Energy Research & Social Science 89 (2022) 102659

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Towards the lithium-ion battery production network: Thinking beyond mineral supply chains

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A R T I C L E I N F O

Keywords:
Lithium-ion batteries (LiB)
Global production network (GPN)
Supply chain
EV
Energy storage
Energy system transformation

A B S T R A C T

The increasing role of electricity as an energy carrier in decarbonising economies is driving a growing demand for electrical energy storage in the form of battery systems. Two battery applications driving demand growth are electric vehicles and stationary forms of energy storage. Consequently, established battery production networks are increasingly intersecting with – and being transformed by – actors and strategies in the transport and power sectors, in ways that are important to understand. Most analyses of battery production adopt a supply chain approach, focussing on the flow and transformation of materials from primary production via manufacturing to final assembly. They pay only limited attention to organisational and geographical relations, and they overlook critical areas of intersection between battery production and OEM manufacturing for automotive and power sectors. As a result, supply chain approaches do not fully account for emergent properties of battery production networks.

To remedy this, we deploy a global production network (GPN) approach that highlights the increasing intersection of battery manufacturing with the automotive and power sectors, informed by original research with key respondents in battery R&D and commercialization at the collaborative interfaces of academia, industry and government. Our GPN approach augments conventional supply chain accounts based on battery manufacturing in two ways: it identifies the economic and non-economic actors, network relations and multiple locations that constitute the global battery production network; and focuses on firm strategies of innovation, cooperation and competition through which this network acquires its organisationally and geographically dynamic character, (specifically increasing inter-industry intersections), and the multifaceted role of the state. The paper concludes by reflecting on the implications of this alternative account for understanding key areas of policy concern, and for analyses of the geopolitical economy of energy system transformation.

1. Introduction

The growing role of electricity as an energy carrier in decarbonising economies is increasing demand for electrical energy storage in different industries, across multiple settings, and at a wide range of scales. In the transport sector, battery systems include neighbourhood-scale forms of mobility (e-scooters), urban and regional scale transport systems (e.g. e-bikes and e-buses), and long-range transport including automobiles and aircraft. Stationary applications range from household battery installations 'behind the meter' to store power from domestic renewable energy generation such as from solar panels (so-called 'power-walls' or 'wall boxes'), to grid-scale dispatchable power systems designed to balance supply and demand across transmission and distribution grids or provide back-up functions for emergency situations during black-outs.

Growing demand for energy storage linked to decarbonisation is driving innovation in lithium-ion battery (LiB) technology and, at the same time, transforming the organisation of established LiB production networks. Battery applications in electric vehicles and stationary forms of energy storage mean that established LiB production networks are increasingly intersecting with – and being transformed by – actors and strategies in the transport and power sectors. The intersections of battery manufacturing with the automotive and power sectors are, therefore, increasingly important to understand, along with the emergent organisational and geographical properties of the battery production network to which these intersections give rise. Indeed, the proliferation of battery systems in response to decarbonisation across a range of industries and spaces is transforming economic relations all along the production network raising several areas of public and policy concern: from the availability of mineral raw materials such as lithium, nickel and cobalt, to bottlenecks in LiB manufacturing capacity; and from regional development opportunities associated with ore mining, cathode manufacture or cell assembly, to the geopolitics of competition and control over supply.

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https://doi.org/10.1016/j.erss.2022.102659
Received 25 January 2022; Received in revised form 2 May 2022; Accepted 5 May 2022
Available online 10 June 2022

In response, a growing body of research addresses the scaling up of battery production and its political, economic and environmental consequences. Work on the growing demand for lithium in energy storage, for example, illustrates how decarbonisation strategies premised on reducing the consumption of fossil fuels *increase* societal reliance on (non-fuel) mineral-based materials [1,2]. Most analyses of battery production adopt a supply chain approach, focussing on the flow and transformation of materials from primary production via manufacturing to final assembly, see e.g. [3,4,5], rather than a network of strategic interactions among economic and non-economic actors. They pay only limited attention to organisational and geographical relations, and they overlook critical areas of intersection between battery production and original equipment manufacturing (OEM)[1] for automotive and power sectors. As a result, supply chain approaches do not fully account for emergent properties of battery production networks.

What is needed, we argue, is an expanded account of the LiB production network that can supplement the insights of existing supply-chain analyses. The goal of such an expanded account is to advance on existing analyses by capturing *both* the material and strategic dynamics of scaling up LiB production; and by examining the organisation of battery manufacturing in a way that can reveal its growing *intersection* with the automotive and stationary energy storage systems (ESS). Specifically, such an account needs to be able to acknowledge four key aspects of battery production and account for their effects: (i) the role of innovation in battery performance, as this has implications for the rate and scale of demand, the scope and scale of material demands, and which actors and locations capture value; (ii) the significance of geopolitically-inflected competition along the supply chain, as this drives both organisational and geographical shifts in production including efforts to regionalise supply; (iii) the role of vertical alliances in end-use markets (e.g. between OEMs and battery producers); and (iv) the importance of infrastructural investment in the power sector (e.g. in alliances between OEMs and international oil companies in the development of supercharging stations for electric vehicles, or the entry of OEMs into residential, commercial and industrial energy provision).

In short, understanding the evolution of the LiB production network requires an approach that can capture key elements of interaction and political-economic organisation across and between, and not only along, existing supply chains. This paper shows how a global production network (GPN) approach can provide a more holistic understanding. The GPN approach is part of a broader family of relational approaches for understanding the organisation of economic activity, and was designed to address the 'organisationally fragmented and spatially dispersed' character of economic structures [6].[2] A 'production network' is an "organisational platform through which actors in different regional and national economies compete and co-operate for a greater share of value creation, transformation, and capture though geographically dispersed economic activity" [6,p. 30]. GPN researchers foreground these organisational platforms to analyse the spatial fragmentation of production and service activities and their implications for uneven and regional development. GPN is, then, a meso-scale heuristic – it operates between structure and agency [6] – and was first developed to understand changes in the geographic organisation of manufacturing and services at the world scale [9,14,15]. A key feature of GPN is its explicit focus on "the relationship between geographic extensification of economic activities and the activities' organizational integration and coordination" [16, p.218]. GPN embraces multiple geographic scales; recognises a plurality of economic actors extending beyond firms; acknowledges the unevenness of regional development outcomes; and explores how the dynamic geographies of production emerge from interactions among a network's constituent parts [16].

To understand battery production as a GPN means highlighting the organisational arrangements through which economic and non-economic actors interact in the production and distribution of energy storage capacity. With its focus on lead firms, inter-firm relations and state strategies, a GPN approach is particularly well suited for examining these intersections which, we argue, are increasingly important for understanding the geoeconomic and geopolitical consequences of scaling up LiB production.[3] GPN has been applied effectively to analyse organisational dynamics elsewhere in the energy sector. Initial work on oil [17,18] has been supplemented by work on natural gas [16], solar photovoltaics [19] and wind [20,21].

Our aim is to situate the battery mineral supply within a GPN that extends 'downstream' through battery manufacturing to end use application; and which shifts the focus from material flows and transformations to the actors, networks and activities that maintain the network and shape its geographies. Our GPN account is informed by a close engagement with existing documentation on the battery sector, and by original empirical material collected via semi-structured interviews with a dozen respondents involved in battery R&D and commercialization at collaborative interfaces of academia, research institutions, industry and government in Australia, the EU and UK between June and September 2021. Our analysis augments conventional supply chain accounts based on battery manufacturing in two ways: (i) by identifying the economic and non-economic actors, interrelations and multiple locations that constitute the GPN – specifically the state as a multi-faceted actor within the LiB GPN; (ii) by focusing on different firm strategies of innovation, cooperation and competition through which this network acquires its organisationally and geographically dynamic character; and (iii) by demonstrating the importance of inter-industry intersections. These latter points are particularly important, as emergent geographies of production (and strategic responses to them by states and corporations) are an important dynamic constituting the network. Our GPN approach is well-adapted for understanding how the business of battery production is increasingly influenced by actors and strategies linked to automobile manufacturing, and to a range of 'infrastructural' actors associated with construction, electric utilities and fossil fuel retailing. In short, it shows how these intersections and network characteristics increasingly drive the organisational, material and geographical forms of battery production.

The paper is structured into five sections. In the next section (Section 2) we introduce battery manufacturing as an organisationally integrated but geographically dispersed process of material production and assembly. Section 3 reviews relevant literature, highlighting its focus on the input-output structures of supply chains and associated work on, material flows, lifecycle analyses and total material requirements. We offer a sympathetic critique of supply-chain approaches but advocate for a GPN perspective better suited to exploring the intersections of battery production with mobility and power sector infrastructures and foregrounding the role of strategic action by firms and states in shaping the organisation and geographies of battery production. Section 4 outlines the battery production network using a GPN perspective. It identifies the actors, network forms and territorial dimensions of battery production, emphasising the network's organisational and geographical characteristics; and it outlines three important dynamics shaping contemporary battery production networks. We conclude in Section 5 with a discussion of findings and their implications for the geopolitical economy of energy system transformation.

[1] Original equipment manufacturers engage in high value manufacturing activities and services, e.g. branding and marketing, and these activities are increasingly outsourced to suppliers [6]: 11.

[2] Informed by world-systems theory [7], GPN evolved from Global Commodity Chain and Global Value Chain approaches [8–13].

[3] An early indication of the potential intersections of e-mobility with static energy infrastructure was use of the Nissan Leaf (first released in Japan in December 2010) to provide dispatchable emergency energy storage following the March 2011 Fukushima disaster.

Table 1
Leading cell and battery manufacturers, by country and company.

Top 5 countries/region, share of commissioned capacity, 2020 (747 GWh)	Tier-1 producers (BMI[a], 2021)	Main countries in which T-1 producer owns battery manufacturing plants
China – 76% (568 GWh)	CATL (HQ: Ningde)	China (Shenyang in JV 'BBA' with BMW Group), Germany (Erfurt)
US – 8% (60 GWh)	BYD ('Build Your Dreams') (HQ: Shenzhen)	China (Pingshan in Shenzhen); Europe (France; Hungary)
	Panasonic	Japan, China, US (Nevada)
Europe – 7% (52 GWh)	LG (LG Energy Solution), subsidiary of LG Chem (HQ: Seoul)	South Korea (Ochang), China (Nanjing), US (Holland, Michigan), Poland (Wroclaw)
South Korea – 5% (37 GWh)	Samsung SDI (HQ: Yongin)	South Korea (Ulsan; Pohang), US (Auburn Hill), China (Tianjin, Xi'an), Europe (Hungary, Austria), India, Malaysia, Vietnam
Japan – 4% (30 GWh)	SKI (SK Innovation) (HQ: Seoul)	South Korea (Seosan), China (Changzhou, Jiangsu), US (Commerce, Georgia; 2 locations in JV with Ford tbc), Hungary (Komaron, Ivancsá)
	Envision AESC	Japan (Kanagawa); US (Tennessee), UK (Sunderland) and China (Jiangyin)
	Gotion High-Tech (HQ: Hefei)	China (Hefei, Anhui province); [Germany (Salzgitter)]

[a] BMI categorises producers of 'automotive grade' batteries into three tiers based on scale, quality and whom they are qualified to supply. Tier-1 producers have >5 GWh of annual cumulative capacity and are qualified to supply multinational automotive OEMs / EV producers outside of China [46,53].
Sources: [34,53,54].

2. Making batteries: an organisationally integrated, yet geographically dispersed assembly process

In this section we introduce battery production as an organisationally integrated, yet geographically dispersed process of materials production and assembly. We highlight how performance requirements for the automotive sector have increasingly shaped battery chemistry and technological development, and distinguish four geographies of production and ownership (Tables 1–3). Overall, this section demonstrates how the network character of battery production lends itself to a GPN analysis.

2.1. *What is a lithium-ion battery?*

A modern battery is a materially complex, manufactured product designed for a particular end market rather than a fully fungible commodity [22]. Batteries comprise multiple cells, and each cell contains three key components: a cathode and an anode, which act as ports of positive and negative charge; plus an electrolyte that surrounds or interconnects the electrodes [23]. Other components (and battery design [24]) facilitate battery performance, such as current collector foils, separators or coatings: like the electrodes, these are highly engineered materials that need to work well together for a battery to perform its desired energy storage function.[4] Tailoring batteries for a particular end use market translates into specific requirements for minerals and mineral refining. Battery producers source components from specialist suppliers around the world, with transactions between battery material and component suppliers, battery producers and end use sectors shaped by carefully designed property rights [25,26]. In short, battery production is an organisationally integrated but geographically dispersed assembly process.

Battery chemistry has evolved over time. While lead-acid batteries continue to occupy the largest share of the overall battery market, LiB have become the major battery growth sector and are likely to be the focus of chemistry development over the next few decades, see [26].[5] Lithium (Li) is the lightest metal in the periodic table, which makes its electrochemical properties available for use with the least weight-impact on the end-use application, in contrast to lead- and nickel-based battery systems.[6] The compound word 'lithium-ion' refers to a "lithium atom with an electron removed, leaving the atom in an electrically positive charged state" [28,p. 100–102]. The size of the lithium ion allows it to migrate through the cell electrolyte and between the electrodes, with charging and discharging changing the direction of travel. LiB were first used in space applications where mass, battery life and safety were primary considerations, but are now a general class of chemical energy storage and widely considered a mature technology.[7]

LiB encompass a family of cathode chemistries, with the choice of cathode chemistry reflecting the application. LiB cathode chemistry development has centred on lithium-nickel-manganese-cobalt oxide cathodes (so-called NMC), which at the end of 2021 accounted for over a third of the general LiB market [30]. EV battery chemistry is differentiated by vehicle type, class and end-market geography: lithium-iron phosphate (LFP) cathodes are used in low-end (mid-range) 'entry level' cars manufactured in China (LFP accounted for a greater share of China's EV production market than NMC in 2021), and increasingly also in Europe, with LFP chemistries expected to dominate over NMC globally by 2030 in most EV markets [216,217]; high-manganese batteries (lithium-nickel-manganese oxide, 'LNMO') for the middle mass-market; and specific chemistries for high-end brands where performance concerns supersede price. For instance, the Tesla Model 3 sedan manufactured in China uses LFP chemistry, while, until summer 2021, the Tesla Model 3 s made in the US used a nickel-cobalt-aluminium (NCA) chemistry in cylindrical form, and thereafter shifted to LFP and prismatic form [31a,31b].

LiB technology is being shaped by four strategic drivers. Two primary drivers are whether a battery needs to be optimised for energy storage or for power delivery; secondary drivers are whether its application has weight and/or cost, or power sensitivities. These drivers reflect the priorities of different industrial sectors: the automotive sector, for example, has different needs to stationary energy storage systems (ESS) which allow intermittent flows from renewable energy sources to be managed and which act as a back-up power for power outages.[8] At the moment, the dominance of the automotive sector in the battery market, and economies

[4] Cathodes involve multiple elements and compounds: intercalation, or the layering of materials into stable structures, is a central (and energy-intensive) process in manufacturing cathode active materials. Similarly, electrolytes are engineered to reduce flammability and improve safety by, for example, adapting the composition of liquid electrolytes or developing solid electrolytes.

[5] In 2015 lead batteries represented over 85% of total battery production [27, p. 2].

[6] An alkali metal, lithium is a highly reactive element; it never occurs in pure form in nature, rendering the development of Li-metal 'the holy grail' of R&D for next-generation LiB, such as all solid-state batteries (ASSB).

[7] LiB chemistry was initially commercialized in portable electronics in the 1990s, where the battery adopted a cylindrical ('jelly-roll') format. Subsequent development has focused on performance (e.g. energy content and power) and adoption of pouch and prismatic formats [29,p. 1944,41].

[8] ESS are designed for a range of scales, from home battery systems (13.5 kWh) to industrial power packs (232 kWh) and grid scale 'megapack' applications (3MWh) [32].

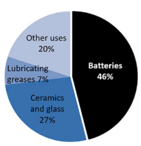
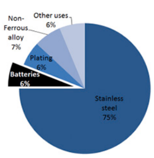
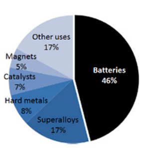
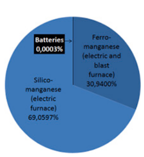
Table 2
Midstream Lithium-ion battery mineral-based material component manufacturing: percentage of total manufacturing capacity by country, and leading firms.

Country	Cathode Manufacturing (3 million tons p.a)		Anode Manufacturing (1.2 million tons p. a.)		Electrolyte Solution Manufacturing (339,000 tons p.a.)		Separator Manufacturing (1987 million sq. m)	
China	30–42%	CNGR, BASF, JM, Umicore, Sumitomo	58–65%	Hitachi Chemical, BTR, Nippon Carbon Co, Ltd	60–65%	BASF, CAPCHEM, GTHR	43%	Furukawa Electric, UACJ, Nippon Denkai, Doosan
Japan	30–33%		19–25%		12–20%		21–40%	
South Korea	7–15%		6–7%		4–15%		10–28%	
US	- / -		10% / -		2% / -		6% / -	
Europe[1]	30% / -		- / -		4% / -		- / -	
Rest of World	3–10%		- / 3%		1–17%		2–7%	

Source: directly from [34: p.19], which is based on data from [58,59,60].[a]

[a] Ref. [59] based on JRC and [58] differentiates country production shares of components relevant to LiB according for Europe, China, Japan, South Korea, and others.

Table 3
Midstream mineral refining and upstream battery mineral mine production for NMC cathode chemistry, by country and company.

	Refined minerals (battery grade)		Minerals (mine production)	
Lithium 	China (60.4%), Argentina (12.5%), Australia (8.8%), Chile (7.5%)	Livent, Ganfeng Lithium, Albemarle, Tianqi Lithium, Yahua Group	Australia (52%), Chile (22%), China (12%), Argentina (7%)	Jiangxi Ganfeng Lithium, Tianqi Lithium, Albemarle, SQM, Livent
Nickel 	China (48.9%), Finland (17.3%), Indonesia (11.3%), Japan (9.1%), Australia (5.8%)	GEM, Tanaka Metal, CNGR, Huayou, Brunp, Jinchuan Technology, BHP	Indonesia (33%), Philippines (12%), Russia (11%), New Caledonia (8%), Canada (8%)	Vale, MIND ID (PT Antam), Sumitomo Metal Mining, Nor(ilsk) Nickel, Terrafame, Jinchuan Group, Tsinghan Glencore, BHP Group
Cobalt 	China (78.6%), Finland (8.7%), DRC (6.7%), Taiwan (2.9%), Cuba (1.6%)	Freeport Cobalt, Umicore	DRC (69%), Russia (4%), Australia (4%), Philippines (3%), Cuba (3%)	Glencore, Gecamines, China Molybdenum (CMOC Intl), Vale, Fleurette Group
Manganese 	South Africa, Gabon, Australia, China, Ghana	CITIC Dameng Mining, Guizhou Redstar, Haolin Chemical, Prince Erachem, Nippon Denko, MMC	South Africa (27%), Australia (23%), Gabon (12%), Brazil (8%), Ghana (7%)	South32, GEMCO (AngloAmerican), Comilog (Eramet SA), Vale, Assmang

Sources: [62](cobalt metal); [63, p.22] (specific cobalt product use in LiB); [64, p.18] (for lithium); [65] from [66,67](for nickel); [68](for nickel); [69](for nickel); [70, p.49] (for cobalt mine production), [71,30,72](for manganese).

of scale in manufacturing batteries for this sector, mean ESS applications are currently borrowing battery technology from the automotive sector and LiB represent the bulk of commissioned utility-scale ESS [33,34,p. 13]. As aviation,[9] marine and ESS applications grow in significance, we can anticipate these sectors may develop battery solutions that approach their preferences more closely [33]. In the ESS market, for example, non-lithium storage technologies (e.g. sodium-ion (Na-ion) batteries) may become cost-effective long-term solutions as sodium is a more abundant element (and associated with lower supply risk), and sodium-ion batteries have greater duration and less stringent density and weight constraints, as well as lower environmental impact [37,38,39]. Second-use automotive batteries might also find applications in the ESS market. Indeed, a growing area of competition among battery producers is to expand their share of the growing ESS market, as this sector is ultimately seen to have a larger market potential than the automotive sector [40].

To date, then, it is the automotive sector that has driven technological trajectories in LiB. Automotive performance requirements have steered LiB chemistries towards improvements in (i) energy density (related to runtime between charges); (ii) specific power (the ability to deliver high current); (iii) fast-charge capabilities; (iv) cost; and (v) safety. Optimising battery design and cathode chemistry for energy density in this sector improves the range of drive; while optimising for

[9] Top LiB have a specific energy of about 250 watt-hours per kilogram. For an airliner the size of a Boeing 737 to compete on routes exceeding 1000 km, a specific energy of 800 watt-hours per kilogram would be needed [35], highlighting the limitation of all-electric aircraft for long-distance routes such as London to New York (5500 km). However, electric planes designed from scratch using today's battery technology could achieve a range of about 800 km, a distance that accounts for 45% of flights [36].

power density improves the possibility of fast charging [42].[10] A significant trajectory within NMC technology has been towards increasing the nickel content relative to manganese and cobalt, as it reduces reliance on cobalt (associated with cost, supply risk and ESG issues) and improves energy density. The evolution towards increasingly 'nickel-rich' cathodes, from NCM 111 to NCM 811, over the past five years or so has effectively tripled energy density on a volume basis. It is also accompanied by a transition in input precursor material, from lithium carbonate (a base lithium compound) to lithium hydroxide (a lithium performance compound) [43].[11]

2.2. Geographies of cell and battery manufacturing

Battery production takes place in large-scale facilities ('gigafactories') in which individual cells are fabricated, combined into battery modules and (sometimes) assembled as packs for a particular end user [44]. A single battery for a Tesla Model Y, for example, comprises 4416 cells, and a single production line can produce around 7 million cells per month [45].[12] Global deployment of battery gigafactories has grown rapidly, from 3 factories (with a total capacity of around 60 GWh) in 2015 to around 150 factories (with a total capacity of 1000 GWh) at the end of 2021. The 'pipeline' to 2030 (i.e. plants currently producing, under-construction or planned) now runs to over 280 with a combined capacity of around 6000 GWh. [46,222]. Gigafactory growth is currently driven by automotive demand, with China and Europe expected to be the largest contributors where battery demand is linked to decarbonisation of road transport [47]. In Europe, for example, at least 11 countries have proposed bans on the sale of new vehicles powered by internal combustion engines between 2030 and 2035. Battery weight, and their high cost as a proportion of total vehicle manufacturing costs (particularly in the context of 'rules of origin' in international trade that specify a certain proportion of local content by value), means there is a significant pull towards market location in battery production [48]. As a result, EV manufacturing by automotive OEMs in Europe, China, Japan and the US is now a key driver of the geography of new battery manufacturing capacity. Table 1 shows how battery production capacity is concentrated in Japan, Korea and China [49]. China alone represented around 77% of global battery production capacity in 2021 [47], part of a national strategy to control the mid-stream sector of the supply chain (BMI 2021). In China, CATL has emerged as significant player with around a quarter of global market share [45].

'National' figures on battery production capacity, however, obscure cross-border investment: China's position in battery production capacity includes facilities owned by Japanese (e.g. Panasonic, in Dalian) and South Korean (e.g. LG Chem Energy Solution (LG) in Nanjing) firms in China, particularly after China relaxed rules on foreign owned battery producers supplying the domestic EV market in 2019 [50].[13] South Korea (5% of global production) and Japan (4% of global production) are home to several lead firms in the battery sector [34], such as LG (22% market share), Panasonic (19% market share), Toshiba, SK Innovation (SKI), or Samsung SDI (Samsung). These firms have made significant cross-border investments in cell manufacturing capacity closely tied to automotive production, including large plants in the US (e.g. Panasonic with Telsa in Nevada; LG with GM in Michigan and Ohio) and Europe (e.g. Panasonic in Belgium and Poland; Samsung in Hungary; and LG in Poland and Germany). US battery production represents around 8% of global manufacturing capacity, although this figure reflects inward investment by Japanese and South Korean firms into the US market. In Europe, prior to expansion plans of emerging battery producers, the only major EV battery manufacturers were Saft and Varta, neither of which had expanded beyond relatively niche production [51]. European battery production capacity is expected to increase 13-fold between 2020 and 2025 (from 28 to 368 GWh) and anticipated to outstrip China as the largest EV market, with battery production growing from 6% to around 22% of global supply (and reducing China to 65% of global production) [47].[14] Just six cell suppliers globally (LG, CATL, Panasonic, Samsung, BYD and SKI) were collectively responsible for more than 89% of all battery capacity and battery metals deployed globally in passenger EVs in 2020. Tesla deployed 22.5 GWh of battery capacity in the second half of 2020,[15] almost as much as its five closest competitors combined (BYD, VW, Renault, Hyundai and Mercedes) [52].

2.3. Supplying gigafactories: geographies of electrode production, material refining and material supply

The assembly process of cell and battery production requires a reliable flow of anodes, cathodes, separators and electrolytes. Many of these materials are themselves products of advanced manufacturing processes, and their production is often organisationally and geographically separate from cell production. Ultimately, then, battery production relies on access to a range of mineral elements and compounds that, currently, are mainly mineral-based materials extracted from the earth rather than recovered via recycling. Most material demand by value in a battery relates to the cathode [55]. Here the primary elements of interest are lithium, nickel, cobalt and manganese, although aluminium, iron, phosphate, sodium and sulphur are also relevant depending on battery chemistry. Decisions about cathode chemistry, derived from desired performance characteristics, are a key determinant of battery production's mineral demand. Graphite, copper, silicon and lithium are used in anode production, while electrolytes consist of lithium, phosphorus, fluorine and solvents [30,48].

Two 'midstream geographies' sit between cell production and the geographies of resource extraction that supply mineral raw materials (see Table 2). The first is the *geography of electrode production* which, if not integrated with the gigafactory, occurs in a separate plant such as those manufacturing cathode active materials operated by Sumitomo, BASF, Johnson Matthey, or Umicore. Electrode production combines refined mineral-based materials into an intermediary form so they can subsequently be integrated into a battery cell. It includes cathode and anode powder production, electrolyte mixing, separator production, binder and conductive additive production, and electrode and cell manufacturing [48].[16] There are advantages to co-locating electrode production with cell manufacture, so this is "the first step in the process where market pull begins to significantly favor co-location with the end-product" [48, p. 94].

[10] Batteries have limited lifetimes and how they are handled at their end-of-life influences the overall environmental footprint of the mineral-based materials they contain, i.e. the extent to which batteries may perform as 'greener', 'low-carbon' technologies. Section 3 points to detailed research on and for end-of-life options.

[11] Illustrated, for example, by NCM 622 chemistry where lithium carbonate is replaced by lithium hydroxide as the input material for cathode manufacturing [43].

[12] The example is of LG's new facility in China, where there are 17 lines enabling the factory to cater for 323,000 cars per year [45].

[13] These rules had required inward investors to establish JV's with Chinese firms (see Section 4), a form of 'obligated embeddedeness' ([166] in [161]),

[14] A recent acceleration of investment in investment in Europe means the projected figure for 2025 is likely to be higher. As of April 2022, 27 plants (with a combined capacity of 789 GWh) were planned for 2030 [223]

[15] This figure is driven by sales of the Model 3, the battery for which has substantially higher capacity than the average of the global EV fleet (55–75 kWh vs. 50 kWh) [52].

[16] A slurry is created for the electrode (by mixing active material components in a solvent with a conductive additive and a polymeric binder). This mixture is known as 'ink', i.e. an anode ink or a cathode ink (and is the anode or cathode active material) and is then 'coated' onto the current collector foil (Cu current collector foil for the anode or Al current collector foil for the cathode) [37,56]. For a details on LiB manufacturing, and energy uses of each phase, see e.g. [57].

Two illustrations of this co-location 'pull' in Europe are Northvolt's industrial project development in Skellefteå, Sweden, which includes plans for in-house electrode production, and Freyr in Vaasa, Finland where Johnson Matthey announced plans to co-locate with Umicore.[17]

The second midstream geography – going further upstream towards raw material supply – concerns the *geographies of material refining and precursor manufacturing* prior to electrode fabrication and cell assembly.[18] This material processing step is very significant because "the material purity required in batteries is high, as impurities can drastically impact the life and safety of the end product" [48, p. 93]. It creates the precursor materials used in electrode and electrolyte manufacturing, such as lithium carbonate or lithium hydroxide or 'battery grade' nickel (such as that produced by Huayou or CNGR).[19] The location of midstream material processing is illustrated in Table 3. China has developed a leading position in this sector – extending across the key minerals of lithium, nickel and cobalt – despite having a relatively limited geologic endowment [48]. This is evident in cobalt, where China's degree of control is around 80% as a consequence of refining in China and equity stakes in overseas refining [30].[20] Processing and purification are weight loss/value adding steps and, in the case of lithium, there is a move towards locating this step closer to the source of extraction, assisted by national policies (e.g. in Chile, Australia and Argentina) to capture greater value from downstream processing prior to export [61].

Finally, *the upstream geography of raw material supply* is to-date largely based on primary extraction rather than recycling, with these mined mineral raw materials originating from diverse geographies. Lithium is extracted via hard-rock mining of minerals like spodumene or lepidolite from which lithium is separated out, such as in Australia or the US; and by pumping and processing underground brines, such as in the 'Lithium Triangle' of Chile, Argentina and Bolivia.[21] Battery demand, and the performance characteristics of the automotive sector, are driving a series of 'resource booms' for lithium centred on a small number of extractive sites.[22] Until very recently, much of the world's global lithium production originated from six hard-rock mines in Australia, four brine operations in the 'Lithium Triangle'[23] and two operations in China; similarly, lithium extraction and processing to lithium carbonate and lithium hydroxide was the domain of only a handful of mining firms (see Table 3), as was the subsequent refining of lithium hydroxide. Recently, more firms are entering the extraction and refining of lithium to battery grade lithium hydroxide (e.g. JV of Pilbara Minerals with POSCO).

Nickel is mined from occurrences in Indonesia, the Philippines, Russia, New Caledonia and Australia; manganese in China, South Africa, US, Gabon and Côte d'Ivoire; and cobalt in the DRC, Russia, Australia, and New Caledonia [74,75]. In cobalt, artisanal and small-scale mining (ASM) are also important contributors to mineral supply [76]. Table 3 shows the concentration of mined production for four key mineral raw materials which reflect current NMC battery chemistry. There is a high degree of geographical concentration in mining: except for nickel, over 50% of production for each of these mineral raw materials comes from two countries and over two thirds of cobalt are sourced from the DRC. These geographies are dynamic: Indonesia is set to become even more significant in the supply of 'battery grade' nickel while investment in Australian cobalt production is anticipated to diversify access to the metal.[24] Mining and concentrating (of ores) and refining (into battery grade mineral-based products) may be geographically dispersed, but these processes are often organisationally integrated. Table 3 illustrates several companies are active across mining, concentrating and refining. As measured by end use in the EV sector, Tesla is the leading deployer of nickel, cobalt and lithium: the company accounted for 12,100 tons of lithium in the second half of 2020, significantly above VW (3600 tons), BYD and Renault; 13,800 tons of nickel (followed by Toyota, VW and Renault); and 1300 tons of cobalt (followed by VW and Mercedes with 900 tons each). By battery supplier, LG is the leading user of lithium, with a 31% market share (followed by CATL and Panasonic); Panasonic leads the use of nickel in the supply chain, with a 35% market share; LG is the leading user of cobalt, with 33% of market share (followed by CATL and Panasonic) [52].

In this section we have shown how battery manufacturing is a classic 'global' assembly process that is organisationally and geographically distributed. A range of different material transformations and suppliers need to be co-ordinated for battery production to occur. Significantly, these techno-material steps are not all integrated within the structure of a single firm but involve co-ordination among a range of actors. The different stages of production are connected materially by physical trade of materials and components, and financially by cross-border and cross-sectoral investment flows. This produces a complex geography that is not reducible to international material flows or the national location of production.

3. From mineral supply chain to global battery production network

This section reviews academic and grey literature on LiB production, noting how much of this work adopts a supply chain approach. It then introduces the Global Production Network (GPN) approach as an alternative perspective. We exclude an extensive technical literature other than key pieces that shed light on organisational and geographical characteristics of global battery production.

3.1. Battery mineral supply chains

A large literature on battery mineral supply chains traces sequential processes of material transformation and trade associated with battery production. A primary focus of this work are the 'upstream' implications of battery manufacturing for supply and demand dynamics in mineral raw materials (see for example [3,4,5]). Research includes (dynamic) material flow analyses ([78,79,80,81]), analyses of trade structures ([21,82,83–85]), supply risk [86] and mineral life cycles, including the battery R&D life cycle [87]. Supply chain analyses of the battery sector highlight the direct, indirect and hidden material flows associated with

[17] Johnson Matthey subsequently announced plans to divest its battery materials business (Nov 2021).

[18] Various degrees of integration can be observed between these intermediary geographies (as we discuss in Sections 3 and 4): CNGR, for example, both produces 'battery grade' nickel and manufactures cathode materials; similarly, Sumitomo Metal Mining undertakes raw material extraction, mineral processing and cathode material manufacturing.

[19] 'Battery grade' is a measure of purity applied to precursor materials destined for battery production. In relation to nickel, 'battery grade' is a colloquial phrase rather than a strict market term, and refers to Class 1 (minimum of 99.8%) nickel content. The high purity battery market represents about 5% of total nickel demand (the bulk of nickel production enters the ferro-nickel market, used in alloying with steel), although this is expected to rise [43].

[20] "China is the primary global supplier of cobalt for batteries, despite having very limited reserves, through its aggressive investment in processing capacity coupled with foreign direct investment for ores and concentrates" [48, p. 94].

[21] Geothermal brines are also explored for lithium extraction, e.g. Vulcan Energy, Umicore [73].

[22] Batteries are the largest component of lithium demand, with this share expected to increase to around 95% of total lithium demand by 2030 [218]. We have placed 'Lithium Triangle' in quotation marks throughout to acknowledge how this phrase attributes particular values and meanings to place (as a site for extracting and supplying lithium to global markets) that are actively contested in the region, as it naturalises resource extraction and overwrites other (economic, environmental, cultural) values attributed to land and landscapes [224,225].

[23] Of these four brine operations, two are located in Chile and two in Argentina.

[24] High pressure acid leaching (HPAL) technology enables Indonesia to upgrade its Type 2 laterite nickel (used for the stainless-steel industry, to which Indonesia is a key supplier) to Type 1 nickel for batteries [77].

total material requirements of a global energy transition [88], and the dynamic interactions between renewable power generation, electricity grids and battery storage [89]. A technical literature on the evolution of battery technology supplements these material analyses, exploring state-of-the-art battery technologies, post-Li and non-LiBs, and technology development and R&D needs in the context of barriers for wider deployment [26]. Some of this work highlights research gaps around organisational and geographical aspects of the supply chain: research on battery patents, for example, notes a need for "a disaggregation of the GVC [Global Value Chain] and a deep knowledge of its various components and technologies" [90], and how its consequences for knowledge and innovation mean that "sectoral configuration…deserves more attention" [91–94].

A broader set of studies seek to contextualize upstream or downstream elements of the battery supply chain. Upstream, a growing body of work considers the contribution of battery mineral production to equitable forms of resource-based development. Cohen and Riofrancos [95], for example, consider the role of lithium extraction in relation to Latin America's Green (New) Deal, while several authors reflect on how battery mineral production reproduces 'colonial' relations of resource extraction that overlook indigenous knowledge [96–101]. Downstream, research focuses on demand arising from battery applications in electric mobility, especially EVs [102,103], and includes work on demand reduction strategies [104–106] and circular strategies to reduce raw material reliance. The latter includes design for reuse and recycling [107], circular business models and supporting policy [108–110], cascading secondary uses that extend batteries beyond end-of-life in their first use [111–115], and recycling [116–121].

Framed as a supply chain, research on battery production also engages with potential geopolitical issues arising from bottlenecks in supply and import dependence around 'critical' raw materials [59,113,122–126]. Some of this work is geological or geometallurgical in nature [127–128] while other studies consider environmental, climate and ethical implications of mineral supply chains [76,129] including accounts of public investment in battery (gigafactory) infrastructure [66], conflict minerals [130] and options for more responsible sourcing [131–133]. There are now several detailed empirical studies addressing information gaps in relation to responsible sourcing of mineral based materials [134–135], regional competitiveness [136], including studies which map the battery mineral supply chain, policy, lead actors and market volumes in national and international contexts (e.g. [34,48,137–140]).

Stepping back, the work we have briefly reviewed shows how decarbonisation, electrification and growing demand for energy storage will augment total material demand even while fossil fuel use may decline [1,2].[25] Mineral-based materials have a central role in emerging low-carbon supply chains [141–146]. Projections of sharp mineral material demand create security of supply concerns and provoke geopolitical competition for the control over parts of mineral supply chains [147–149]. China's dominant market share in refining mineral products - and the country's efforts to offset raw material supply risks by investing in overseas sources of supply (see [150]) have raised concern about resource availability. There are now policy initiatives in the US and the EU focussed explicitly on battery minerals alongside other materials for a low carbon energy transition, that aim to create alternative supply chains and establish technological advantage [151,48].

3.2. The geopolitical consequences of expanding battery production: the value of a GPN approach

The geopolitical consequences of expanding battery production extend beyond security of mineral supply to the rapid deployment of gigafactories, and the advancing electrification of the energy and mobility infrastructures to meet decarbonisation targets. Recent work on the geopolitics of energy system transformation acknowledges some of the broader geopolitical and geo-economic consequences of decarbonisation and how, as roles for renewable power generation and electrification increase, a new 'energy order' may emerge from the ubiquity, flow character and lower energy density of renewables relative to fossil fuels [147,141,152–154]. As we have seen, however, the 'supply side' focus in this work means that issues of physical material supply dominate and key organisational elements of demand and the role of end-use actors in restructuring supply chains are often overlooked. It is in this context that there have been recent calls for a 'whole systems' approach to understanding the geopolitics of energy system transformation [147]. A primary aim of a whole systems approach is to understand how the geopolitical consequences of energy transition extend beyond the comparatively narrow issue of mineral and material supply security (although important) and also include shifts in the geographies of innovation, manufacturing and demand.

Our deployment of a GPN approach in this paper aligns with this objective, as we think a different way is needed to understand the battery supply chain as a significant part of the geopolitical economy of energy transformation. While GPN has yet to be applied to the battery sector, it has been used in the context of upstream lithium extraction. Researchers examining the efforts of states in the 'Lithium Triangle' to develop a downstream industry [155,156] have found GPN's focus on extra-national relations useful for countering national-scale modes of analysis which 'push questions about the transnational organization of production into the background' [17]. Obaya et al. [157] adopt a GPN perspective to explore how lithium extraction in Argentina is embedded in a wider network of relations that are structured in ways that constrain state efforts to promote forward/downstream linkages. Bos and Forget's [158] analysis of lithium production in Bolivia captures the capacity of a GPN perspective for understanding the 'multi-scalar strategies and practices of forward and backward integration' in a production network, and the role of the state as an 'inter-scalar mediator' in this process. Their analysis considers the 'Lithium Triangle' as a 'global node' in a wider network, and highlights efforts by the Bolivian state to integrate its resources into this network via a strategy of majority state control in alliance with external (German, Chinese) partners. In sum, existing applications to battery minerals adopt GPN as a loose heuristic – a way of invoking the organisation and control of downstream production and its influence on extraction – but papers remain focused on regional/national challenges of harnessing lithium extraction for resource-based development. By contrast, we deploy a GPN approach to (1) consider the organisation of battery production from mineral extraction through to end-uses in mobile and stationary energy storage and differing firm strategies along this chain; (2) highlight the increasing intersection of battery manufacturing with the automotive and power sectors; and (3) identify the multiple roles of the state in shaping the geographies of battery production. By exploring these three features, our GPN analysis augments conventional supply chain accounts and demonstrates how the global battery production network acquires its organisationally and geographically dynamic character. With regard to the state, GPN research acknowledges the role of geopolitics in network formation [159–161]; considers how state action secures the conditions for accumulation around new technologies and

[25] Total material demand will rise in absolute terms, as new energy infrastructure will require more mineral-based materials in the economy. Relative material demand will vary by time and place: it is likely to rise significantly during construction in energy transition, but may then diminish as new ownership models and practices of material recovery take hold (e.g. new batteries may draw on higher levels of recycled rather than primary mined content, if recycling infrastructure is developed that enables high-quality recyclates [114]. As Krane and Idel [1, p.1] point out, "since renewable systems need no fuel, they depend on trade only for the acquisition of materials and components during construction. Once the system is operating, no trade [except for maintenance and expansion, *authors' addition*] is required to sustain it."

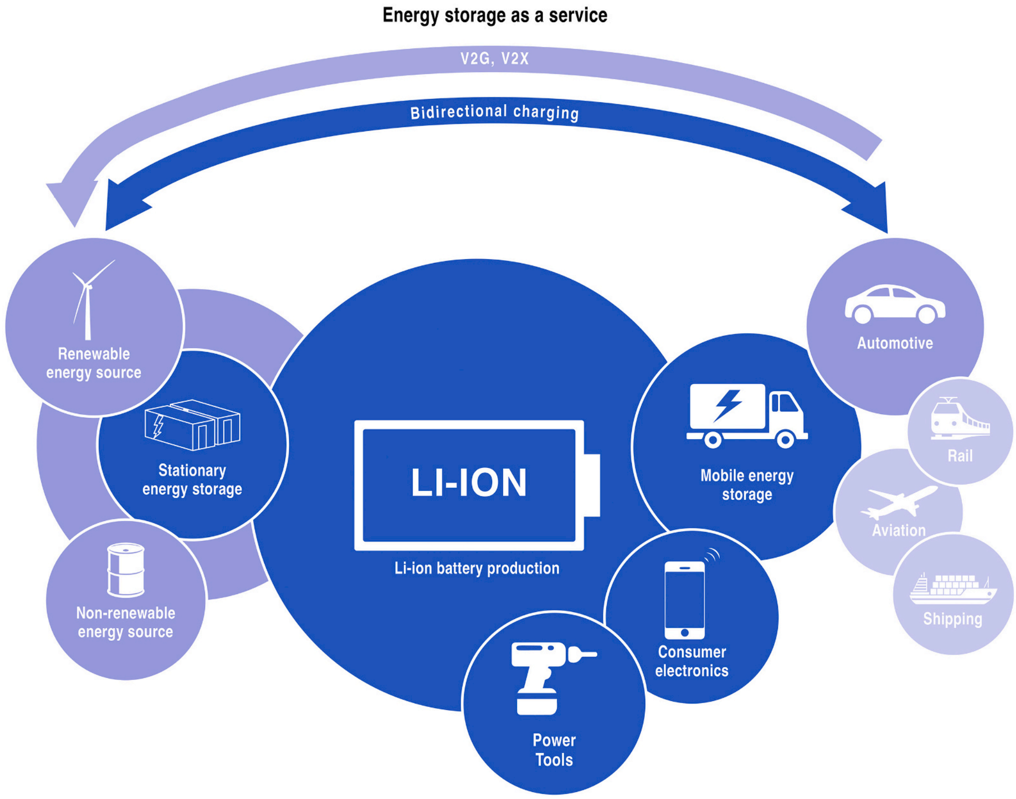


Fig. 1. The LiB Production Network: initially focused on consumer electronics and power tools, the network increasingly intersects with OEM manufacturing for mobile and stationary ESS.[27]
Source: authors, based on [203,213] for V2G, V2X, and bidirectional charging.

infrastructures[26]; and unpacks the state's multiple functions in constituting production networks to reveal roles as facilitator, regulator, producer, and buyer [162]. Such distinctions are particularly apposite in the context of the LiB production network which, as we show in Section 4, is strongly shaped by state action: to facilitate the growth of mobile and stationary energy storage markets (e.g. petrol and diesel engine phase outs, EV uptake); regulate investment and trade (e.g. local supply chain obligations for foreign investors, trade policy); and act as a buyer via, for example, public procurement of battery-driven public transport vehicles or strategic purchases of critical minerals.

4. The lithium-ion battery production network

Our goal in the remainder of the paper is to move beyond a supply chain approach focused on material transformation to consider battery production as a global production network i.e. an "organisational platform through which actors in different regional and national economies compete and co-operate for a greater share of value creation, transformation, and capture though geographically dispersed economic activity" [167, p. 29]. To that end, this section draws on interviews with key respondents to outline some core elements and structures in the battery production network, before highlighting contemporary dynamics shaping the network's evolution. By adopting a GPN approach, we aim to show three things. First, at a general level, we aim to show how the battery GPN is constituted by strategic actions of firms and states which create more or less durable relations among actors – it is out of these strategies and relations that the organisational and geographical form of the production network arises. Second, we distil several distinctive organisational structures within the overall production network, centred on contracts, direct investment and joint ventures among automakers, battery producers and mineral suppliers. Third, we show how the organisation – and geographies – of the battery production network are increasingly shaped by the way battery production intersects with two other production networks: automotive manufacturing (primarily EVs for road transport, but also rail, shipping and aviation); and fixed energy infrastructures for stationary ESS – in both domestic (powerwall) and public (grid-scale utility) domains – and in charging facilities for EVs (Fig. 1).

Our starting point is the production and assembly of cells and batteries in large 'gigafactories,' a primary focus of investment and state strategy.[28] Significantly, however, our interest in the gigafactory is not as a space of material assembly and material transformation but as a critical organisational nexus. We view the gigafactory as a configuration of firms (cell and battery manufacturers, end user vehicle manufacturers, specialist suppliers) shaped by relations of competition and cooperation, with its location and scale influenced by state strategy. We

[26] The significance of this work, particularly that adopting Jessop's 'strategic-relational approach' which views the state as an "institutional ensemble," is that it moves beyond thinking about state action as 'policy' and aspires instead, to understand policy frameworks "as the outcomes of struggles within the state at different spatial scales and between the institutions of the state and other social formations" [165, p. 298], drawing on [163–164]).

[27] Note: While the mobile energy storage focus of this paper is on the automotive sector, we also depict other mobile energy storage end-use markets in this figure to illustrate the possible extent of sectors serviced by battery production.

[28] 'Giga' simply refers to gigawatt hours – a measure of battery capacity – and signifies production at scale. Tesla led the way in capturing public imagination around gigafactory development, with announcements of factory development in the US, China and Europe.

unpack the production network in two stages: in the next section we focus on inter-firm relations, using the GPN concept of the 'lead firm' to highlight relations of competition and co-operation; we then consider the role of state strategies in targeting this organisational nexus and their influence on the geographies of the GPN.

4.1. Battery manufacturing: established and emerging producers, and the growing role of automotive OEMs as lead firms

Battery manufacturers in the LiB GPN can be categorized into two broad groups. The first group of firms comprises established battery producers – Panasonic, LG, SKI, Samsung, BYD, and CATL – who now serve as Tier 1 battery suppliers to automotive OEMs. In the case of Panasonic, LG, Samsung and CATL, LiB manufacturing developed initially through the lead position of these firms in consumer electronics, and over time it has become a specialised business division of these firms.[29] BYD's route, by contrast, is somewhat the reverse as its early development in the late 1990s focused on specialised rechargeable battery technology (to substitute Japanese imports), growing to supply half the world's mobile phone batteries. It has subsequently built on this specialist manufacturing expertise to develop a lead role in downstream transport applications of battery technology.

The second is a more diverse group of emerging battery producers (Table 4). This group consists of (i) joint ventures, into which automotive OEMs are entering with established battery producers, primarily through agreements around cell and battery development (and often as an evolution of previous agreements around battery assembly).[30] Examples include Toyota with Panasonic (Prime Planet Energy and Solutions), GM with LG (Ultium cells) and Ford with SKI (BlueOvalSK)[31]; (ii) current Tier-2 battery suppliers to the automotive OEMs (e.g. CALB and SVOLT) that have supply agreements with Tier-1 automotive suppliers such as Continental or Elring Klinger; and (iii) a 'start-up' group of industrial project developers such as Northvolt, Britishvolt, or Freyr developing new gigafactory production in advance of anticipated demand.

Across both these broad categories of battery manufacturers we find automakers increasingly acting as lead firms in battery production, with the investment strategies of automakers driving production location, battery chemistry and rate of production, and co-ordinating network organisation (Table 4). However, battery manufacturing lies outside the skill set of traditional auto-manufacturers, and many of their traditional strategies for controlling outsourced production in the context of ICE vehicles – dual sourcing, cost competition, etc. – are less effective when it comes to EVs, as the battery accounts for a much larger proportion of the total cost of an EV vehicle than the engine in an ICE vehicle, and carries more risk for transport (battery materials are legislated as hazardous, and significant value is locked-up while in transit). The expansion of battery production to meet EV demand, therefore, is associated with organisational and geographical innovation as automakers seek to gain access to battery technology. In this section we discuss how organisational ties between automotive OEMs and battery producers are a key structure in the current LiB production network and an influence on its geographies. The broader point here is that these core structures make the contemporary LiB production network different to one centred on portable electronics or, in the future, one anchored by production for marine, aviation or stationary ESS markets.

The centrality of automakers to battery demand is reflected in the intersection and growing integration of these two different networks. Organisationally this is taking several different forms (Table 4), including *long term contracts* between automotive OEMs and battery cell producers to secure access to battery cells; *direct investment* by automanufacturers in battery production without a joint venture partner; and *joint ventures* based on shared investment by automotive OEMs and battery cell producers to pool and manage risk. We briefly review examples of each of these organisational relations by reference to specific firms and their partnerships starting with (1) long-term contracts and direct investment by OEMs in battery production, and then (2) joint ventures.

4.1.1. Long-term contracts and direct investment by OEMs in battery production

OEMs use long-term contracts and off-take agreements to secure battery supply (Table 4, column 2). The Renault group, for example, has a long-term contract for the supply of batteries with LG, but has also concluded a partnership agreement with Envision-AESC to co-locate a battery plant with automotive production at Renault's French production hub, and a memorandum of understanding with French battery specialist Verkor which may have the potential to phase-out LG supplies over time [170]. Leading automotive OEMs are increasingly concluding direct offtake agreements with battery mineral producers, rather than relying on battery manufacturers to source these materials. Tesla, for example, has agreements with Piedmont Lithium for lithium from spodumene, with BHP for nickel sulphate [175], and with Glencore for cobalt from the DRC. Similarly, BMW has direct agreements with Glencore and with the Moroccan mining company Managem for cobalt, as well as sourcing for its cell suppliers CATL and Samsung SDI.

More recently, OEMs have supplemented these supply agreements by making direct investments in new battery manufacturing start-ups with the potential to become large-scale future suppliers (Table 4). VW, for example, buys cells from LG, SKI and CATL on long-term contracts but has also acquired a 20% stake in the Swedish battery developer Northvolt and in the US solid-state battery (SSB) specialist QuantumScape where it is the largest shareholder (both Northvolt and QuantumScape anticipate production from 2023).[32] The mechanism for direct investment varies, but includes initial investment at the start-up phase (e.g. Series A and B funding) with OEMs increasing their shareholding as start-ups seek public listing. This strategy enables OEMs to manage technological risk while allowing various pathways for IP development. An example of early phase collaboration (i.e. prior to substantial direct investment) is the relationship of Stellantis and UK solid-state battery technology start-up Ilika Plc, which sees the former (via its industrial automation arm, Comau) involved in designing and scaling up Ilika's production line.

Northvolt is one of several new industrial project developers with gigafactory plans to have concluded substantial contracts from, and investment by, automotive OEMs (Table 5). These projects emerge with the support of public-private funding, such as that promoted by the European Battery Alliance in which EU member state budgets are channelled towards Important Projects of Common European Interest (IPCEI). This internationalisation of state capital highlights the growing role of the 'EU macro-regional state' in shaping the battery production network, and how its role extends from facilitator and regulator to financing support for new production. A characteristic of the new industrial project developers is their adoption of a regionalised vision of battery production within a particular geographic context, taking

[29] In the case of CATL, a specialist spin-out from TDK.

[30] Tesla has evolved its OEM investment in battery production to bring some battery production in-house, see Section 4.

[31] Other examples are BMW with CATL and BYD with Toyota, or partnerships, e.g. Envision-AESC with Renault.

[32] QuantumScape (where VW is the main investor) and Solid Power (where Ford is the main investor) offer competing ASSB electrolyte material pathways based on oxide and sulphide respectively (see [176, p. 20]; [177]).

Table 4
Illustrative key tie-ups between automotive OEMs and battery makers.

OEM	Battery supplier (*future* supply in italics)[a]	Joint venture (JV) or partnership		In-house: automotive OEM	
		w/tier-1 or tier-2 battery producers	w/start-up; ind. project developer[b]	Cell production	Battery assembly
Toyota	CATL	JV w/Panasonic and w/BYD Partnership w/ CATL	n/a		
Tesla	LG, CATL, BYD	JV w/Panasonic (US)	n/a	Tesla (US, CN, DE)[c]	
BYD	own supply	JV w/Toyota and w/ Ford	n/a	BYD	BYD
BAIC Group	SKI	Partnership w/Ningde Times	n/a		
Geely (Volvo)	Samsung (Volvo)	JV w/ CATL; Partnership w/LG	n/a		
SAIC Group (MG; Zhiji)	CATL	Partnership w/CATL, Alibaba, Zhangjiang Gr.	n/a		
GM	LG	JV w/SAIC; w/LG; JV w/Nikola (trucks)	n/a		GM
Ford	Samsung, BYD	JV w/SKI 'Bue OvalSK'	Solid Power		
BMW	CATL, LG, Samsung, *Northvolt 1*	JV w/CATL	JV w/ *Northvolt 1*; Solid Power		BMW plants in DE,US, TH[d]
VW (including Scania)	Samsung, LG, CATL, SKI, *Northvolt 1*	JV w/Gotion High-Tech[e]; Supply in CN: JV w/ FAW, SAIC, VW Anhui (JAG), JAC	JV w/ *Northvolt1*[f]; QantumScape	*Northvolt 2* w/ Gotion High-Tech	*Northvolt 2* (first a JV, then VW acquired)
Daimler (Mercedes-Benz [MB])	LG, SKI; Farasis Energy	Partnering w/CATL; Li-Tec Battery, Accumotive (acquired from JV w/Evonik), ACC	n/a	MB in DE, CN, TH, US, PL[g]	Daimler
Renault Nissan Mitsubishi	LG (Renault Group [RG])	JV w/Envision-AESC (Nissan; RG)	*Verkor (RG)*	w/Envision-AESC in FR,UK[h]	
Tata JLR	(BYD?)		n/a		
Hyundai Motor (Kia)	SKI	Negotiating JV w/ LG and POSCO	n/a		Hyundai
Stellantis[i]	Samsung	JV Opel–Stellantis; SAFT-Total and PSA	ilika		

[a] Tier-1 suppliers to automotive OEMs (e.g. Elring Klinger, Continental) also source batteries.
[b] We define a partnership with an industrial project developer as one where an OEM invests in equity raising.
[c] This entry refers to Tesla's gigafactories in Buffalo, NY; Shanghai and Berlin-Grünheide.
[d] This refers to Dingolfing (DE), Spartanburg (US), Chonburi for Rayong (TH), see also Fig. 2 in [14].
[e] The 26% share in Gotion High-Tech, a first for an automotive OEM to invest in a battery supplier in China.
[f] With 20% ownership in Northvolt, VW also has a seat on the battery cell technology Board of Directors.
[g] MB plants in Kamenz, Stuttgart-Untertürkheim, Sindelfingen, Beijing, Bangkok, Tuscaloosa and Jawor.
[h] The Envision-AESC plants will be at Douai (France) and in Sunderland (UK) at Renault Group and Nissan sites.
[i] Stellantis (a 50–50 merger: Fiat-Chrysler (FCA) and PSA, 2021) exemplifies Tier-2 supplier sourcing i.e. SVOLT.
Sources: Company websites; [168–174].

Table 5
Industrial project developers with gigafactory plans.[a]

Industrial project developer with gigafactory plans		Links with battery start-up
Northvolt (HQ: Stockholm)	Sweden (Skellefteå, Västerås); Poland (Gdansk); Germany (Salzgitter); California with Cuberg	Acquisition of US start-up Cuberg for battery cell technology
Britishvolt (HQ: Northumberland)	UK (Cambois close to Blyth, Northumberland)	Potentially Ilika, with APC funding to design UKBIC pilot production; Glencore as strategic investor
Freyr (HQ: Luxembourg)	Norway (Mo i Rana), Finland (Vaasa)	24 M for production technology
Verkor (HQ: Grenoble)	France	Renault Group

[a] Betz, Degreif and Dolega ([134, p. 32] provide a more comprehensive list of announced project plans, and [66] outline geographies of planned battery production.

advantage of 'green' electricity supply – i.e. from hydropower.[33] Northvolt, for example, announced in 2017 it would "develop the world's greenest battery cell and establish a European supply of batteries to enable the future of energy" while Freyr aims to establish a 'Baltic Battery Belt' covering Norway and Finland.[34] A common factor across these projects is their access to innovative battery technology for commercialization, either via licensing (e.g. Freyr and 24 M's solvent and binder-free processing technology) or acquisition (e.g. Northvolt and Cuberg's NMC cathode, lithium-metal anode and non-flammable liquid electrolyte cell technology) (see also [180]). They also offer a product portfolio featuring multiple cell formats (e.g. pouch, cylindrical and prismatic) and targeting a range of OEM manufacturers within and beyond EVs, including heavy duty mining and construction, aviation (see Northvolt, Freyr) and ESS. These product-service portfolios allow for several different governance structures to evolve in anticipation of future JVs with multiple automotive OEMs around the development of battery chemistry (e.g. Northvolt, VW and Volvo), and contract manufacturing for customers in consumer electronics and ESS (e.g. Northvolt and Lingonberry cylindrical cells and prismatic battery modules).

4.1.2. *Joint ventures: Toyota and Tesla with Panasonic*

Panasonic was a commercial pioneer of LiB technology in portable electronics and an early entrant to the EV market: a 1996 agreement saw the company supply lithium-ion and nickel-metal hydride batteries to Toyota, including the company's flagship Prius [181]. Panasonic invested in Tesla when it went public in 2010, and the two companies entered into a US$ 5 billion gigafactory joint venture in 2014 to manufacture and supply NCA cells [182,183]. As the battery market has developed, Tesla has harnessed cooperation with Panasonic to enter the ESS market, initially via sales of its Powerpack (grid) and Powerwall

[33] The Global Battery Alliance (GBA) and the European Battery Alliance were initiated at the 2017 World Economic Forum, in the context of security of supply concerns) [178,179]. Both organisations seek to ensure sufficient supply of mineral raw materials for the battery GPN, and their local/regional deployment.
[34] Using Vaasa in Finland, a site originally scouted by Northvolt.

(home) energy storage units (from 2015) and, more recently, via power generation. For example, Tesla has deployed its battery and solar systems[35] in Hawaii, where the Kauai Island Utility Cooperative (KIUC) uses the Tesla Powerpack system (manufactured in the Panasonic-Tesla gigafactory in Nevada) and buys solar-generated power from Tesla on a 20 year contract.[36] Acting increasingly like a battery manufacturer, Tesla has scaled up its battery sales and installed grid-scale ESS systems in Puerto Rico, California, Texas[37] and Australia where, in collaboration with a French renewable power company (Neoen), Tesla constructed the 100 MW Hornsdale Power Reserve (South Australia) and the 300 MW Victorian Big Battery at Moorabool [184]. As Tesla has harnessed its manufacturing joint venture with Panasonic to enter the energy storage market, so Panasonic has sought to reduce its dependence on Tesla as customer and diversify to other car manufacturers [185]. For example, Panasonic is now exploring options for a Gigafactory development in Europe with Equinor and with Norsk Hydro.[38]

4.2. The Role of (Macro-Regional) States: regionalising battery production networks

In this section we outline the role of national and regional governments in the global LiB production network. We show how state actions – facilitated by the Green (New) Deal (US and EU) and net zero policies – underpin the growth of battery markets and, in some instances, seek to regionalise battery production networks. We explore these processes via brief illustrative moments from three distinct policy areas: (1) climate, (2) mineral occurrences and ownership of mineral reserves, and (3) provision of incentivizing infrastructures. We also comment on the role of trade policy in shaping the battery production network (see (2) below).

4.2.1. States as facilitators and regulators - climate policy

Significant portions of the energy storage market are ‘political markets’ in the sense that supranational institutions have designed climate scenarios [186–190], and state and local governments have implemented decarbonisation policies - acting as facilitator and regulator - that create a demand for mobile and, to a lesser extent, stationary energy storage. Examples include consumer subsidies for electric vehicles; national mandates for energy storage capacity per unit of renewable electricity generated; national and state targets for EV sales and tailpipe emission reduction, and municipal targets for carbon-neutrality. California‘s Zero Emission Vehicle (ZEV) mandate has provided a point of departure for China's New Energy Vehicle (NEV) policy, which replaces large price subsidies with mandates on car manufacturers ([191,192]).[39] The NEV policy in China complements the recent relaxation of a regulation that required foreign firms enter into a JV with a local firm for battery production in China (see VW and FAW, SAIC[40]) and a policy prioritization of battery swapping ([193,194]).[41] In the EU, alliances such as the European Battery Alliance facilitate state intervention in industrial policy in the context of decarbonisation, together with two European IPCEIs that allow state aid to be directed to participating firms e.g. funding for Umicore, LGES and Northvolt (see also [66]).[42]

Table 6
Illustrative government initiatives around lithium, and nickel.

Lithium		Nickel	
Australia[a]	‘Lithium Valley’: Kwinana industrial zone for LiOH refining; Kemerton Strategic Industrial Area, WA	Finland	‘GigaVaasa’: Battery mineral refineries (FMG, Terrafame, Freeport Cobalt, Keliber, BASF, Nornickel, Northvolt)
Chile	Production Development Corporation (Corfo) attempt to attract POSCO for LiOH production[b]	Indonesia	Indonesia Morowali Industrial Park; increasing mine state-ownership; raw nickel export ban; LiB production agreements with CATL and LG; supporting Hyundai in EV production
Germany	BGR, GZI, VW, Daimler, BASF, Fairphone partnership for Atacama		

[a] In 2020, the Australian federal government released the first Low Emission Technology Statement.
[b] The large lithium producer Albemarle was urged by the government's economic development agency (Corfo) to offer discounted prices for basic lithium compounds, in an effort to attract downstream investment e.g. the bid won by the Samsung-POSCO consortium with China's Sichuan Fulin Industrial Group and Chile's Molymet.

4.2.2. States as facilitators, regulators and producers - mineral occurrence and ownership

States are also adapting regulation around mineral occurrences and ownership of mineral reserves to regionalize battery production and precursor battery materials (Table 6). Indonesia, for example, banned nickel ore exports in early 2020, and acquired shares in mineral-material production with the long-term aim of EV production.[43] A consortium of four state-owned firms - the Indonesia Battery Corporation (IBC) – has been established to guide co-operation between battery developers and investors, following LG’s announcement of developing an integrated battery industry in Indonesia.[44] IBC will invest in nickel mines, smelters, and associated upstream industries, and act as a major (51%) shareholder in the upstream EV battery sector. In a similar way Finland is building on its existing mining industry (Terrafame, Keliber) as both the largest nickel producer in the EU and the only EU member state with industrial scale cobalt production [197]. Government initiatives have also been unfolding around lithium occurrences (e.g. in Chile and Western Australia) - as states seek to generate additional value from mineral processing and other downstream activities (Table 6). The Biden Administration’s use of the US Defense Production Act to support domestic production and processing of the minerals and materials used for large capacity batteries – including lithium, graphite, cobalt, manganese and nickel - is further evidence of how states are using a range of governmental powers to promote domestic upstream activity and shorten battery supply chains.

[35] In 2016, Tesla acquired the solar-panel installer SolarCity.
[36] On Ta‘u (American Samoa), Tesla runs a microgrid of about 5000 solar panels and 60 Tesla power packs.
[37] In California, these include a 20 MW battery at Edison's Mira Loma substation east of Los Angeles, and construction with PG&E Corporation of a 180 MW system in the San Francisco Bay Area. In Texas, Tesla has installed a 100 MW battery at Arlington for about 20,000 households.
[38] The latter has occurred in parallel with Tesla engaging in alternative sourcing via LG and CATL.
[39] NEV had two phases: phase 1 (2017) and phase 2 (2020). In phase 2, new affiliations were made eligible for credit transfer e.g. SAIC-VW and FAW-VW in each of which VW (as the foreign OEM) holds 25% share ownership.
[40] Other JVs are SKI with BESK; BYD with Toyota; BYD batteries to Ford's JV with Changan Automobiles.
[41] Battery swapping reserves ownership of the battery to the manufacturer, while renting the battery to the EV owner.
[42] The UK government agreed to fund some of the development of Britishvolt [195].
[43] See Indonesian state-owned Antam, which acquired stakes from the local unit of Brazilian miner Vale and from Japanese Sumitomo Metal Mining, to control close to 30% of Indonesia's nickel reserves.
[44] The four SOEs include oil and gas giant Pertamina, state-owned electricity company Perusahaan Listrik Negara PLN, mining holding company MIND ID, and nickel and gold miner PT Aneka Tambang ‘ANTAM’ (Indonesia, 2021), each owning 25% in shares. LG announced a USD 9.8 billion investment commitment to develop a battery industry. CATL has intentions to invest [196].

4.2.3. States as facilitators, regulators and buyers - provisioning of incentivizing infrastructures

States have sought to regionalize battery production through a range of mechanisms with infrastructure provision playing a key role. For the Tesla-Panasonic joint venture, for example, Nevada provided tax exemptions and reduced energy costs along with highway development. Since 2017, the city of Vaasa in Finland has been developing an energy cluster anchored around battery manufacturing – GigaVaasa – by attracting companies, such as ABB, Hitachi ABB Power Grids, Wärtsilä, Danfoss and Yaskawa, which utilise energy storage in their products. Infrastructure planning for the cluster includes transport provision, allocating city land to Freyr, and using battery factory waste heat for district heating [197]. In addition to competitive positioning as battery production zones, 25 cities are now 'EV capitals' with over 50,000 passenger EV registrations.[45] This means over 10% of the global EV fleet (approx. 10 million vehicles) is concentrated in just 25 city-regions, and explains why battery development has prioritized cost and faster charging for suburban cars, while extending drive range for family and premium models [199–201]. Also, states and municipalities are reviewing public transport infrastructure for electrification, with the state in some instances becoming a 'buyer' of electric buses. The EU Clean Vehicles Directive, for example, requires more than 20% of newly registered buses to be emission-free in 2025 and more than 30% in 2030,[46] and in Australia the government of Victoria has begun testing e-buses [202]. States have invested in research infrastructure in a bid to attract gigafactory development (and other precursor-material production). Examples include the UK Faraday Battery Challenge, the Australian government's support for the Future Battery Industries Cooperative Research Centre; Japan's creation of a Lithium-Ion Battery Technology and Evaluation Centre; and the Japanese Rising I and II, US Battery500 and EU Battery 2030+ research initiatives. Other state efforts to capture investment in battery production have centred on EV charging standards and related infrastructure development, such as the Japanese-Chinese alliance (Japanese CHAdeMO, Chinese ChaoJi) for bidirectional charging which enables 'vehicle-to-grid' (V2G) or 'vehicle-to-anything' (V2X) applications.[47]

4.3. Emerging dynamics in the battery production network

In this penultimate section we consider three emergent dynamics in the global battery production network with significance for its future organisation and geographies: (1) vertical integration; (2) regulatory development in key areas of policy concern; and (3) emerging business models in relation to mobile and energy storage. We highlight competitive dynamics around mobile and stationary energy storage that see automotive OEMs increasingly integrating with battery production, manufacturing both for electric mobility and ESS at grid, commercial and domestic scale (Fig. 2).

4.3.1. Vertical integration

Across the LiB production network there is growing evidence of vertical integration, as lead firms extend control over formerly separate components of the manufacturing process. Integration can occur either directly by bringing activities 'in-house' through acquisition, or via offtake agreements that commit downstream buyers to purchase a substantial portion of an upstream producer's output. Gigafactories are the epicentre of this process that includes both backward (upstream) and forward (downstream) integration (represented in Fig. 2 by dynamics 1a, 1b, 1c and 1d). Several lead firms based in Asia have long-standing vertically integrated supply chains, and some producers in North America and Europe are seeking to develop similar structures [204]. Northvolt, for example, has in-house production plans that range upstream to active material production (including some prior metal chemical production) and downstream to recycling, while Verkor's in-house production plans extend upstream to electrode and cell assembly.

Vertical integration allows lead firms to manage physical supply risks and commodity price volatility, reduce costs (thus freeing up cash) and optimise gigafactory assets by developing a suite of products. It is a strategic response to double-digit growth in demand and uncertainties around raw material supply – notably since price spikes for battery minerals in 2015 - a period characterised as one of "market immaturity for lithium-based minerals" [205, p.4]. There are also signs that a sharp rise in lithium carbonate prices in 2021, and the growing "raw material disconnect" between battery demand and mineral mining and processing capacity, are driving a similar response from end users of battery minerals as they look to reduce exposure to price risk, taking strategic positions upstream in processing plants and mines [219,221].[48] The most developed example of vertical integration is BYD (Table 4), which not only manufactures a diverse range of electric cars, buses, trucks and energy storage solutions but also makes their most valuable components (battery cells and transistors) and owns upstream material extraction and refining [206]. Tesla is adopting elements of this strategy, having announced plans to manufacture cells (currently sourced from Panasonic, LG and CATL and assembled by Tesla into batteries) and develop its own lithium mine in Nevada (Verpraet 2020). Developing a product portfolio enables customization of battery production for different customers, while also creating opportunities for downstream integration (see Tesla in relation to electricity generation via its ESS products, for example). Vertical integration is frequently associated with logistical efforts to shorten supply lines, involving the co-location of anode, cathode, cell and battery production close to automotive OEM hubs.

A similar process of vertical integration is also occurring in midstream material processing, with several mergers between miners and refiners of battery-grade lithium, nickel, cobalt and manganese. For refiners, backward integration addresses supply concerns; and, for extractive companies, downstream integration with value-adding stages can improve returns and provide a reliable route to markets in cell fabrication [205]. For example, the large conglomerate POSCO has attracted leading producers of lithium (such as Pilbara Minerals) to South Korea to produce lithium hydroxide and lithium carbonate; and in Australia a 'Lithium Valley' is emerging centred on lithium hydroxide refining projects of Tianqi Lithium, SQM, and Albemarle in the Kwinana industrial zone close to Perth. An interesting example of vertical integration here is Lithium Australia, which aims to create a circular battery economy via operations spanning the lithium supply chain from extraction and refining, through cathode manufacturing to recycling of end-of-life batteries [205].

4.3.2. Deepening significance of the state as a regulatory driver, especially around trade and material sourcing

The economic importance of battery manufacturing for national economies means trade policy, regulation and systems of state support

[45] Shanghai leads in cumulative EVs, counting more than 310,000 registrations in 2019, followed by Beijing, Shenzhen, and Los Angeles. Bergen and Oslo lead in EV sales shares. Of the 25 EV capitals, four have building codes that require 100% of EV-ready spaces within specified building types. Numerous cities also have all-electric targets for municipal, and taxi fleets [198].

[46] The EU Clean Vehicles Directive has increased forecasts for e-bus manufacturing at Mercedes, Volvo, VDL, Ebusco, BYD and Switch [201].

[47] V2X makes it possible to connect an EV to a variety of energy systems. V2G supplies power back to the general grid only, while V2X can be directed more precisely to, for example, also power office buildings or private homes [203].

[48] For example, the CEO of Ford noted (March 2022) how the company intends to control the supply chain "all the way back to the mines" that produce battery materials; and Elon Musk has indicated (April 2022) if the price of battery minerals remains high then Tesla "might actually have to get into the mining and refining directly at scale" as the"pace of extraction/refinement was slow" [220].

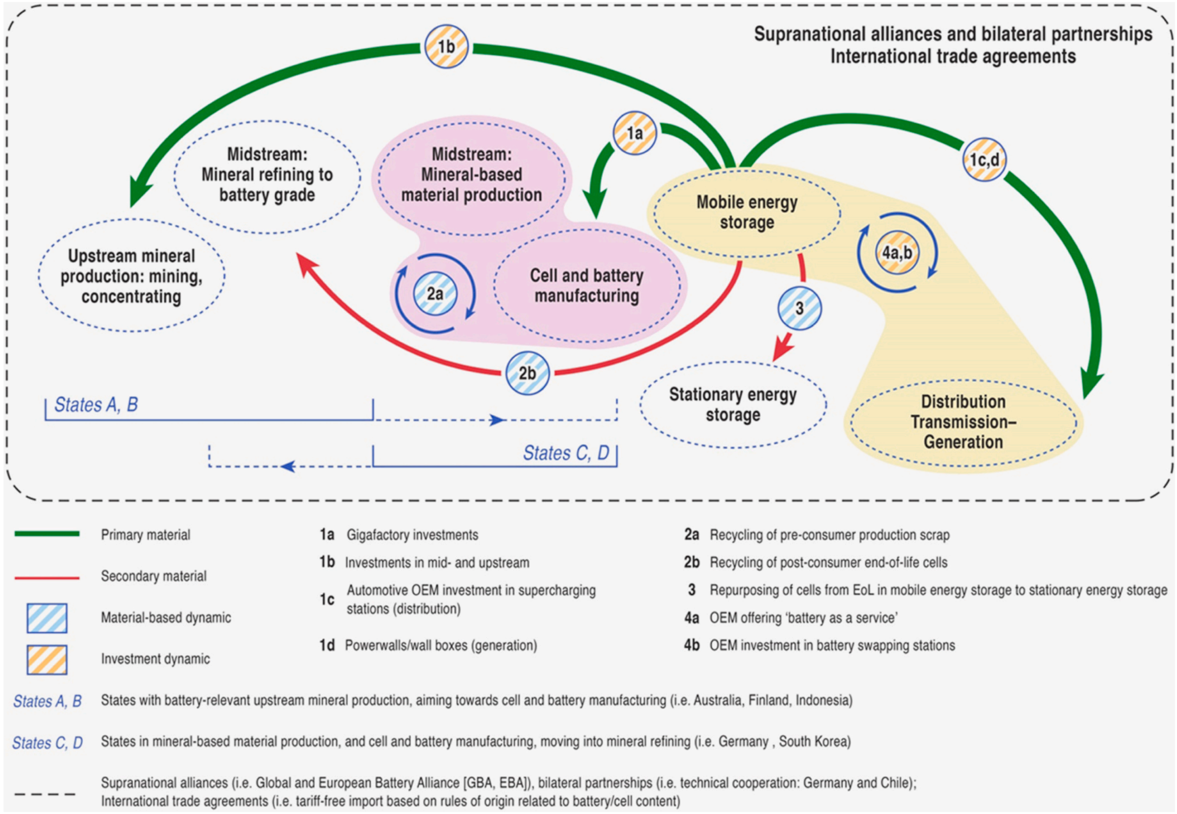


Fig. 2. Selected dynamics in the battery mineral production network: Source: authors' elaboration

will continue to exert significant effects on the geographies of global battery production. Their overall effect is likely to be a shortening of supply chains and a regionalisation of production networks, as evidenced by Europe's accelerating efforts to establish a full domestic battery value chain. Similarly in the US, Biden's Infrastructure Bill sought to commit $174 billion towards creating a domestic supply chain for batteries and EVs. The resulting US Infrastructure Investment and Jobs Act (2021) allocated around $15 billion to the development of batteries and a national EV charging infrastructure, and the Biden Administration has subsequently used its Presidential powers (via the Defense Production Act) to bolster domestic mining and mineral processing for battery minerals. The US International Trade Commission's recent settlement of an intellectual property dispute between LG and SKI over battery chemistries – prohibiting SKI importing some types of LiB batteries for 10 years and "effectively banning the company from supplying EV batteries in the United States unless the company can source all the needed materials there" [172] – highlights how intellectual property and trade regulation also works to regionalise production networks.

Trade rules are likely to be a significant shaper of the LiB production network over the next few years, and are particularly significant for the rapid growth of gigafactory capacity in Europe (see Section 2). Local content requirements embedded in trade agreements are an important regulatory tool for the EU in delivering its policy goal of regionalising the battery production. These specify a level of local content, measured as a percentage of the final value of the vehicle, and currently allow up to 70% of the value of the car to be sourced from outside the EU. From January 2024, however, this will reduce to 50% and – as batteries can be up to 40% of the final value of the car – this will effectively require automakers to source batteries from within the EU. There are specific implications for the UK, post-Brexit, as 'rules of origin' requirements negotiated under the EU-UK Trade and Cooperation Agreement to secure tariff and quota free trade mean EVs must have 55% UK/EU content by 2027, and must also have an originating battery pack [207].[49] However, automotive OEMs in the UK who export to non-EU countries are likely to find any battery components manufactured in the EU will attract import tariffs, as the battery will be classed as coming from a third country [33]. The combination of these trade rules is driving new gigafactory capacity development in the UK while, more generally, the weight of batteries and additional costs associated with the hazards of transport due to the flammability of batteries are pushing "EV manufacturing to be located relatively close to battery manufacturing, probably in the same country or region" [207, p. 2].

A second emergent regulatory dynamic concerns material sourcing and reuse (see Fig. 2, dynamics 2a and 2b). Financial market rules on disclosure related to ESG are already having some effect, and supernational initiatives (such as the Global Battery Alliance's battery passport, a programme to make the entire value chain transparent and provide a battery benchmarking framework for validating and tracking progress) and corporate efforts to pilot material provenance with blockchain (such as Glencore and Umicore's work around cobalt) indicate the capacity of regulation to drive new business models and organisational alliances around material provenance and the circular economy [208].[50] The proposed EC Battery Regulation, for example, includes targets for recycled content[51] and incentivizes industrial actors to close battery material-loops by recycling production scrap and spent

[49] Originating battery packs must have either 65% UK/EU content for the cell or 70% for the battery pack [207].

[50] See Re|Source, a pilot blockchain solution for end-to-end cobalt traceability involving China Molybdenum Co (CMOC), Eurasian Resources Group (ERG), Glencore, Umicore and Tesla.

[51] These targets include lithium which is currently recycled well below target ([3], [109]).

EV batteries [109].[52] These will encourage midstream mineral refiners (e.g. Glencore, Hydro) and battery material producers (i.e. manufacturers of cathode active materials, e.g. Umicore, BASF, Johnson Matthey) to enter partnerships with automotive OEMs or industrial project developers (Britishvolt, Northvolt, Freyr) for recycling. On their own and in combination, 'design for recycling' requirements and extended producer responsibility will influence upstream mineral sourcing decisions. They will also encourage downstream integration of recycling with cell and battery manufacturing and, potentially, facilitate circular business models based on 'minerals as a service.' Northvolt 1's inhouse Revolt recycling project, for example, aims to take back 100% of batteries at end-of-life and secure 50% recycled material in all new battery cells by 2030.

4.3.3. Emerging business models

Over time, the battery production network will be shaped by consolidation of 'battery as a service' (BaaS) business models (see Fig. 2, dynamics 4a and 4b). Europe is currently a core geography for BaaS, particularly in Norway, Sweden and the Netherlands where EV adoption rates are high. China too has examples of BaaS – including cell and battery giant CATL - and the country's new NEV policy supports expansion of this approach. Leasing batteries, rather than selling them as part of the EV purchase, can spur EV uptake by reducing the sticker price for vehicle consumers, while also offering improved battery performance: battery swapping gives battery suppliers (as owners of leased batteries) access to extensive data on battery use and battery health, and access to a concentrated battery mineral source (for reuse, recycling or repurposing) as the battery returns to the supplier at end-of-life.

Nio, an EV manufacturer sometimes described as the 'Tesla of China', is rolling out BaaS under its Nio-Power business unit, offering both charging and battery swapping to EV owners.[53] To facilitate these ambitions, Nio has signed a strategic collaboration with Chinese oil company Sinopec to build a network of 5000 charging and swapping stations for EV batteries, with the first opening in Beijing in 2021 [212].[54] Epiroc, a leading Swedish supplier of rock excavation equipment, is entering the 'energy storage as a service' business segment through provision of the first BaaS in mining operations, serving Brazilian mining firm Vale at its two Canadian mines. Epiroc owns and monitors the rechargeable batteries used by Vale, replacing and updating them as required.[55] Various other initiatives extend the BaaS model by cascading end-of-life EV batteries into ESS applications (see Fig. 2, dynamic 3).[56] Nissan and Sumitomo, for example, are repurposing EV batteries for street lighting and large-scale ESS in Japan; while Nissan has collaborated in an ESS for energy management in the Netherlands, repurposing battery packs from Nissan's LEAF EV to deliver back-up power and grid stabilization services at the Amsterdam Arena.[57]

In this section, we demonstrated how a GPN approach moves beyond supply chain analysis to highlight important geographical and organisational structures shaping battery production. We have necessarily adopted a simplified view, focussing on lead firms (established and emerging battery producers) and the role of states (through policies on climate, minerals, and infrastructures), and identifying a handful of significant dynamics within battery production networks. Nonetheless, we have shown empirically in this section how GPN's relational perspective can analyse the organisational platforms through which LiB production takes place; and identify how relations among the firms, states and other actors comprising these platforms influence the dynamic geographies of LiB production.

5. Conclusion

Current policy approaches to energy transition imply very significant increases in demand for minerals and mineral-based materials, of which mobile and stationary forms of energy storage account for the lion's share.[58] A net-zero target consistent with 1.5 degrees may require a five to six-fold increase in annual base metal production by 2050 (e.g. copper, nickel, aluminium), with demand for lithium projected to grow to over 100-times its current level under such a scenario [215, 186, p. 271]. Caveats and uncertainties necessarily attend projections like these, not least because such rapid increases in demand are likely to tighten markets for existing battery minerals (like nickel), propelling shifts towards other battery chemistries such as LFP and manganese-rich cathodes [186]. Nonetheless, it is clear that growing demand for electrical energy storage is producing new transnational economies of battery production, as firms, states and other actors compete and co-operate in the creation, transformation and capture of value via energy storage. The relations and dynamics that make up these transnational economies are not well understood and, importantly, go beyond issues of material flow. The multiple stages of production and assembly involved in battery production may be geographically dispersed and linked by material flows, yet they are also organisationally integrated across multiple (and often competing) states in ways that need to be better understood.

We have sought in this paper to demonstrate how a GPN approach to LiB production can augment conventional supply chain accounts of battery manufacturing. We have highlighted two primary insights: the role of economic and non-economic actors, network relations and multiple locations that constitute the global battery production network; and the strategies of innovation, cooperation and competition through which this network acquires its organisationally and geographically dynamic character. GPN can show, for example, how in Europe government incentives to regionalise supply chains, transboundary investment (both within and into the EU), and organisational strategies of vertical integration are driving new geographies of battery production at a range of scales (e.g. the 'Baltic Belt'). Through a GPN approach, then, we have highlighted a structuring tension currently shaping battery production networks between, on the one hand, continued efforts to reduce cost which drives a form of 'globalization'; and, on the other, efforts by states to regionalise and localise supply chains. The latter, however, are constrained by existing geographies of production, so that

[52] The recycled content declaration requirement is proposed to apply from 1 January 2027 to industrial batteries, EV batteries and automotive batteries containing cobalt, lead, lithium or nickel in active materials. Mandatory minimum levels of recycled content would be set for 2030 and 2035 [209].

[53] Nio is planning a SSB for 2022 that is compatible with a number of its vehicle models and is implementing a 'fully-automatic battery swap in just a short coffee break' of 3 min only [210,211]. In April 2021, Nio unveiled a second-generation battery swap station in Beijing allowing 312 daily battery swaps.

[54] More than 200 sensors, and four collaborating cloud computing systems, manoeuvre the EV into the station and users can self-service the battery swap while remaining in the car.

[55] In addition to Nio and Epiroc, CATL, Octillion and others are working with the BaaS model; Hyundai and LGES, with others, are exploring EV battery leasing. SKI is investing in battery swapping stations in China.

[56] These involve five state-owned reuse and repurposing centers for EV batteries in South Korea, BYD and energy storage in Shenzen (China), BMW with an energy storage farm in Leipzig (Germany), Renault with renewable ESS on Porto Santo island, and with backup power for elevators in Paris, and several other firms.

[57] To be used for back-up power during major events replacing diesel generators, assisting utilities during periods of high demand and grid stabilization services. It contains both new battery modules and second life battery packs from Nissan [213,214].

[58] Wood Mackenzie figures [215] indicate around a third of increased base metal demand will come from EV and energy storage markets; the IEA's WEO [186] estimates EVs and energy storage account for over 60% of total 'mineral requirements for clean energy technologies' under a net zero scenario, with lithium, graphite, nickel, manganese, and cobalt accounting for over a third of total demand.

securing domestic supply chains (e.g. building a 'British' battery) frequently involves both inward investment by specialist suppliers and cross-border trade (e.g. importing materials and components, and securing export markets). In short, the tension between globalizing and localising supply chains, and how this tension is mediated by existing geographies of production, drives the configuration of the LiB production network.

We have shown how battery production has become increasingly tied to the strategies of automotive OEMs. Automakers' investment decisions, their performance requirements and the contracts they conclude with material suppliers are increasingly shaping battery production networks. EV mandates, and municipal and state decarbonisation strategies more generally, have spurred battery demand and created an organisational environment in which automotive companies increasingly occupy the lead firm position in battery production networks. The scale economies now available in battery production for the EV market, together with the sunk costs of gigafactory investments, create a material momentum in supply that means many non-EV battery uses (from the nascent aircraft market to diverse ESS applications) are currently derivative of EV. But we have also shown how automakers are collectively experimenting with organisational strategies that consolidate their role in the network by, for example, augmenting supply contracts with collaborative joint ventures and strategies of vertical integration. In addition, we have shown how the organisational structure of the battery production network increasingly extends downstream, via business models that offer energy storage as a service, and recycling and extended producer responsibility initiatives. Some of these organisational models redefine ownership at the level of minerals, while others centre on the combined qualities of minerals and mineral-based materials in the form of a battery. Here the evolution of value capture strategies around batteries, from a product offer to a service, aligns with increasing concerns about access to minerals and governance of their environmental and social impacts (as reflected, for example, in the anticipated EU Battery Regulation).

To conclude, this paper has demonstrated the value of a GPN approach for understanding the geopolitical economy of energy system transformation. GPN has been successfully applied to other energy sectors, but until now there has been no systematic effort to think through the organisational and geographical structures of LiB production. As economies decarbonise, and renewables replace fossil fuels in energy systems in ways that significantly expand demand for minerals, new production networks are emerging that intersect with and disrupt established networks. Understanding these intersections, and their implications (for scaling up non-fossil energy systems, for geographies of economic development etc) is increasingly important. At the same time, production networks associated with the new energy economy are distinctive in ways that potentially challenge existing GPN analyses. The cost of the battery means EV manufacturing networks are qualitatively different to those associated with producing petrol or diesel cars; and, for the most part, battery minerals are not consumed in use (like the bulk of oil and gas) but can be recovered and used again, opening up novel value capture possibilities downstream. In short, the application of GPN to understand the geopolitical economy of energy system transformation can be a mutually rewarding agenda.

Declaration of competing interest

Gavin Bridge reports financial support was provided by UK Energy Research Centre.

Acknowledgements

We acknowledge funding support from the UK Energy Research Centre Phase 4 funding programme (EP/S029575/1), and the opportunity it has provided for research conversations with fellow participants in Phase 4 Theme 1 (on the Geopolitical Economy of Energy System Transformation) to which our work on the Lithium-Ion Battery production network contributes. We thank our anonymous informants and respondents for generously allocating their time to speak with us and for sharing their knowledge and insight; Mike Bradshaw, Neil Coe, Tiago Alves-Teixeira, Jessika Richter, Jakob Kløve Keiding and Juan Tan for their comments on a pre-submission draft; Chris Orton for his assistance in preparing the figures; and the Reviewers and Editor for their comments on the submitted paper. Responsibility for the final content of this paper remains with us.

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