover [38]. It points to a sustainably cheap yet powerful means of making available affordable renewable energy for all [35,37]. The two other "takeaways" are that the 500 mile charge is on the horizon given the innovative, albeit, for the moment, incremental innovation improvements in battery technology. The "war" is between Tesla, on one side, and the, surprisingly sometimes slower, Asian automanufacturers and energy storage engineers. On the sidelines, but waking up fast, are the traditional premium engineering car firms of Germany to whom the input suppliers are moving closer, with Tesla stimulating them all into becoming more alert [4,9,15]. Finally, the future is expressed more in the research being funded by the likes of ARPA-E than the large corporates, again excluding Tesla. The other candidates are not as promising, although not negligible, in turning unfamiliar notions, like sulphur flow or zinc–bromine batteries, into what may be valuable forms of renewable energy in the future.

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