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

Philip Cooke,

Mohn Center for Innovation & Regional Development,
Department of Engineering,
Western Norway University of Applied Sciences,
Bergen,
Norway

Author residence: Cardiff, Wales (UK)

Name: Philip Cooke

Email: cookepn@cardiff.ac.uk

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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 that powers 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 that would make a transformational difference to the replacement of renewably fuelled vehicles and storage systems that are currently still predominantly driven by fossil fuels. The challenge has led to a 'war' of manufacturers, miners and refiners realising the challenge has come alive while most have been vacillating. At an individual level, Elon Musk for all his faults, deserves credit for 'moving the market' in these two important industry sectors. The paper anatomises key events and processes stimulating change in this global economic activity by a qualitative 'pattern recognition' methodology which proves valuable in achieving rational, probabilistic forecasts. Established incremental innovation characterises first response in the 'war' but research agencies like ARPA are active in funding research that may produce radical battery innovation in future.

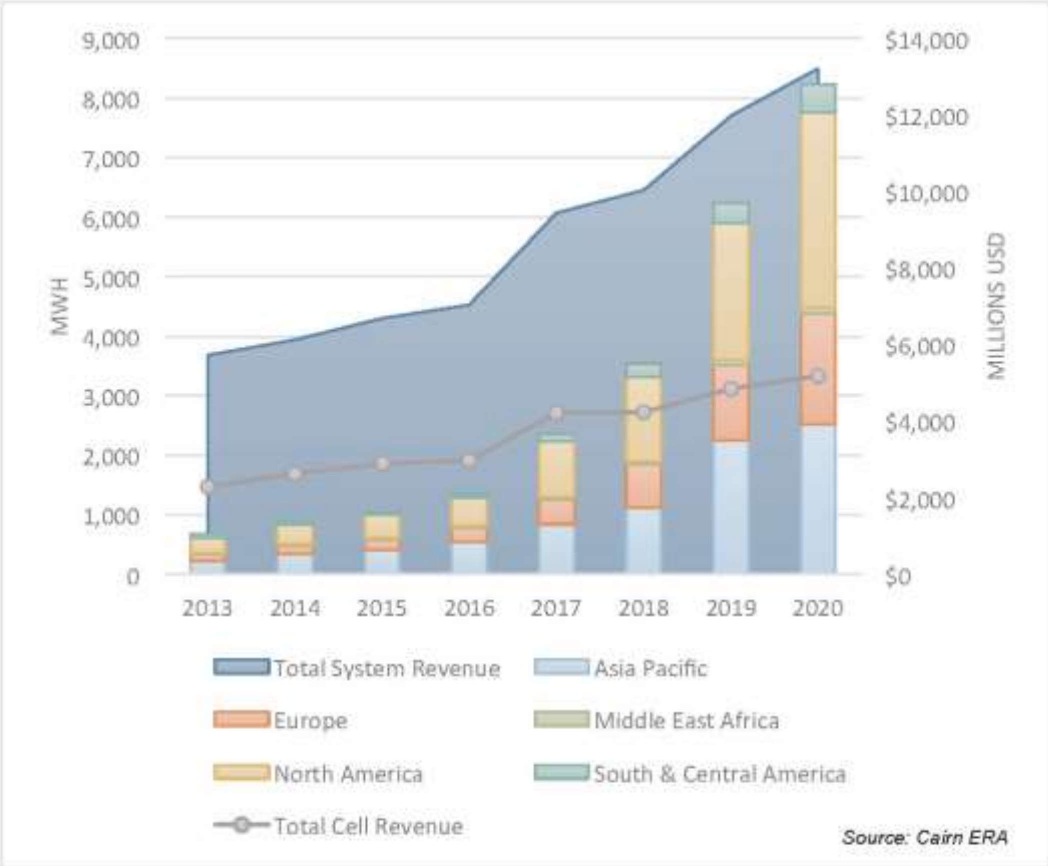
Introduction
It is noticeable in the reports of corporate investment strategies, which include in some cases stories of strategic failures of corporate strategy that a competitive battle has begun between the producers and consumers of lithium ion batteries (LIBs) that fuel electric vehicles (EVs), solar 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 storage and stationary energy storage may become a common household appliance in the near future. Batteries and thermal storage options such as power-to-heat and heat pumps in combination with solar power systems have potential economic attractiveness to households and small businesses. In September 2015 Tesla, for example, started shipping its first 7kWh LIB home batteries (Powerwall) to 100,000 US customers at a retail price of $3,000. Variants of Tesla's LIBs were at that time unavailable as 'sold out' for 2016. In Germany, a combined solar-storage system was expected to be more affordable than grid electricity by 2016. Panasonic, Samsung SDI and LG Chem LIBs were expected to be cost competitive for solar-storage systems by 2020 (EU, 2015). In what follows, this account will analyse the state of play on LIB technology and its likely successors, the production system and 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. Next there will follow 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 (Stokes, 1997) faced with technical change. Finally the contribution is interesting in analysing some theoretical issues of a geopolitical nature occasioned by the 'related variety' expressed by the recombination of innovation elements and their economic geography, displaying special interest in agglomeration effects, mining, metal processing and resource agglomeration and disagglomeration effects. The article will finish with a Discussion and Conclusions section tying the preceding narrative.

The Nature and Substance(s) of the Contemporary 'Lithium Wars'

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 the US Department of Energy with announced a possible solution with a newly announced round of $30 million in funding for next-generation technology leading to batteries that can store electricity in bulk for at least 10 hours. This was merely a taster of a grander project which was that the new round of funding aims at systems that can supply electricity into the grid for up to 100 hours. The funding agency for this programme is the Energy Department's Advanced Projects Research Agency – Energy (ARPA-E) office, whose sister agency funded the Internet. From the ARPA-E viewpoint, LIBs work efficiently and effectively for small-to-mid-range storage, but the costs start to increase significantly in relation to scaling up into the 10 hour range and beyond. 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 a greater share of low-cost, intermittent sources of wind and solar in the future generation mix. Thus the energy policy community recognises energy storage will play an increasingly critical role in the resilient grid of the future. 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 predominate, as occurred with negative implications for firms, hospitals and other intensive industrial and domestic users as occurred 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. Today's dominant storage options have limitations that inhibit their use as long-duration solutions, particularly their high cost.

So, not only is demand for LIB batteries and their successors increasing many fold because of deep structural shifts in the power mix of economy grids but it is also intensifying due to demand for bigger battery packs for already in-use applications by established technology developers. 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 jointly produced with Panasonic LIBs 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 breakthrough. Thus the 500 mile EV is thought unlikely to be achieved until at least 2010 and for the affordable mass-market EVs until beyond 2030 (Knowles, 2020).

Chart 1.1 **Global Stationary Storage Battery Energy Capacity by Region in MWH and Cell and System Revenue in Millions of USD Forecast: 2013-2020**



As noted above, by 2020 battery systems for stationary storage were anticipated to be likely to have grown in demand as an integral tool used by electricity providers to balance generation and load and between supply and demand. This was precisely the problem experienced in 2019 by the UK grid. Cairn Energy Research Advisors (CARE, 2015) expected this market to grow by 51.1% each year from 2015, reaching a global revenue total of $6.7 billion in 2015 to $13.2 billion in 2020. If fulfilled, this would be a significant change for the electricity industry: the electricity grid has existed for more than 150 years and has never before used batteries as an important tool for grid management. Essentially, everything about the electricity industry was seen as in a process of changing. Traditionally, generation fluctuated to meet a flexible load demand. Now, generation is becoming more unpredictable and less flexible while demand is becoming more responsive due to new forms of price signals such as demand response and Time-of-Use rates. At the same time, more renewables are being absorbed by the electricity system and being buffered by batteries.

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 (LIB) for EVs, energy storage systems, and battery management systems (BMS. In January 2017, CATL announced plans to fashion a strategic partnership with Finland's Valmet Automotive based at Uusikaupunki, focusing its collaboration on project management, engineering and battery pack supply for EVs and Hybrid EVs. As part of the partnership, CATL acquired a 22% stake in Valmet. Valmet Energy in 2019 contracted to Umicore's Kokkola cobalt refinery to design a clean energy cobalt processing plant. Belgian miner Umicore acquired Kokkola from US firm Freeport-McMoRan. Its Kokkola facility refines 10% of the world's lithium for LIBs, the remainder being refined in China. CATL in 2017 signed a supply agreement from Swiss metals giant Glencore to supply 'sustainable' Congo cobalt ore to the Umicore refinery in Ostrobothnia, Finland's 'lithium province'. Pressure from German automotive companies, notably VW was key to attracting CATL to locate LIB production in Arnstadt, Thuringia (former east Germany) and BMW also announced a $4.7billion contract with CATL for small car LIBs (De Carlo & Matthews, 2019). CATL's annual sales reached 11.84 GWh of energy storage capacity in 2017. Based on annual shipments, CATL is the world's third largest provider of EV, hybrid EV (HEV) and plug-in hybrid EV (PHEV) battery solutions behind Japan's Panasonic and China's BYD. CATL's strategic aim is to have a global LIB production capacity of 50 GWh by 2020. By December 2019 CATL announced that Tesla had secured a battery supply deal with CATL, to supply cells for Gigafactory 3 in Shanghai and potentially expand to other production facilities. In 2019, Tesla announced a battery supply deal with LG Chem (S. Korea) for the Model 3 produced at Gigafactory 3 in Shanghai, making it likely LG Chem would ultimately split the Chinese order capacity with CATL. The latter would supply LIBs for Tesla Model 3 while LG Chem would supply LIBs for Tesla Model Y (SUV) production. CATL is primarily using LiFePo (large scale grid storage and buses) and NMC (nickel-manganese-cobalt) chemistries in prismatic cell formats. Accordingly, the Tesla order would require branching into cylindrical cells, the high-efficiency use of which Tesla has been pioneering for electric vehicle battery packs.

Moving on, now we turn to China's leading LIB producer 'Build Your Dreams' (BYD). Founded in 1999 the company has developed its own iron-phosphate-based lithium-ion (LiFePo) battery following over 10 years' R&D. The core battery technology can be applied in all the main types of EVs and has a lifetime of over 10 years with a charge time to 50% of its capability in 10 minutes. The company started by supplying batteries to mobile telephony companies such as Nokia and Motorola. In 2003 BYD made the acquisition of Qinchuan Motors of Xi'an which gave it the opportunity for the company to expand from part and battery supplier to car marker. In 2008, BYD purchased SinoMOS Semiconductor of Ningbo to facilitate its upstream value chain and accelerate its development of EVs. , BYD plans to sell some 9 million electric vehicles by 2025 to surpass the leading global automakers in EV technology. However BYD also plans to expand LIB production to control its own and other clients' market access (Zhang & Cooke, 2010). Accordingly, in late 2019 BYD announced its EV plans in China with a new battery gigafactory that will be able to produce 20 GWh of battery cells for its EVs. Thus BYD is investing $1.5 billion in the facility located in Chongqing, Sechuan, southwest China's regional capital (with a municipal county population of 28,846,170). Such LIB output makes BYD's gigafactory one of the largest battery production facilities in the world (compared to Tesla, Nevada with 35 GWh which is currently the world's largest gigafactory). Chongqing was BYD's second new battery gigafactory when Qinghai opened in mid-2018. Located in the western province of Qinghai where 83% of China's lithium is located. This facility has an expected battery output of over 24 GWh. BYD focuses mostly on the production of prismatic LiFeP04 battery cells. These differ from most automotive industry Nickel Cobalt Aluminium (NCA) and Nickel Manganese Cobalt (NMC) battery cells in longevity. Between all its established and planned factories, BYD's total production capacity will near 100 GWh by 2030 to support its anticipated increase in EV production (Bell, 2019).

Regarding other Asian LIB competitors, On December 5th 2019, General Motors (GM) announced it was setting up a joint venture with South Korea's LG Chem to mass-produce LIBs for electric cars. LG Chem is a major supplier of LIBs to German firms VW and Daimler subsidiaries like Audi and Mercedes-Benz. The new joint venture partners plan to invest a total of$2.3 billion to build a new facility, which will be located in Lordstown, Ohio. The new plant is designed as GM's 'captive' gigafactory. It is planned to have an annual capacity of more than 30 GWh. Among GM's 20 envisaged new EV models is a new Chevrolet, set for release in 2020, and a battery-electric pickup truck by late 2021. GM also announced that the new joint venture was hoped to create 1,100 new jobs in Lordstown, where the company made the controversial decision in 2019 to close one of its big car manufacturing plants. 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 decision is thus made more in desperation – faced with foreign and Tesla competition in the EV market - than counting as a mass-market coup for GM. The South Korean company stated it would invest $916 million in its US subsidiary by 2023 to set up the joint venture with GM (Hawkins, 2019).

Earlier in 2019 LG Chem had agreed to invest $424 million from 2020 in a new factory at Gumi near auto-city Busan, South Korea to produce cathode material for LIBs sold currently to GM and VW. LIB cathode production will start from late 2022. As noted earlier, cathodes in LIBs are made of lithium combined with other metals such as nickel, cobalt and manganese (NCA; NMC). LG Chem's new factory expects to create about 1,000 domestic jobs in South Korea. The company currently operates two other cathode production plants in the country and is building one in China. In 2019 LG Chem agreed to purchase Congo cobalt from Glencore, something Tesla has also begun seeking due to global shortages of other mineral alloy ores. As industry expert Fred Lambert notes:

> 'Cobalt is a controversial mineral due to most of it coming from mining operations in Congo, a place that has historically been affected by conflict and corruption, which has resulted in child labor in some mining operations' (Lambert, 2020b)

Accordingly, Tesla has clarified its corruption and child labour compliance accords and sought to reduce its future LIB dependence on cobalt. LG Chem's moves followed Japanese company Toray's decision to invest in a new lithium separator plant also in Gumi in 2017. Such separators render LIBs safe and key to customer safety requirements following Samsung's disastrous experience with LIBs in Galaxy smartphones bursting into flames in 2017. Toray's materials subsidiary in South Korea announced investment of some $ 200 million at its separator film production facility in Gumi, and $120 million at its separator coating plant in Ochong, Daegu where LG Chem has had its main LIB plant supplying Kia, Hyundai, GM and VW (Audi) since 2011 when it opened the world's largest LIB megafactory.

Not surprisingly then,Toyota Motor Corporation and Panasonic are combining resources in a joint venture that begins in 2020 to produce EV batteries. It is only a few years ago that, as GM and VW were investing in major supplier LIB deals, that Toyota expressed reluctance to build its own gigafactory because its forecasts were indicating relatively slow progress in the growth of mass-market LIB-driven EVs over hydrogen. But the move into rapid global gigafactory growth by Tesla and huge investments by Chinese and South Korean LIB suppliers have led to a rapid re-think. Thus to compete with Chinese manufacturers, especially rapidly growing into the EV area, five Panasonic battery manufacturing facilities in Japan and China will be made part of the new partnership to boost their production to reach 50 times the current capacity. The pooling of resources could provide both companies with much-needed network resources to increase their EV market presence.

Illustrative Note on Methodology and the Pattern Recognition Question
The presentation of these narratives and empirical material is illustrative of the 'pattern recognition' approach developed in this kind of prefigurative study. 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). Qualitative research of such 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' (Tetlock & Gardner, 2016). It involves focus group interaction involving 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 subject to criticisms for its prevalence of unconscious or unadmitted biases that vitiate results, over-reliance on modelling frameworks that profess to but, by definition, cannot predict the future, let alone predict the recent past, and a reluctance to utilise, for example, social scientific 'anthropological' methods. These engage representative structured samples of respondents to explain rather than mutely predict human behaviour from past extrapolations without engaging with the objects of the research purporting to be of interest. Much useful research learning arose from the growth of targeted socio-economic research funded by policy sub-agencies of umbrella bodies like DG Research (& Innovation) of the European Union. Examples drawn especially from innovation studies pioneered much research that required 'knocking on factory doors' to test corporate truth claims

So, echoing the tone of this contribution's graphic representations thus far, we propose to check the accuracy of the predictions in Chart 1.1 regarding expected growth in demand by MHW and $US to the extent it is ascertainable for 2020 or the nearest relevant date, from 2013. According to BloombergNEF's (2019) report on the subject of global cumulative energy storage the global sum for 2018-2020 was a 'modest' 9GW rising to less than twice that (17GW; also predicted) by 2020. This compares poorly with the CARE (2015) forecast of 3.5GWH that was the prediction for 2018 with 8.3 GWH being forecast for 2020. BloombergNEF's (2019) near and present metrics are either factually inaccurate over-statements or CARE's (2015) forecasts are over-conservative under-statements. Bloomberg NEF's (2019) report predicts 1,095 GW by 2040 inviting a $662 billion investment from the market and still being quoted definitively by OilPrice.com the following year (Paraskova, 2020). So, we need a tie-breaker, which is the IDTechEx report (Gear & He, 2019) which forecast 6.2 GWH having been 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 '100MW (120MWh) in 100 days' was the challenge from Elon Musk to the South Australian government in 2017) compares with BloombergNEF's forecast over 2019-2029 of 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. But, of course, with unexpected events, such as coronavirus, conceivably having a significant effect on investment and energy storage demand (China's shutdown is measured on March 1st. 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.

The Global Production Network for Mining, Refining and Processing LIB and post-LIB Minerals

First, we 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 easily the largest. The others 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 classed as a critical raw material by the EU due to both being an essential mineral in creating a sustainable planet, especially in LIBs, and because 55% of global ore supply originates from the politically unstable Democratic Republic of the Congo (DRC). The large percentage of cobalt that originates from the DRC highlights the importance for companies to follow Due Diligence procedures with regards to responsible sourcing. 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 (Cobalt Institute, 2020). Before moving on to Glencore (and other miners and refiners of note) we remain with Finland's exceptionalist cobalt niche.

Some indication of the sometimes cutthroat manoeuvring foe 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. A separator is a permeable membrane placed between a battery's anode and cathode. Accordingly, Tesla remained unsatisfied with Panasonic's supply of batteries and management weaknesses at Gigafactory 1 blaming slow pace, high wastage and inconsistent quality. Thus as noted previously, Tesla began negotiations with CATL, to join LG Chem and Panasonic to become a third main supplier with to its Shanghai gigafactory. However, one of its 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. Grohmann manufactured robotics used in battery and electronics production for Tesla at its Gigafactory in Nevada. In 2017 Tesla acquired Grohmann as a global single source for battery pack manufacturing, which was the cause of friction over quality with Panasonic. Elon Musk insisted that Grohmann must sever its supplier ties with German auto-assemblers, which upset 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 announced it was struggling to meet battery demand for its new 'intelligent' EQC model as Tesla had bought Grohmann which had hitherto been hired by Mercedes to build up its own battery manufacturing capacity (Lambert, 2020b). Further than this market 'insurance' move by Tesla, industry reports (Burton & Bieshuevel, 2020; Lambert, 2020a) also reported the company in talks with Glencore to negotiate a long-term contract to ship cobalt from DRC to its new Gigafactory in Shanghai.

However the Glencore agreement indicates the metal will remain vital to Tesla's forthcoming anticipated expansion in China and Europe. Glencore, the world's largest cobalt miner, is in a prime position to benefit from a boom in EV demand. Until now, the company has 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. Thus BMW will buy cobalt from Morocco and Glencore mines in Australia, while battery materials suppliers Umicore (Belgium) and GEM (China) also signed lock-in contracts. Tesla's cobalt, as noted, will come from the Democratic Republic of the Congo where as much of 20% of the country's output is produced at 'artisanal' mineshafts where fatalities and human-rights abuses are 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.

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 largest 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 that accounts for some 7% of Freeport-McMoRan's profits. The corporation has been frequently implicated in legal cases indicating corruption and pollution on a grand scale. Many miner/refiners have been mentioned, order as follows: (1) Jinchuan Group (China) & 7kt., (2) 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. (Kay, 2018). Main nickel mining and refining production is found as follows. According to the International Nickel Study Group (INSG, 2019), 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) is a second miner in the world and leading nickel (244kt.) and iron miner. Next is Norilsk Nickel (Russia) which produced 244 kt., followed by Jinchuan (China) at 124kt. and Glencore (Swiss) at 124 kt., BHP Billiton (Australia) 91 kt. and Sumitomo (Japan) with 65 kt., Sherritt (Canada) at 63 kt., Eramet (France) 55 kt., Anglo-American (UK) 42 kt., and Minara (Australia but wholly-owned by Glencore) 39 kt. McKinsey (2018) concludes with the assumption that LIB technologies will be the prevalent battery technology for the foreseeable future. They envisage lithium demand rising from 87kt 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.

According to Azevedo et al., authors of McKinsey (2018), 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. Lithium cobalt oxide (LCO) has traditionally been the most widely-used cathode material in lithium batteries but is now being superseded on cost, pollution and child labour exploitation. UK chemicals company Johnson Matthey has innovated reduction in the amount of cobalt in its enhanced lithium nickel oxide (eLNO) batteries. These contain higher levels of manganese, which could cut cobalt costs in half**.** Johnson Matthey selected Poland for a factory to mass-manufacture the products, opening in 2022, to produce 10,000 tonnes of battery material a year. BASF and Umicore, rivals from Germany and Belgium, are also working on lower-cobalt chemistries Amongst these are Platinum Group Metals' and Oxis Energy's experiments to create lithium sulphur batteries (Jolly, 2020). However, first on McKinsey's list of innovative pathways is Lithium nickel oxide (LCO) but it is dismissed as more suitable for portable rather than EV electronics based on its expensive reliance on cobalt. Second is Lithium nickel manganese cobalt (NMC) 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 proportions, but companies such as South Korea's SK Innovation (EVs and batteries for Hyundai) and LG Chem are close to producing cathodes with 80% nickel and only 10% cobalt in the NMC 811. Third is Lithium nickel cobalt aluminium (NCA) 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. 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. 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 (NMC) batteries. For the VW 2020 model the cells are NMC 811, reflecting improvements.

Paradoxically, nickel has high power density but poor stability on its own. Manganese is the stable partner and the two work well in combination. Nickel is predominant over cobalt because it is cheaper. Small amounts of silicon at the anode play a role in boosting 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.

In order to pursue our qualitative 'pattern recognition' research methodology in the space available we compare and contrast these findings from two reports of comparable status and presence. The first is the Arthur D. Little (2018) 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 emerges. 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 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. A. D. Little's expectation 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 maximum energy performance but Chinese innovation of rotary ceramic kilns has cheapened and extended LFP life but superior technologies like hydrothermal methods are expected to maintain utility for high power applications in EVs, EV trucks and grid storage. NCA is thought 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 A.D. Little's authors Baes et al., (2018) see it is a possibility for their future use in EVs. NCM and especially NCM 811 is expected to be chosen for all EV manufacturers (except Tesla) for the foreseeable future. LMO is considered comparably to LFP as delivering high power, 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 ay be capable of achieving a battery breakthrough. However, as noted, Tesla has moved partly to NCM for solar- storage application.

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. However each is supported by ARPA-E the US Department of Energy's Advanced Research Projects Agency. Regarding battery technology we refer to the first five assessed for fair comparison though there are more 'outsiders' some of which have been merely skated over earlier, for example, in Jolly (2020). Accordingly, the first technology to be reviewed is Sulphur Flow Batteries. Former researchers at Tesla created Form Energy at Somerville Massachusetts. These enable seven days a week backup capability at least ten times cheaper than other rechargeables. Sulphur flow batteries have the lowest chemical cost but suffer from low efficiency. 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 suggests clearly that this technology has breakthrough potential but is far from the market. Electricity to Hydrogen involves the University of Tennessee breaking water into hydrogen and oxygen then using the hydrogen in fuel cells. But such conversion is inefficient and prohibitively costly. Ruled out on feasibility and projected cost. Zinc-bromine flow batteries are the specialty of Primus Power, Hayward, CA, that already manufactures 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, Beijung, China. Antora Energy of Fremont, CA. uses electricity to heat carbon blocks to over 2,000°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 practicality. Physics dictates that every energy conversion involves losses. Accordingly, the efficiency of some of the systems being designed is deemed questionable. But 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.

Conclusions

There are three of these 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 include in some cases stories of strategic failures of corporate strategy, that a competitive battle had at last begun between the producers and consumers of lithium ion batteries (LIBs) that fuel electric vehicles (EVs), solar tiles for roofing and solar-storage systems for households and small businesses. The dyadic 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 have been subject of the foregoing narrative. These range from 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 that were once bywords for conflict and corruption but divested much of its Congo and cobalt holdings, 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' (Unruh, 2000).

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 quantitative 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 is 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 NCM811 which even Tesla the leading global EV and storage firm has reluctantly turned to from NCA which powered its pioneering EVs since its beginning and particularly will, for now, serve its Megapacks in energy storage systems it is about to build in California. For this author, that vignette of the deal between Tesla the state authorities and the Pacific Gas & Electricity was one of the most heart-warming to discover. It points to a sustainably cheap yet powerful means of making available affordable renewable energy for all. 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 auto-manufacturers 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 to becoming more alert. Finally, the future, here expressed more in the research being funded by the likes of ARPA-E, than the large corporates, again excluding Tesla is not as promising, but also not negligible in turning unfamiliar terms like Sulphur Flow or Zinc-Bromine batteries into what may be valuable forms of renewable energy for the future.

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