The Extractive Industries and Society 16 (2023) 101328

Contents lists available at ScienceDirect

The Extractive Industries and Society

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

Original article

Lithium, Brexit and Global Britain: Onshoring battery production networks in the UK

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ARTICLE INFO

Keywords:
Lithium
Global production networks
Electric vehicles
Automotive sector
Strategic coupling
Entrepreneurial state
State accumulation project

ABSTRACT

As demand for electrical energy storage scales, production networks for lithium-ion battery manufacturing are being re-worked organisationally and geographically. The UK - like the US and EU - is seeking to onshore lithium-ion battery production and build a national battery supply chain. Governmental, industrial and research actors are engaged in securing battery mineral materials and developing battery manufacturing capacity, in the context of the country's exit from the EU and a perceived 'global battery race' in which geopolitical goals shape links with new and old partners. We identify the primary global networks of lithium mining and refining, battery chemical production, technology development and finance in which the UK's battery manufacturing capacity are increasingly embedded. We foreground the role of the UK state, and how it has sought to assemble discrete capacities in automobile manufacturing, battery R&D, materials chemistry, minerals exploration, mining and green finance into a national battery sector. We mobilise a Global Production Network (GPN) perspective to highlight the cross-border geographical and organisational structures through which onshoring is taking place. We extend GPN research on the role of the state by showing how the UK's growing lithium networks intersect with a plural and differentiated state accumulation project of green industrial transformation. We outline the selective nature of this state accumulation project, highlight instances of coupling creation as the state seeks to strategically couple regional assets with firms in GPNs, and point to a convergence of industrial and innovation policy characteristic of the entrepreneurial state.

1. Introduction

Lithium-ion battery production is rapidly scaling up, as electromobility gathers pace in the context of decarbonising transportation. As battery output accelerates, the global production networks and supply chains associated with lithium-ion battery manufacturing are being re-worked organisationally and geographically (Bridge and Faigen 2022). Geopolitical objectives are a key driver of emergent geographies of production, as highlighted by EU and US efforts to develop domestic battery manufacturing, onshore lithium supply and challenge China's dominant position (Blondeel et al., 2021; Narins 2017; Riofrancos 2022; Mayyas et al., 2023). Popularly referred to as a global 'battery race', this geopolitical dynamic suggests the reassertion of national territory as a container of production in a reverse 'global shift' (Gong et al., 2022). The UK too is seeking to onshore global production networks for lithium-ion batteries (LiB) and build a domestic battery supply chain. The UK case is instructive as the geopolitical dynamics of onshoring centre on maintaining the UK's role as an automobile manufacturing platform in the post-Brexit period rather than a general 'global race'. Furthermore, emergent geographies of UK onshoring indicate incorporation into alternative global production networks rather than the territorially contained supply chains imagined by 'deglobalisation'.

This paper explores evolution of the LiB sector in the UK, and ongoing work by governmental, industrial and research actors to secure battery manufacturing and battery mineral materials. We adopt a Global Production Network (GPN) perspective that centres on interactions among firms, states, and other actors, and which identifies the global lithium economies and organisational networks in which the UK is increasingly embedded. In tune with recent GPN work, we pay

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https://doi.org/10.1016/j.exis.2023.101328
Received 7 March 2023; Received in revised form 31 July 2023; Accepted 10 August 2023
Available online 22 September 2023

particular attention to the state's role in co-ordinating strategic action and constituting production networks. We consider how the UK state has sought to assemble relatively discrete capacities in automobile manufacturing, battery research, materials chemistry, minerals exploration and green finance into a national battery sector, as part of a state accumulation project of green industrial transformation. We show how the structural shift to EV manufacturing in the automotive sector creates an incentive to onshore battery production, and how this localisation of battery manufacturing is intensified by local content requirements in the EU-UK Trade and Co-operation Agreement that followed Brexit. We further show how the UK state has sought to support domestic and international strategies to secure battery mineral-based materials in the upstream supply chain. This includes classifying lithium as a critical mineral, establishing a Critical Mineral Strategy and Critical Minerals Intelligence Centre, and developing strategic mineral partnerships.

We develop our account by reference to recent government strategies and industry initiatives, drawing on original semi-structured interviews with a dozen key respondents across battery R&D and commercialization (research, industry and government) in the UK, Australia, and the EU. Our research conversations with respondents were conducted through web-based communication platforms between June 2021 and March 2022. These conversations lasted between 60 and 90 minutes and, in some cases, a subsequent round of interviewing was conducted to follow-up or clarify points of discussion. Our findings offer new empirical insight into the way onshoring dynamics are shaping the geographies of lithium-ion battery production as it scales, through the case of the UK. By highlighting the state's multiple roles in constituting battery production networks - and its strategic selectivity towards different supply chain segments - the paper advances an under-explored aspect of GPN research. The remainder of the paper is divided into four sections. In Section 2, we situate contemporary lithium dynamics within the context of research on global production networks and state strategy. Section 3 explores UK efforts to onshore lithium-ion battery production and develop a domestic supply chain. We show how these efforts are tied to concerns about the fate of the UK automotive sector, and how geographies of EV manufacturing, LiB production and the supply chain are being shaped by EU-UK trade regulations post-Brexit. In Section 4, we identify some of the lithium economies of which the UK is increasingly a part, working 'upstream' from gigafactory development through cathode materials to mineral raw material supply. Section 5 reflects on the paper's contribution and its implications for understanding lithium dynamics.

2. Global networks and state strategies: shaping the lithium-ion battery chain

Efforts to onshore battery production and develop domestic battery supply chains are occurring in several jurisdictions. The US Inflation Reduction Act (2022), for example, creates strong incentives for onshoring and 'friend-shoring' battery mineral materials and components, while both the Trump and Biden Administrations have used the US Defense Production Act to support domestic production and processing of critical minerals.[2] Within the EU, state aid has been directed to developing a battery value chain as Important Projects of Common European Interest (Bridge and Faigen 2022), and the proposed EU Green Deal Industrial Plan (reacting to the US IRA) offers further support for development of European supply chains and industrial capacity in the battery sector (European Commission, 2023).[3] The UK too is seeking to onshore battery production, in the context of a globally integrated national economy shaped by decades of neoliberal economic policy, and against the backdrop of the UK's exit from the EU. This effort involves a diverse range of actors at different scales, domestic firms, and national and regional government, including international and mobile capital. Accordingly, we frame the paper around efforts to build a UK battery supply chain by adopting a Global Production Networks (GPN) perspective. GPN is attentive to the re-scaling of economic activity via the actions of firms and states, and its relational perspective and network orientation place actions in the UK within a wider political-economic context. However, to understand the specific role of the UK state in shaping its battery sector, we supplement GPN's focus on the state's role in strategic coupling with work on the entrepreneurial state and state accumulation projects.

2.1. Global production networks and the 'onshoring' of lithium economies

GPN is a conceptual framework, widely used within the subdiscipline of economic geography, to analyse the "organisationally fragmented and spatially dispersed" character of commodity production (Coe and Yeung 2015). Much like global commodity chain (GCC) and value chain (GVC) research, GPN arose out of efforts to understand changes in the geographic organization of manufacturing and services at the world scale (see, for example, Neilson et al., 2014; Parrilli et al., 2013; Bair and Werner, 2011; Hess and Yeung, 2006; Bair, 2005). This family of literatures are characterised by a shared "conceptual architecture of chain *governance* and network *dynamics* – crucial theoretical shorthands for the ability of lead firms to coordinate value-added activities of a multitude of economic actors" (Neilson et al., 2014:1, emphasis in original). Network dynamics, for example, are explained in GPN research by reference to its orientating concepts of value, power, and embeddedness (Hess 2009; Bair 2005). The state has been a focus of GPN (and GCC and GVC) research since its inception (Hess 2021; Werner 2021; Horner 2017; Smith 2015). GPN literature explicitly understands states as porous structures transcended by the co-ordinated production activities of multiple firms (Henderson et al., 2002; Coe et al., 2004; Dicken 2015). Researchers have highlighted the geographically uneven development outcomes associated with capital accumulation through global production networks (Bair and Werner 2011; Werner and Bair 2019; Bair et al., 2021), the role of labour (Smith et al., 2018), and the reshaping of patterns of work and social reproduction (Barrientos 2019).

The GPN perspective has been widely applied to manufacturing (Vanchan et al., 2018; Lund and Steen 2020; Raj-Reichert 2020), services (Coe et al., 2014; Kleibert 2013) and resource sectors (Bridge 2008; Irarrázaval and Bustos-Gallardo 2019; Bridge and Bradshaw 2017; Bridge and Dodge 2022). Its multi-scalar focus, and interest in how a plurality of economic and political actors shape organisational geographies of production, have proven useful for understanding the formation and scaling of lithium economies and their integration into battery production networks. Bos and Forget's (2021) analysis of lithium production in Bolivia, for example, highlights how the national state mediates between local and global scales; while Obaya et al. (2021) show how efforts by the Argentinian state to promote downstream linkages from lithium extraction are constrained by the way lithium extraction and processing are embedded in global networks (see also Dorn and Huber 2020, Dorn and Peyré 2020). Bridge and Faigen (2022) deploy GPN to lithium-ion battery production and identify an intensifying nexus of battery manufacturing with the automobile sector. They outline three dynamics at this nexus (vertical

[2] 'Friend-shoring' (or ally-shoring) has entered US policy language on critical minerals since the 2020s (see, for example, The Whitehouse 2021). Friend-shoring is embedded in the US Inflation Reduction Act (IRA) which (amongst other things) provides support for the US EV market via tax subsidies: the IRA extends eligibility for Clean Vehicle tax credits to EVs built of minerals and components sourced through North America or countries with which the United States has a free trade agreement (Majkut et al. 2023; Vivoda 2023).

[3] The EU Battery Regulation (adopted June 2023) is also relevant here as it prescribes material content and end-of-life handling practices that, by keeping battery materials within EU borders, promotes onshoring (European Parliament 2023, European Council 2023b).

integration, deepening influence of states, new business models) that are transforming the lithium-ion battery supply chain into a production network as it scales.

GPN research has focussed primarily on the "organisationally fragmented and spatially dispersed" networks associated with 'offshored' production, reflecting its origins in understanding a 'global shift' of manufacturing from the global North in search of lower labour costs and access to markets (Coe and Yeung 2015; Dicken 2015). The 'production networks' disclosed by GPN researchers are, in effect, the architectures of economic globalisation as they describe the "organisational platform (s) 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" (Coe and Yeung 2015: 30). Nonetheless, there is growing interest among GPN researchers in the 'onshoring' and 're-shoring' of manufacturing activity to North America and Europe (Vanchan et al., 2018; Lund and Steen, 2020; Gong et al., 2022; Nujen et al., 2022). This relocation of manufacturing (back) to parts of the global North has several drivers, including differential energy and material costs (e.g. the US, subsequent to the hydrocarbon 'fracking' boom), policy concern to 'rebalance' national economies in the wake of the global financial crisis, post-pandemic concerns about the security and resilience of supply and (as we illustrate in Section 3) strategic geo-economic and geopolitical objectives (Kuzemko et al., 2020; Pla-Barber et al., 2021; Gereffi 2021). Engagements with onshoring by GPN (and other) researchers highlight the shortening of some supply chains and trajectories of regionalisation, contributing to a more fluid "account of…bi-directionality or even multi-directionality in the evolution of global production" (Vanchan et al., 2018). Gong et al. (2022), for example, consider how GPNs are being reworked by crises and shocks, geopolitical uncertainties, climate change and new technologies. They review evidence for the regionalisation and domestication of value chains, offering the Biden administration's pledge "to restore the resilience of US key supply chains purportedly made vulnerable through extensive offshore production" as an illustrative example of 'globalisation in reverse' (p.166). Riofrancos (2022: 2) focusses on US and EU efforts to 'onshore' lithium extraction and refining after decades of offshoring, showing how auto-producers and states in the global North share an interest in shortening supply chains for battery production, naming this alignment a 'security–sustainability nexus.' Riofrancos' work is not framed by GPN but clearly identifies how state industrial policy is "shift(ing) the front lines of lithium extraction" and producing new geographies of battery mineral mining at the world scale (p. 17). We find recent GPN work on onshoring useful for drawing attention to how "national and regional forces…encourage shorter and closer value chains" while recognising these localised supply chains "remain, nevertheless, globally connected" (Pegoraro et al., 2022). It is alive, then, to the combined effects of technological change, geopolitics and state strategy on not only geographies of production, but also on the organisational structures through which actors in different regional and national economies compete and co-operate.[4] In short, GPN is well suited to examine how the UK state is seeking to re-draw contemporary LiB production networks and develop battery production domestically.

2.2. *The state in GPNs: strategic coupling, the entrepreneurial state, and state accumulation projects*

GPN research has developed a conceptual repertoire for analysing how states regulate, harness and constitute production networks (Glassman 2011; Smith 2015; Teixeira 2023). GPN's primary encounter with the state has been via industrial and trade policy: Smith (2015), for example, highlights international trade regulation as "the key nexus of state action in global production." Horner (2017), however, identifies multiple functions of states within GPNs that exceed their role in industrial and trade policy, including their activity as strategic facilitators, purchasers of goods and services, and owners of capital. Horner's typology of state action within GPNs has proven useful for identifying the state's multiple roles in constituting LiB production networks (Bridge and Faigen 2022), from market interventions (e.g. petrol and diesel engine phase outs, EV uptake), regulations on investment and trade (e.g. local supply chain obligations for foreign investors, trade policy) and strategic purchases of critical minerals.

GPN's concept of strategic coupling offers a way to explore how these multiple roles of the state facilitate the onshoring of production, as regions and states seek to attract "GPNs by providing conditions for the creation, enhancement and capture of value" (Rutherford et al., 2018). Strategic coupling describes a complementary alignment between "regional assets…and the strategic needs of companies operating in GPNs" (Breul et al., 2019: 831), a process often described as 'matching' in GPN research (see Dawley et al., 2019: 861; also Bridge and Dodge 2022). Strategic coupling emerged from efforts to theorise how developmental states in East Asia supported domestic manufacturers in developing strategic partnerships with global firms, and how these partnerships effectively globalised regional development (Coe et al., 2004; Yeung, 2016). Subsequent work has identified several 'modes' and 'types' of coupling with different developmental outcomes (Coe and Yeung 2015). MacKinnon (2012: 239) distinguishes between structural, strategic and organic types of strategic coupling, identifying variations in structural (core-periphery) power against which coupling processes play out.[5] Structural coupling is facilitated by long-standing asymmetries in political-economic relations between host regions and external capital, with regions plugged into GPNs through inward investment and with only limited local linkages (Dawley 2011; Mackinnon 2012; Pavlínek 2018; Teixeira 2023). Strategic and organic forms of coupling imply less asymmetric sets of relations, involving either "conscious selection and partnership" or "co-evolution of regional assets and lead firms in GPNs" respectively (MacKinnon 2012: 239). Here, "more balanced coupling relations" are enabled by the constitutive role of state structures (Fu and Lim 2021: 1). Work by Dawley et al. (2019) on renewable energy manufacturing in the UK's Humber region highlights the importance of antecedent processes – what they term 'coupling creation' – for understanding the varied outcomes of strategic coupling. They identify three significant episodes in coupling creation – harnessing and matching regional assets, brokering and negotiating coupling, and valorising and materialising the coupling once manufacturing begins (Dawley et al., 2019). Empirical specification of these processes provides an opportunity to explore the agency of regional institutions within production networks, and of regional initiatives within GPNs, in both successful and unsuccessful instances of coupling creation (Dawley et al., 2019; Kleibert 2013). Thus recent research on strategic coupling offers two distinct yet complementary angles of analysis: attention to 'modes' and 'types' highlights coupling's varied outcomes (MacKinnon 2012), while a focus on 'coupling creation' reveals the episodes and agencies through which coupling is attempted and sometimes achieved

[4] This perspective is particularly pertinent to the UK automobile sector which is simultaneously undergoing two profound changes: a technological and market shift from ICE to EV, which re-works the value of existing cost-capability ratios in the sector and introduces novel supply chain requirements; and the consequence of the Brexit decision, which has cut across the "dense and complex cross-border supply chain exchanges within the automotive value chain" (Pegoraro et al. 2022). Bailey and Propris (2017) note that "on average, only around 40% of the components that comprise a UK assembled car are sourced locally, as against 60% in Germany (SMMT, 2016), given the nature of fragmented supply chains in UK Automotive".

[5] Yeung (2009, 2015) theorised three similar modes – organic, structural and functional – to explain "the role of transregional mechanisms in shaping development trajectories in core, emerging and peripheral regions" (Yeung 2021: 998).

(Dawley et al., 2019).

The emphasis here on regional institutional agency, and on the capacities of the state to shape regional assets and select strategic partners, resonates with what has come to be known as the 'entrepreneurial state' (Mazzucato 2013; Mazzucato and Semieniuk 2017). 'Entrepreneurial' here signals an active, risk-taking role for the state as a "visible hand" giving direction to innovation and markets, rather than merely 'fixing' market failures. It offers a way to think about ostensibly 'developmental' aspects of an otherwise neoliberal state, in which the "state not only 'crowds in' business investment but also 'dynamizes it in', creating the vision, the mission and the plan" (Mazzucato 2015: 135). The entrepreneurial state is evident in '*mission-oriented*' innovation policies like those associated with green industrial policy: here the state establishes a target and trajectory (such as carbon emission reduction to achieve Net Zero), directs public finance to transformative innovation in this area, and seeks to make and shape markets such as those for renewable energy or electric vehicles (Mazzucato 2018; Schot and Steinmueller 2018; Diercks et al., 2019; Raven and Walrave 2020; Tödtling et al., 2022).[6] A key tool of the entrepreneurial state, for example, is to converge the trajectories of innovation and industrial policy rather than leaving each to the play of the market. This has been a feature of industrial policy in the OECD since its 'return' after the financial crisis (Cowling and Tomlinson, 2011), and of green industrial policy and the green entrepreneurial state in particular (Mazzucato 2015; Voldsgaard et al., 2022).

Work on the entrepreneurial state highlights the centrality of the state to innovation and its selective and asymmetric support for industrial transformation, but does not typically consider the entrepreneurial state's intersection with transboundary GPNs. Here we find useful the notion of a *state accumulation project,* as it highlights how the state strategically selects value-chain segments controlled by transnational corporations, adjudicates among different actors, and manages the institutional compromises underlying trade and investment policy (Rutherford and Holmes 2008; Rutherford et al., 2018; Jessop, 2002).[7] We note that the dynamics of selection and management characteristic of state accumulation projects are similar to those explored in work on 'modes' and 'types' of strategic coupling: the former foregrounds state agency while the latter focuses on regional initiatives. In their research on Ontario and Quebec's automotive and information technology (IT) sectors, Rutherford and Holmes (2008) show how the state privileges large transnational firms and their production networks over smaller suppliers in the context of geoeconomic competition. The state manages growth, innovation and the onshoring of GPNs in the automotive and IT sectors in a way that is selective and directive, rather than neutral and (merely) facilitating, warranting description of these sectors as a 'state accumulation project' (Rutherford and Holmes 2008). Their use of this term draws on Jessop (2002) 'strategic-relational' approach to the state, which recognises how "states are not neutral terrains on which political forces struggle with equal chances to pursue their interests and objectives and with equal chances of realizing their goals… Instead the organization of state apparatuses, state capacities, and state resources…all mean that state favours some forces, some interests…some projects more than others" (Jessop 2014: 4). While 'entrepreneurial state' highlights the state's risk-taking role in the context of innovation and industrial policy, 'state accumulation project' draws attention to its selection of actors and places. The utility of this approach, for our purposes, is that it can show not only how government policies (e.g. industrial policy, innovation policy) shape GPNs, but also how state strategy (towards green industrial transformation, for example) is "driven by both accumulation and political projects, which are strategically selective of groups and places and 'set the rules' under which investment takes place" (Rutherford et al., 2018: 574; Jessop 2015; Smith 2015).

3. Onshoring lithium-ion battery production: the 'visible hand' of the entrepreneurial state

In this section we examine how lithium dynamics in the UK are strongly shaped by the automotive sector, and the role of UK industrial policy, research policy and trade diplomacy in developing and onshoring some segments of LiB production networks and facilitating access to others. The UK case is unusual within growing work on lithium, as it focuses on the 'downstream' end of the LiB network in contrast to an extractive frontier. Its insights, however, are no less significant: by interpreting the nexus of automotive and battery manufacturing in the UK as a state accumulation project, in which the state acts in an entrepreneurial and selective way to support and onshore some segments of the battery value chain, we show how emergent (global) geographies and organisational networks of lithium-ion battery production are constituted through state action. We also shed light on the role of regional institutional actors in coupling creation, specifically in harnessing and matching regional assets, but also in relation to episodes of brokering and negotiating, and valorising and materializing coupling. We highlight instances of structural and strategic coupling in relation to the onshoring of productive capacities along the battery value chain, but also continuing 'gaps' in domestic capacity that have material consequences for the UK automotive sector as it pivots to electric vehicles. These gaps reflect limits in the scope and scale of the UK government's efforts to act as an 'entrepreneurial state' with regard to lithium-ion batteries, particularly in the context of growing competition from Europe and the US in the wake of the US Inflation Reduction Act.

The UK state has increasingly positioned green industrial transformation as a state accumulation project. This materialises in multiple ways across different sectors (notably renewable energy, e.g., offshore wind), but the most significant for the LiB/automotive sector has been the Industrial Strategy (UK GOV 2017) introduced by Theresa May's government in the wake of the Brexit decision. The Industrial Strategy centred on four 'grand challenges,' of which two - the Future of Mobility and Green Growth - directly related to an impending transition in the automotive sector from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs). Politically, the Industrial Strategy can be seen as a "core response to the disaffection" that triggered the decision to leave the EU (Berry, Froud and Barker 2021: 2). Indeed, post-Brexit state support for manufacturing - and automotive in particular - has become tied to a populist imaginary of 'levelling up' Britain's stark regional inequalities with government no longer subject to EU state aid rules. The Boris Johnson government (2019) turned the Industrial Strategy into a series of ad-hoc commitments but continued to foreground EV manufacturing and the battery supply chain as part of its "Ten Point Plan for a Green Industrial Revolution". In sum, the LiB/automotive nexus in the UK constitutes a state accumulation project that, like industrial policy more generally, is "driven by concerns over competitiveness, globalisation, de-industrialisation, unemployment and…comparatively slow growth" while, at the same time, being "a catalyst for designing

[6] The UK's 2017 Industrial Strategy - which centred on four "Grand Challenges" – illustrates the 'mission-oriented' character of the (green) entrepreneurial state. Two of the four challenges - clean growth and the future of mobility – related to transforming automobile production: support took the form of a series of 'vertical interventions' (i.e. sectoral support targeting firms and industries) focused on the domestic export base (Berry 2020) via a 'sector deal' (2018) in which "both government and industry will invest about a quarter of a billion pounds to develop and manufacture electric vehicles."

[7] Rutherford et al. (2018) argue that state actions create a series of challenges which the state subsequently also has to manage and that "these challenges are reflected in the post-2008–09 crisis revival of industrial policy."

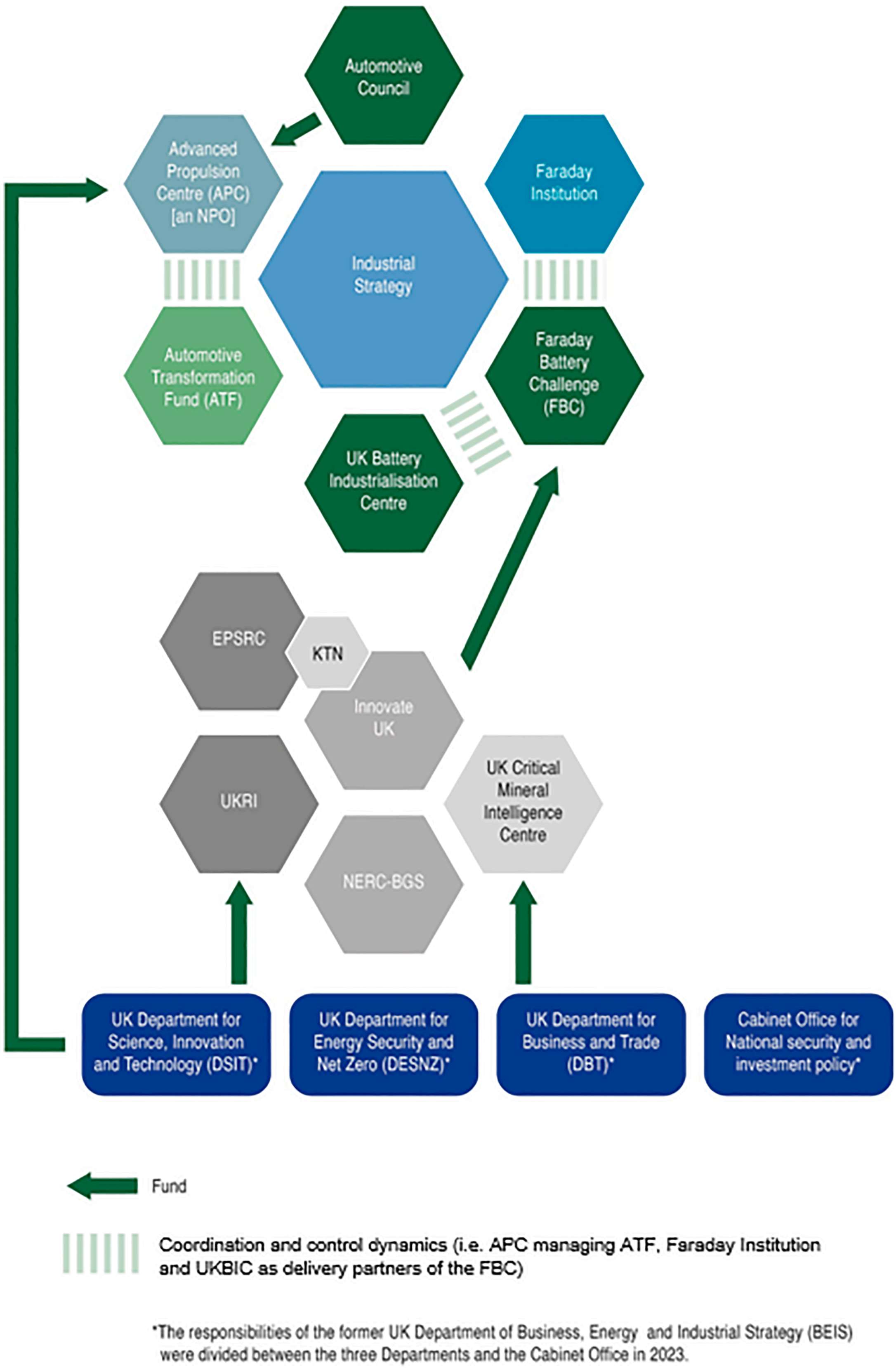


Fig. 1. UK industrial policy and research policy converging around battery technology development, including for its international positioning.
Source: authors based on UK BEIS (2022), UKCMIC (2022), Innovate (2022b), Respondents 2, 6, 8, 9 and 10, 2021.

Table 1
TCA Rules of Origin for the automotive sector.

1 January 2021 – 31 December 2023	
Battery packs intended for use in EVs	70% max non-originating product
Battery cells or modules intended for use in EVs	70% max non-originating product
Hybrids and EVs	60% max non-originating product
1 January 2024 – 31 December 2026	
Battery packs intended for use in EVs	40% max non-originating product
Battery cells or modules intended for use in EVs	50% max non-originating product
Hybrids and EVs	55% max non-originating product
From 1 January 2027	
EVs	55% UK/EU content, plus an originating battery pack Originating battery pack must have either 65% UK/EU content for the cell, or 70% for the battery pack

Source: based on Mishcon de Reya (2021).

economic recovery strategies" (Bailey et al., 2015: 2).[8] In the rest of this section we unpack three different dimensions of this state accumulation project relevant to lithium: battery manufacturing, battery research and development, and critical minerals expertise and finance (Fig. 1).

3.1. *Anchoring the automotive sector: the significance of cell and battery manufacturing*

The primary strategic driver of efforts to onshore battery production is securing the future of the UK's automotive manufacturing sector. The UK has the sixth largest motor industry in Europe: around 30 manufacturers produced close to 1 million cars and light vehicles and 1.6 million engines in 2021, contributing £14 billion to the UK economy and accounting for 10% of total UK goods exports (BEIS 2023; SMMT, 2023).[9] Automotive manufacturing in the UK employs 155,000 workers – around 6% of total manufacturing employment - with an estimated 347,000 further jobs supported by the industry in the wider economy (BEIS 2023). Most of the UK automotive sector is foreign owned – the largest producers are Nissan, Jaguar Land Rover (Tata), BMW Mini, Stellantis-Vauxhall and Toyota – and 80% of its output is exported. The UK is, in effect, an international production platform for lead firms in the automotive sector which locate in the UK to take advantage of a permissive business environment, a sizeable domestic market, and access to Europe. Some 50% of exports are destined for the EU, where the European Parliament has agreed to adopt zero-emission requirements for new cars from 2035 (Faraday 2022a).[10] The EU 'Fit-for-55′ regulation on CO_2 emissions (March 2023) pushes the automotive industry towards this goal, requiring 55% CO_2 reduction for new cars from 2030 to 2034 compared to 2021 levels (European Council 2023a).

Concerns about the future of the sector centre on lithium-ion batteries and arise from the intersection of two specific contexts. First, structural shifts in the global automobile market associated with the international phase-out of ICEVs upend established locational logics of automotive manufacturing, exacerbate branch plant characteristics of the UK automotive sector, and produce new supply chain vulnerabilities. Batteries are large, heavy, hazardous and, accordingly, expensive to transport, creating incentives to co-locate EV and battery production within the same country/region (Bailey and Rajic 2022). The substantial cash value tied up in batteries during transit also favours shorter production chains and just-in-time production. Second, the UK's exit from the EU has introduced friction into highly integrated automobile manufacturing supply chains. While the EU-UK Trade Co-operation Agreement (TCA) mitigates many of these frictions, Rules of Origin in the TCA relating to EV manufacturing further incentivize localisation of battery production and automobile manufacturing. In short, LiB production serves as an effective geographical 'anchor' for automobile production, and the employment generated.

The motor industry was among the most ardent business proponents for staying in the single market and customs union, and among the most vocal to resist a no-deal Brexit. The TCA was widely welcomed by the UK motor industry as it enables tariff-free and quota-free trade between the UK and the EU if certain local content conditions are met (Williams 2021; Bailey and Rajic 2022).[11] Rules-of-Origin requirements in the TCA specify what percentage of total content value must derive from the UK or EU if tariff and quota-free access is to be secured, and their effect is to "limit the proportion of imports from outside the UK and the EU that can be used to create the product" (Mishcon de Reya 2021). However, these figures are "a challenge for EVs where the most expensive single component (the battery) is necessarily sourced from overseas – usually China, South Korea or Japan" (Mishcon de Reya 2021; Hancké and Mathei 2021). To acknowledge this difference in the supply chains for ICEVs and EVs, the TCA established transitional product-specific rules for batteries, hybrids and EVs. Local content requirements for EVs were initially set at 40% (vs. 55% for ICEs) ratcheting upwards to 55% over 6 years i.e., 45% of the vehicle by value can originate outside the EU or UK (see Table 1).[12] The transitional regime establishes a window for UK automakers to adjust, in which UK and EU battery capacity and supply chains can be built.[13]

The initial 40% threshold for EV local content was considered a British 'win' in TCA negotiations (Bailey and Rajic 2022), yet local content

[8] Bailey et al. (2019) observe that industrial policy has roots in the contradictions and failures of a neoliberal economic model but has "almost always done double duty" in managing macro-economic and political objectives.

[9] In 2019, prior to the pandemic, the UK produced 1.6 million vehicles and 2.5 million engines (Faraday Brexit Briefing, 2021). In 2022, however, total UK car and van production fell to 775,000. SMMT (2022) offers higher figures for employment in automotive manufacturing than BEIS (2023): 170,000 direct jobs and 670,000 indirect.

[10] "Average EU wide fleet targets for new cars will be 95gCO2/km from 2021", to be reduced further by 37.5% by 2030. Electrification is to-date the key commercially viable option for passenger cars to meet the targets" (APC 2021, p. 4)

[11] Thus avoiding a situation where import tariffs of 10% would have been imposed under WTO rules for cars manufactured in the UK when exported to the EU, in the context of low profit margins - £450 on a £15,000 car, according to Bailey and Rajic (2022) - this would have significantly affected profitability.

[12] The TCA allows 'bilateral cumulation' – i.e. materials from the UK can be combined with those from EU when calculating the percentage of originating materials – which "may mean UK manufacturers seeking more parts supply from the EU than from e.g. Asia" (Mishcon de Reya 2021).

[13] Automotive OEMs in the UK exporting to third, non-EU countries may attract import tariffs for any battery components manufactured in the EU, as the battery origin will be classed as a third country (Respondent 2).

requirements are a significant challenge for the UK motor industry. The requirement for an originating battery pack (Table 1) creates a need to localise battery production and much of the supply chain. This need is particularly acute, as the EU is pursuing its own "active industrial policy when it comes to the EV supply chain, in an attempt to make the EU into one of the main EV production centres in the world" (Bailey and Rajic 2022: 26). The European Battery Alliance (EBA) is key formation here, together with pooled state aid by EU member states to establish EU-wide collaboration for battery supply chain segments (known as Important Projects of Common European Interest (IPCEIs)). EBA and IPCEIs illustrate how battery manufacturing and a sustainable and innovative battery supply chain are a multi-regional state accumulation project for the EU (expressed, for example, via its support for Northvolt's gigafactory) at a scale yet to be matched by the UK. The institutional capacities built through EBA and IPCEIs also reflect decisive state support for participating firms that is reflected, for example, in compromises embedded in trade and investment policy, i.e., where giga-factories may receive key policy support. While the macro-context for geo-economic competition may be China (with three quarters of global capacity for lithium-ion battery manufacturing), the primary challenger for the UK is Europe where gigafactory capacity is projected to grow to over 1100 GWh (more than 40 plants) by 2030 (Faraday 2022b).[14]

Without domestic battery production, car manufacturers may decide that producing EVs in the UK is not viable and relocate production to the EU (Faraday 2022b). Battery and automotive interests, such as the Society of Motor Manufacturers and Traders (SMMT) and the Faraday Institution (2022c: 10), have argued vigorously for building gigafactories at speed in the UK with a view, amongst other things, to maintaining (and creating) employment during the ICE to EV transition: forecasts indicate that every GWh per annum of battery module and pack assembly supports approximately 180 battery manufacturing jobs, and that each gigafactory job supports 1.8 jobs in the battery supply chain (Faraday Institution 2022c).[15] An *Electrification Skills Framework*, developed by the Faraday Institution, WMG University of Warwick and the High Value Manufacturing Catapult, identifies "key principles and skills needed to make the UK a world leader in battery technology and the green industrial revolution" with the objective of providing clarity around the capabilities, competencies and required standards for navigating the transition to EVs (Faraday 2022b: 4).[16] The stakes are high: large job losses (with significant regional implications) are a likely consequence of failure to develop battery manufacturing at scale, as vehicle manufacturers in the UK wind down production of petrol and diesel vehicles ahead of the phase-out deadline (Faraday 2022a; Bailey and Rajic 2022; Pegoraro et al., 2020). An automotive CEO put this succinctly: "if batteries go out of the UK, then automotive production will go out of the UK" (Ralf Speth, quoted in Bailey 2020). In the remainder of this section, we outline how the UK state has sought to onshore battery production by attracting investment into segments of the value chain, and by developing a battery research ecosystem (Faraday 2022).

3.1.1. From the Automotive Council to the Automotive Sectoral Deal

In the wake of the financial crisis of 2007/8, foreign-owned automotive suppliers in the UK retrenched nationally (e.g. back to France, Germany and Japan). In response, a group of supply chain manufacturers created the Automotive Council (2009) in an effort to "anchor UK suppliers and generate the next generation of UK suppliers in electrification technology" (Respondent 3, 2021). The Automotive Council (2013) collaborated with the Coalition Government in 2013 to produce a report *(Driving success: a strategy for growth and sustainability in the UK automotive sector)* that identified a "need to secure the long-term future of the sector by growing the UK share of the value chain and…(get) ahead of the game in research and development (R&D) on ultra-low emission vehicles" (p.8). It saw this problem primarily as one of innovation, but also noted a strategic need to secure domestic production via inward investment. *Driving Success* announced the formation of the Advanced Propulsion Centre (APC), a private-public partnership to develop, commercialise and manufacture low carbon powertrains. We show below how the APC's role has increasingly extended 'upstream' from power trains to battery production, cell manufacturing, and the extraction and refining of battery mineral materials.

The Automotive Sectoral Deal, announced in January 2018, scaled up the private-public collaboration initiated by the APC and was one of the first mission-focused 'sector deals' embedded in the UK Industrial Strategy (2017). The Deal observed that "in the next 10 years, the sector will see more change than in the previous hundred. From the engines that power our cars, to the way we control them and our attitudes to owning them, technology is changing what the industry looks like and where money can be made." It highlighted the growing urgency for a 'strategic transition' to scale EV production in the UK, given geo-economic competition from countries like Germany and China which had already established themselves as leaders in battery development and manufacturing. In responding to the 'grand challenge' of future mobility, the Deal sought to "put the UK at the forefront of the design and manufacturing of zero emission vehicles." It recognised the UK's history in battery innovation and continuing capacity for technological development but also highlighted, for the first time, the need for "a 'gigafactory' capable of producing the quantity of battery cells needed to meet the future demand for batteries from vehicle-makers as well as establishing the requisite supply chains of the future." We outline below how formation of an Automotive Transformation Fund (2022) has intensified this shift, and how the recent turmoil around the Britishvolt/Recharge Industries[17] project makes the need more urgent still.

3.1.2. Securing the supply chain: the Automotive Propulsion Centre and the Automotive Transformation Fund

The Advanced Propulsion Centre (APC) is a 'co-investment' platform in which the Automotive Council and UK government each commit £500 million over 10 years to advanced R&D projects (Respondent 3, 2021).[18] APC aims to bridge between technological innovation and industrial production – "between those who have good ideas and those who can bring them to market"– with the goal of enhancing the UK's geo-economic position as a 'Propulsion Nation' (Warwick University, 2014). The APC manages the Automotive Transformation Fund (ATF) which was launched in 2022 as a form of stimulation funding intended to lower risk and 'crowd in' private investment. The ATF marks a significant shift towards funding larger capital projects across a spectrum of key EV technology areas (e.g., batteries, cells, and the gigafactories for battery production; electric machines and drives) as well as supporting the upstream supply chain. We show in Section 4, for example, how ATF funds supported development of

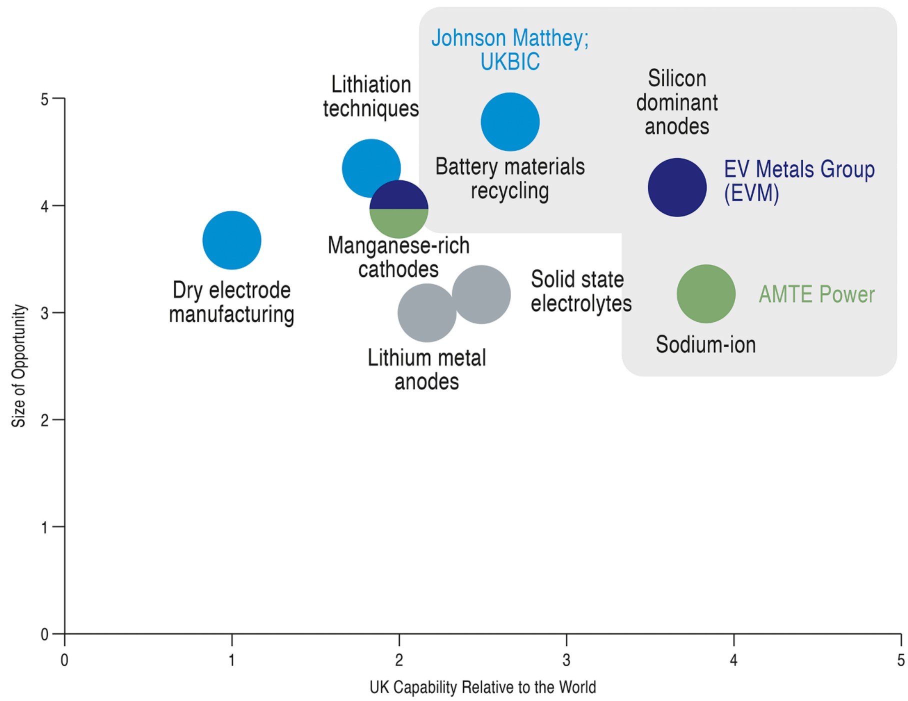
[14] As Faraday (2022a) puts it, the UK "is not moving fast enough compared to its European competitors." If the UK is to maintain its automobile sector – and "maximise the economic benefits from the transition from the internal combustion engine (ICE) to electric vehicles (EVs)" - an estimated 10 gigafactories are needed by 2040 to service demand for battery production estimated at 200 GWh p.a. (Faraday 2022b).

[15] Faraday (2022b) forecast that by 2040, if ten gigafactories with 20 GWh capacity each were to be built, 36,000 jobs could be created in battery manufacturing with 65,000 supporting jobs in the supply chain.

[16] This refers to producers for the mass EV market and exporting to Europe, rather than specialised niche producers.

[17] This notation references the acquisition of Britishvolt by Recharge Industries in February 2023.

[18] The 10-year funding horizon of the APC was extended, in 2022, via the Automotive Transformation Fund, which provides capital rather than R&D funding see 3.2.1 below.



Category	Technology	Potential UK players*	Examples of leading players abroad*
Cross-cutting technologies	Battery recycling	RS Bruce, uRecycle, Johnson Matthey, UKBIC, EMR, Fenix	Umicore, BASF, Gangfeng Lithium, Li-Cycle, Redwood Materials, CATL
	Dry electrodes	PPG, UKBIC	Tesla, VW, AM Batteries, LG
	Lithiation techniques	n/a	Varta, LG, Nanoscale Components
High performance, specialist applications	Solid state electrolytes	Ilika, Britishvolt, Emerson &Renwick, UKBIC, Morgan Advanced Materials	Solid Power, Quantumscape, Prologium, Factorial Energy, SES, Blue Solutions
	Lithium metal anodes	Livent, Leverton Lithium, Sigma Lithium	Abermale, Gangfeng Lithium, Hydro-Quebec, Li-Metal
High volume performance	Silicon dominant anodes	Nexeon, Talga Technologies, EV Metals Group**, Alkegen	StoreDot, Enevate, Enovix, Sila Nanotechnologies
	Manganese-rich	EV Metals Group**, Vale, iCoNiChem	BASF, Haldor Topsoe, NanoOne, Umicore
Entry level, low cost	Sodium-ion	Faradion, Deregallera, AMTE Power, Phillips 66	CATL, HiNa Energy, Haldor Topsoe, NAtron, Tiamat, Altris AB

*Non-exhaustive
**Assumed to have acquired Johnson Matthey's battery material IP

Fig. 2. Promising battery cell technological developments[24].
Source: adapted from APC (2022)

a Northeast Electric Vehicle Hub that has attracted gigafactory investment (Envision AESC with Nissan in Sunderland and, until entering administration in early 2023, Britishvolt near Blyth). In sum, the ATF has an entrepreneurial orientation towards scaling-up, and represents a

> "change in mindset…from de-risking investment in technology to make sure it can work and it's suitable. It's about the supply chains and ramping them up…. Basically, the Automotive Transformation Fund is about, "Right, this is going to happen now." What our challenge is, is scaling up quick enough to meet demand."
> (Respondent 3, 2021)

Attracting gigafactory investment has been a key objective as it anchors automotive manufacturing, creates significant employment, and can initiate a wider supply chain. Gigafactories are billion-pound investments with relatively low margins, but their strategic value lies in their anchoring capacity and driving a supply chain where most of the value added is created. Much of this value is specifically related to cathode manufacturing as explained below:

> "When you break open a battery cell, 40% to 50% of the value is in the cathode. Another 10% is in the anode, and then the other 10%, 15% is in the electrolyte. Right there, you've got 75% of the battery value in three components. Very crudely, that's why we've got things (in the APC portfolio) relating to cathode, anode, electrolyte…. The

reason why cell assembly is there is because of its strategic importance, it is the anchoring investment that anchors the automotive industry to the UK, but then it also attracts what the high-value bits of the supply chain are, which is the anode, cathode, electrolyte. It's the cornerstone investment that unlocks the value and keeps the automotive industry here…. Cathode is probably the most important for the UK to get at two reasons, 50% of the value (and) there's a rules of origin thing as well that's underplayed in this (…), where the TCA basically said that…. you have to have the cathode and X percentage of the battery made in the UK or the sale made in the UK for it to be originating."

(Respondent 3, 2021)

The contribution of cathode manufacturing to the overall value of the battery means that EV manufacturers in the UK who want to export to Europe will "need to get a UK cathode manufacturer for them to avoid the tariff and not make their products uncompetitive" (Respondent 3, 2021). Here the aim to onshore gigafactories, and specifically cathode manufacturing, is tied to retaining, reviving and reinforcing UK capabilities in relation to automotive (EV) manufacturing. It is also tied to the potential for unlocking future economic value from circular business models, such as the reuse and recycling pathways opening up with access to cathode material capabilities tied to battery manufacturing (Respondent 3, 2021).[19] As we show in Section 4, however, cathode manufacturing is a conspicuous gap in the UK's efforts to develop a battery supply chain.

3.2. 'Foundries of the fourth industrial revolution:' national battery research infrastructure

Battery development is a focus for government R&D spending and investment. The recent 'Levelling Up White Paper', for example, proposed three public-private partnerships – Innovation Accelerators –for Greater Manchester, the West Midlands and Glasgow City-Region, with the lofty aim of "replicat(ing) the Stanford-Silicon Valley and MIT-Greater Boston models of clustering research excellence and its direct adoption by allied industries." Tagged as 'Fourth Industrial Revolution Foundries,' these research clusters aim to leverage scientific research and innovation for more equal economic growth across the UK and "reverse the historic decline in manufacturing in the UK." Increasingly, however, UK science and research capacity in relation to batteries has become part of a strategic international positioning of 'Global Britain' in the wake of Brexit, with battery research capacity and battery technology development a vehicle for wider geopolitical objectives (Gamble 2009; Fothergill et al., 2019) – see Fig. 2. The Faraday Battery Challenge (FBC) is an example of this science-led approach (see below) which aims to bridge both research policy and industrial policy.

3.2.1. Faraday Battery Challenge

A government investment of £330 million over a 5-year period (from 2017), the FBC provides scientific, technology development and manufacturing scale-up capability for batteries in the UK. The FBC's technological target is to develop cost-effective, high-performance, durable, safe and recyclable batteries across rapidly expanding markets such as EVs. The research core of FBC is the Faraday Institution where 500 researchers work on "application-inspired battery research" across 27 UK universities focussed on low technology readiness levels (TRLs). FBC also encompasses collaborative research and development programmes, centred on mid-technology readiness levels; and, since September 2021, the UK Battery Industrialisation Centre ([UKBIC], based in Coventry), an open-access scale-up facility focused on developing the manufacturing capabilities necessary to scale battery technologies and move them rapidly to market i.e., TRLs 7–9 (Faraday, 2022c; Respondent 11, 2022). UKBIC has manufacturing capability for battery electrodes, cells, modules and new pack structures at industrial rates. It takes no intellectual property and aims to support UK businesses (and firms looking to expand into the UK) "to bridge the gap from battery R&D to mass production….by eliminat(ing) the need to invest in a £100+ million CAPEX facility during product development" (Innovate UK KTN 2022, pp.23). FBC is an explicit effort to connect three distinct stages of the battery innovation chain – from low TRL to high – with the goal of "ensur(ing) the UK leads the world in the design, development and manufacture of batteries for the electrification of vehicles." We show below how UK leadership in these R&D value chain segments of the LiB value chain contrasts with its limited success in attracting gigafactory investment to sustain the mass-market automotive sector. This distinction between R&D and commercialisation on the one hand (where accumulation centres on intellectual property and the revenues from licensing products and processes) and large-scale manufacturing on the other, suggests how LiBs are a differentiated rather than singular state accumulation project.[20]

3.2.2. Battery science collaboration, trade and finance

In the wake of Brexit, the UK government has sought to develop bilateral science and technology agreements as part of a reimagined 'Global Britain,' with battery science providing a vehicle for collaboration. When the UK and US revised the Atlantic Charter (June 2021), for example, their parallel Joint Statement emphasised battery technologies and critical supply chains as key areas for strengthening collaboration in science and technology. This agenda was taken forward via a US-UK Battery Technology Research and Innovation Online Summit (2022) which highlighted UK expertise in battery research and innovation and promoted academic and industrial partnerships.[21] Development of UK battery science and manufacturing capability is also imagined by UK government as part of a growing 'green industrial base' with export potential through 'green trade'. The UK Board of Trade, for example, has highlighted the battery sector as part of a wider need to develop alternative sources of supply for critical technology components and refined minerals to counter the dominance of China. It cites the UK-Australia Clean Tech partnership as an example of how governments can support resilience and green technology development through trade (UK Board of Trade 2021). Carving out new trade relationships with Australia – via AUKFTA (2021) – incorporates tariff-cuts around clean technologies including EVs, as part of a wider effort to project the UK into the Indo-Pacific region[22] including potential involvement in the Quadrilateral Security Dialogue (US, Japan, Australia, India) which committed (September 2020) to securing critical infrastructure such as

[19] The limited volume of batteries and battery materials reaching end-of-life has been a primary obstacle to developing battery recycling at scale, although this is changing as EV applications rapidly expand. At a recent battery sector event in the NE of England (June 2023), a battery industry participant noted how "OEMS are now seeing that wall, or wave of second life batteries coming" and are partnering with energy firms to extract value from the residual energy storage and power capabilities of EV batteries. Marston (2023) adopts a similar metaphor, referring to a 'tsunami' of end-of-life batteries, rising worldwide from 1 million tonnes per year in 2030 to 20 million tonnes by 2040, with annual concentrations of battery waste in the UK (estimated at 600,000 tonnes per year by 2045) representing a potential strategic asset.

[20] These include lightweight applications like defence drones or heavy goods vehicles, and other battery chemistries such as sodium (in relation to grid storage) and lithium-sulphur.

[21] The summit concluded bilateral collaboration (among academic institutions, and between academia and business) was possible at lower TRLs, although competitive obstacles worked against collaboration and joint venturing at higher TRL commercial projects (Innovate UK KTN 2022, p. 38).

[22] With Australia and the US, the UK is also in a trilateral security pact (AUKUS) centred on nuclear-powered submarines to support Australia in the Indo-Pacific region. Here, the expertise from work carried out by Rolls Royce near Derby and BAE Systems in Barrow is key (UK 2021).

clean energy supply chains (Reuters 2021; Hemmings and Rogers 2020).[23] Linked to this export potential for UK goods and services, the UK Board of Trade (2021: 22) highlights the instrumental role of the City of London as "an ecosystem for green investment" based, in part, on the City's role in initiating green bonds and developing ESG criteria. These initiatives further suggest a plurality of state accumulation projects in relation to LiB and their different intersections with GPNs, which we explore further in Section 4.

3.3. A 'Superpower in the race for critical minerals': flexing minerals expertise and finance

The geopolitical scramble for battery mineral resources has amplified over time, with lithium and cobalt now included on critical mineral assessments in a range of countries. The EU added lithium to its critical minerals assessment in 2020, over a decade after the EU Raw Materials Initiative first drew up a critical materials list as a priority action (EC, 2008). The UK, following a Global Britain model after exiting the EU, has also drawn on its political institutions to shape an agenda for mineral resource access. The British Geological Survey was commissioned to craft the first UK Critical Minerals Strategy, published in July 2022 (UK BEIS 2022). Acknowledging the country's long history of mining and refining, the Strategy identifies national mining and minerals expertise (embodied in institutions such as the Camborne School of Mines) as "essential to the new, Green Industrial Revolution" and enabling the UK to "now be again…a leading player in the global race for critical minerals" (UK BEIS 2022, foreword). The Critical Mineral Strategy, for example, targets an acceleration of UK domestic capabilities including "maximising what the UK can produce domestically", promoting the UK "as a strategic location for refinery and midstream materials manufacturers" and "re-establish(ing) the UK as a centre of critical mineral and mining expertise." To that end, a newly established Critical Minerals Intelligence Centre (UKCMIC) will collect and analyse information on supply, via research on mineral occurrences and extraction potential in the UK and by adopting a global perspective on mineral supply chains (BGS 2022a and b; UKCMIC 2022). The UK's list places lithium on the boundary between 'elevated' and 'high' criticality, with a view to UK economic vulnerability and global supply risk. Such categorisations are performative (Machacek, 2017): they situate lithium within different governmental policy initiatives, enable companies to argue the case for political and institutional support to mitigate supply risk, generate speculative interest in domestic exploration, and provide a rationale for international collaboration and strategic partnerships. For example, the assessment of lithium as having elevated/high criticality led to its inclusion within UKCMIC's national "evaluation of prospectivity" which, considering parts of the UK "underexplored" for critical raw materials, identifies eight regional targets for more detailed research and exploration (Deady et al., 2023: 38).

Since inaugurating its Critical Minerals Strategy, the UK government has launched the Innovate UK KTN-led Global Expert Mission (GEM),[25] the £15 million CLIMATES programme (Innovate UK KTN 2022a), and established several multilateral and bilateral strategic mineral partnerships. It contributed to establishing (2022) the Minerals Security Partnership (UK, Australia, US, Canada, Finland, Germany, France, Japan, South Korea, Sweden, and the European Commission) to facilitate supply chain investment, incentivise supply chain diversification and promote production, processing and recycling (CRM Alliance 2022). It has also collaborated internationally in pursuit of the Critical Minerals Strategy via the IEA, IRENA, G7 and G20; and has concluded bilateral agreements with the US around critical minerals[26]; with Australia (a key lithium partner), via a Critical Minerals Joint Working Group (2020); with Canada (2022) for strategic cooperation on economic resilience, including critical minerals and supply chains; with South Africa (for platinum group metals, iridium, vanadium and manganese) (UK GOV 2022); with South Korea to strengthen supply chain resilience, including critical minerals; and with Saudi Arabia,[27] a growing mineral collaboration which facilitated UK-registered EV Metals Group (EVM, 2023), a global (battery) metal and technology corporation headquartered in Perth, in launching the Australian Lithium Alliance (Mining Weekly 2023; Bloomberg 2022).[28]

Significantly, then, state action to promote national mining and minerals expertise is increasingly positioned as more than an opportunity to create jobs or address regional inequalities. Technical and commercial mining expertise and knowledge, including mining finance, help to position the UK as a scientific superpower: they are identified as being foundational to national security (securing supply chains essential to

[23] Although critical minerals are not a primary focus of "the Quad," the Quad Leaders Summit recently (May 2023) launched a Clean Energy Supply Chains Initiative to "facilitate research and development and feasibility study projects to lower clean energy manufacturing and deployment costs, enhance regional energy security, and expand and diversify the regional production of necessary materials and technologies." In practice, most co-ordination in the region is bilateral, and a key nexus of activity in the Indo-Pacific is the relationship of the Quad with South Korea: while not a member of the Quad, South Korea has "established cooperation mechanisms with Quad nations, particularly Australia, to strengthen critical mineral supply chains and reduce reliance on China" (Liu 2023) e.g. a 2021 Memorandum of Understanding on Cooperation in Critical Mineral Supply Chains, encompassing rare earths, lithium, graphite, cobalt, and nickel. We thank Louis Fletcher for bringing this to our attention.

[24] Fig. 2 illustrates the geoeconomic positioning of the UK in relation to battery technology development, plotting the country's capabilities relative to the world (x-axis), against, the size of opportunity (y-axis). The accompanying table contextualizes this geoeconomic positioning, according to four broad categories of technology (colour-coded). It showcases the relevance of lithium (and 'primary lithium' from extraction as opposed to lithium from recyclate – see the category 'cross-cutting technologies') next to other mineral elements such as sodium battery chemistries, and UK actors as well as other actors.

[25] GEM (2023) has the aim of 'building strategic partnerships, providing deep insight into the opportunities for UK innovation and shaping future bilateral collaboration programmes.'

[26] The 'Atlantic Declaration' between the UK and US (June 2023) includes two provisions pertaining to critical minerals: (i) a statement of intent to negotiate "a targeted critical minerals agreement covering the five relevant critical minerals most important for electric vehicles – cobalt, graphite, lithium, manganese, and nickel – that are extracted or processed in the United Kingdom," in which these minerals are designated 'domestic sources' for US EV manufacturing, making them eligible for clean vehicle tax credits (Section 30D) of the Inflation Reduction Act; and a "one-year Joint Clean Energy Supply Chain Action Plan to "identify and decide on near-term actions our two countries can take in parallel and together to accelerate the buildout of capacity in our countries and third countries sufficient to meet the clean energy demands of the future." Designating UK materials as 'local content' for US EV manufacturers is confined to upstream mineral extraction and processing and does not extend downstream in the value chain to cells, batteries, or cars.

[27] In May 2023, the UK and Saudi Arabia upgraded their pledge to deepen collaboration on critical minerals (January 2023) by signing a 'declaration of intent' centred on critical mineral supply chains, collaborative research in clean mineral production and knowledge exchange on projects, skills development, and practical initiatives relating to critical minerals. Significant here is Saudi Arabia's launch of a US$15bn fund to invest in foreign mining assets, co-owned by Saudi's state-owned miner, Ma'aden, and its sovereign wealth fund, the Saudi Public Investment Fund (FT 2023). The fund will make Saudi a strategic player in the future of the critical mineral supply chain, and a potential supporter of the UK mining sector, as part of the country's Vision 2030 which seeks to diversify away from fossil fuel extraction.

[28] The Alliance underpins agreements with ASX-listed mineral explorer Zenith Minerals for lithium minerals in Western Australia. Further, the bilateral agreement supports Tees Valley Lithium UK (both cases explored in Section 4). These initiatives are matched by public-private partnerships such as Future Battery Industries Cooperative Research Centre (FBICRC, 2023) which seek to extend value generating activities beyond mining in Australia.

clean manufacturing technologies in the UK) and the possibility of remaking global production networks at the world scale through international collaboration. The strategic, geopolitical potential of UK geological expertise in a decarbonising world - where mining and minerals become more important than hydrocarbons - is articulated most clearly by the Council on Geostrategy, a non-governmental think-tank: "the UK should not accept at face value the dominance of specific countries in key points of the supply chain. These are industries in flux, and in periods of high growth there is opportunity to take market share for those who are committed and nimble" (Council on Geostrategy 2021). Here, then, mining and minerals expertise linked to the battery sector are not only a way to reduce supply risks and establish foundations for manufacturing, but also to align "nations such as Japan, Canada, Australia, Indonesia and others behind the opportunities of the Net Zero agenda and the reduction in exposure of the London Stock Exchange to – and by extension British pensioners' dependence on – coal mining, and the further development of the UK as a centre of mining financing and research" (Council on Geostrategy 2021: 14). Here we see a further dimension of LiB as a state accumulation project: that of decarbonising financial capital by shifting it from fossil energy carriers to mineral-based materials, such as the metals needed for energy system transformation.

In this section we have positioned efforts to onshore LiB production and develop a supply chain within a state accumulation project of green industrial transformation. We have shown how this project is differentiated into (at least) three dimensions when it comes to batteries: battery manufacturing, closely anchored to the automotive sector in the UK; battery research and development, based on future intellectual property, technology licensing and commercialising next-generation batteries; and critical minerals expertise and finance, and its potential for global partnerships and for decarbonizing 'high-carbon-assets'. Section 4 explores how these dimensions are embedding the UK in global production networks for lithium.

4. The UK's evolving lithium economies

In this section we consider the lithium economies of which the UK is increasingly a part, working upstream along the production network from gigafactory development through cathode materials to mineral raw material supply (see Fig. 3), describing developments until July 2023 (and noting that the investment landscape continues to evolve, see UK GOV 2023). Lithium is not the only mineral element that matters for lithium-ion battery production, but it provides a specific lens for positioning the UK within evolving global lithium networks. Given the dynamic nature of developments in this space, our approach is illustrative rather than encyclopaedic. Our aims is to capture key features, as of mid-2023, and we make no claims to being comprehensive. Our approach here, then, is selective and focused on the local and global dynamics of lithium: we have, for example, not included reference to nickel refining (where the UK has the largest refinery in Europe) or to cobalt or copper. Viewing the UK in relation to wider geographies of production offers a window on how geo-economic competition and state strategy are shaping global and lithium dynamics, and shows how efforts to onshore battery production and develop a domestic supply chain are embedding the UK in global networks of production and finance.

4.1. Gigafactories: battery and cell assembly

Capacity to produce and assemble cells and batteries in large 'gigafactories' in the UK is widely regarded as key to retaining a UK automotive sector, and there is concern about the UK's ability to deliver enough large-scale gigafactories by the 2030 petrol and diesel deadline (AMTE Power 2023). Demand for EV battery manufacturing capacity in the UK is expected to be around 100 GWh per annum in 2030[29] (and nearly 200 GWh in 2040) with four-fifths arising from the manufacture of cars and light commercial vehicles (Faraday 2022a; BEIS 2023). Mass market battery manufacturing is embedded in the Automotive Sector Deal (2018) as a shared objective of government and industry and is a target of the Automotive Transformation Fund. In this section we consider three high profile gigafactory investments in the UK (Envision-AESC, Britishvolt/Recharge Industries, Tata/JLR), two smaller UK-based cell and battery manufacturers seeking to commercialise and scale (AMTE Power, Ilika plc), and an example of a land parcel looking for investors (West Midlands Gigafactory).

4.1.1. Envision-AESC and Nissan

In the early 1980s, the Thatcher government positioned the UK as a 'gateway to Europe' (Conn 2018), attracting Nissan's investment in Sunderland with significant state financial support including discounted land and capital equipment grants (IMECHE 2014; Farnsworth et al., 2017).[30] Nissan began producing the Leaf EV model at its Sunderland plant in 2012, with batteries assembled locally by the Japanese company AESC (then 51% owned by Nissan and, since 2018, 80% owned by a Chinese energy conglomerate as Envision-AESC).[31] Uncertainty over future trading arrangements in the years running up to the UK's exit from the EU reportedly led Nissan to consider divesting from the UK. State aid was promised to entice Nissan to remain, and government commitments were made that Nissan would not be "adversely affected" after the UK left the EU (Sabbagh and Jolly 2019).[32] Regional support included development of an International Advanced Manufacturing Park (IAMP) adjacent to Nissan's facility, funded by South Tyneside Council and Sunderland City Council, to serve as a hub for next generation EV production (Batterynews 2021).

In July 2021, ten years after the first LEAF, Nissan announced a £1 billion investment in partnership with Envision-AESC. Designed with an annual capacity of 12 GWh - six times the current Sunderland battery plant, with expansion up to 35 GWh - this is the first 'at scale' battery plant in the UK. The role of the regional state in 'harnessing and matching assets' (Dawley et al., 2019) was significant here, including state aid, infrastructure support via the IAMP, and development of a renewable energy microgrid by Sunderland City Council that will supply electricity to the plant. The IAMP, microgrid and investing partners bring together electric vehicles, renewable energy and battery production in what the company calls 'Nissan EV36Zero'. The gigafactory will provide batteries for a new EV model platform in the Renault-Nissan-Mitsubishi alliance, sufficient for 100,000 EVs per year (Elective 2021; BBC 2021). Envision AESC is a Tier-1 battery producer

[29] Gigafactories come in a range of sizes, although an average mass-market battery manufacturing facility is between 10 and 30 GWh. Announced UK battery manufacturing capacity (as of May 2023) was around 12 GWh (HC 2023). Given that "you typically need two or three years to develop a gigafactory and to get it up to speed, and maybe one or two years planning before that…we need at least two or three to be decided on in the next two or three years in order to hit those 2030 targets and to be on track" (Stephen Gifford, Chief Economist, Faraday Institution quoted in HoC 2023)

[30] Total initial government investment in attracting Nissan has been calculated at £125 million by 1988. At this point Nissan's initial investment was £50 million, rising to £900 million by 1993 (Farnsworth et al. 2017).

[31] Battery production at AESC's existing Sunderland plant appears to involve imported batteries that are then assembled for the Leaf model (Batterienews, 2021).

[32] Subsequently the Covid-19 pandemic and constraints in supply of semiconductors (Yeung 2023) impacted automotive production in the UK and globally (The Guardian 2022). Farnsworth et al. (2017) describe how Brexit gave Nissan leverage over the UK government, reporting a range of projects that received UK government funding which mirrored 'immediate tangible requests' from Nissan.

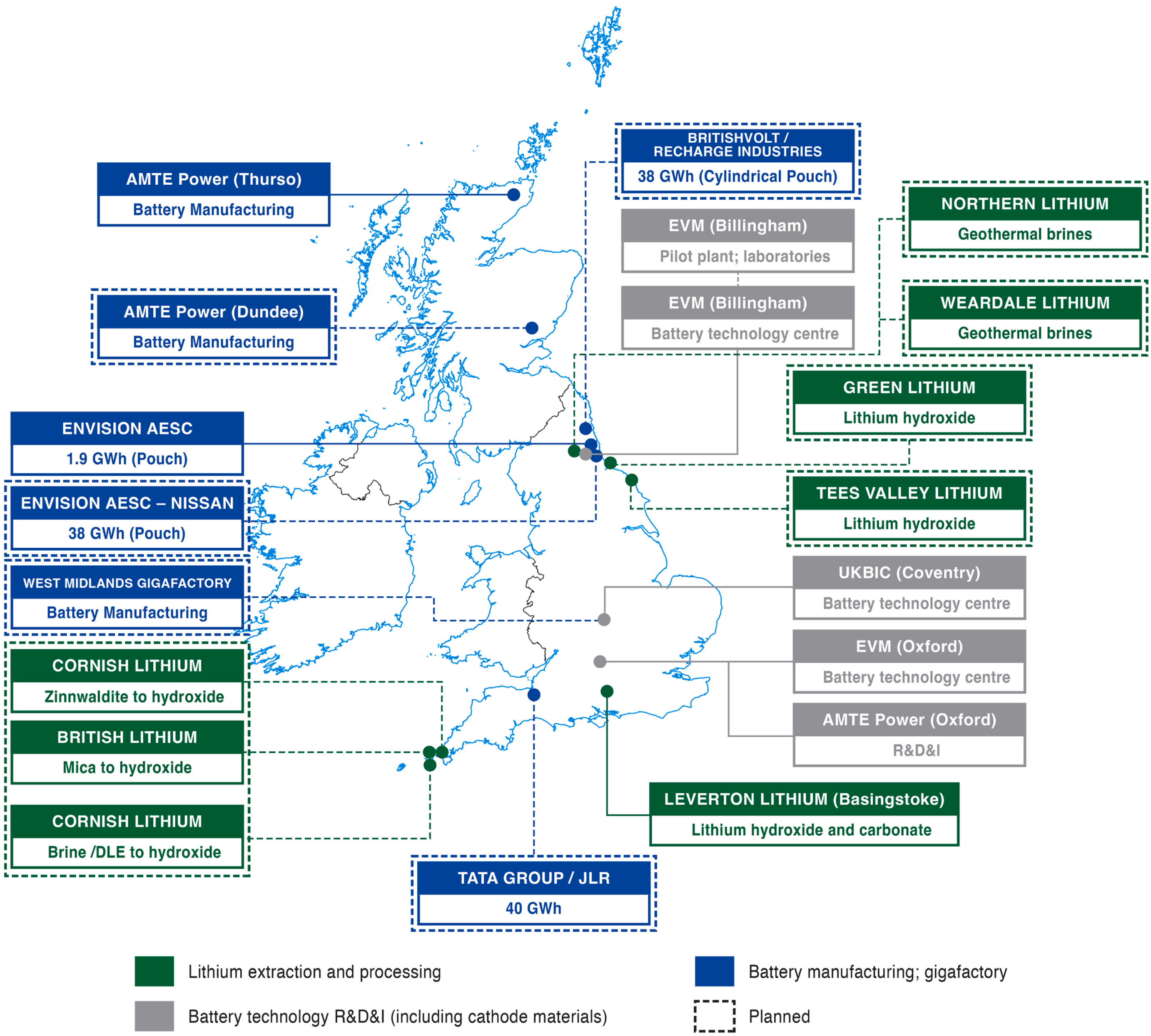


Fig. 3. Lithium and the UK battery landscape.
Source: adapted from Benchmark Minerals (2022).

supplying multinational automotive OEMs outside of China that, in addition to the Renault-Nissan-Mitsubishi alliance, include Mercedes Benz and BMW (Moores, 2021; Bridge and Faigen 2022). The Sunderland gigafactory complements the company's strategic needs - its global expansion plan targeting 400GWh by 2026, forming part of a corporate network that has headquarters and two battery production plants in Japan, three plants in the US, two in Europe (France, Spain), and four plants and R&D in China (see Fig. 4).

4.1.2. Britishvolt/Recharge Industries

Battery start-up Britishvolt (BV) was envisioned as a second, high volume battery producer in the UK. Inaugurated in 2019, BV entered into collaborative agreements with APC and UKBIC in early 2020 and, in 2021, it acquired land for a 30 GWh production plant at a former power station near Blyth, Northumberland that had recently been connected by subsea cable to Norwegian hydroelectricity. The UK Government's ATF committed £100 million in January 2022, contingent on BV securing battery manufacturing equipment from South Korea and Germany (UK BEIS 2022; The Guardian 2022a). The prospect of ATF money enabled BV to partner with a real-estate fund manager (Tritax, owned by Abrdn) and access £1.7 billion in private funding to build the plant. Collaboration with the Faraday Institution and the Warwick Manufacturing Group would enable progress towards battery production. Britishvolt promoted its future batteries' green credentials: carbon dioxide emissions from battery manufacturing would rank lower than equivalent gigafactories in Europe, South Korea, Japan and China; and BV

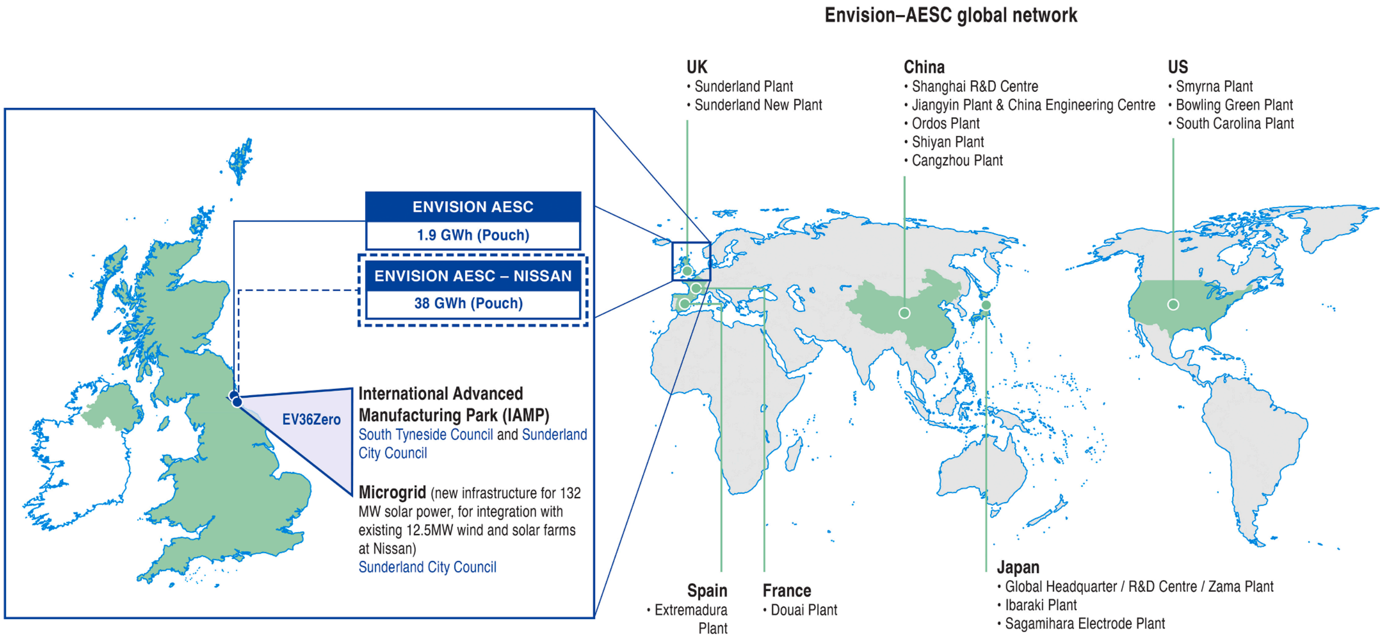


Fig. 4. EV36Zero initiative in the Envision-AESC global LiB production network.
Source: adapted from UKBIC 2023; Envision AESC 2023.

partnered with the mining firm Glencore, which committed £40 million, to develop battery recycling in the UK (UK BEIS 2022).[33]

BV declared insolvency in January 2023 with a reported debt of £120 million (BV 2023; The Guardian 2023a). Although the company was developing a prototype battery, it had neither a proven product nor a committed volume customer.[34] Several contenders[35] emerged to pick up BV's land package and, in February 2023, an Australian start-up – Recharge Industries, owned by New York fund Scale Facilitation Partners – acquired the business and assets with plans to develop a gigafactory on the Northumberland site and, at the same time, produce batteries at a former car manufacturing hub in Geelong, Victoria, Australia (The Guardian 2023b; Financial Times 2023). Recharge has yet to raise the capital for investment, but proposes to build lithium-ion batteries free of materials from China or Russia. Its pitch reportedly "lent on strategic and diplomatic ties and received support from the British government's trade envoy for Australia" (The Guardian 2023c).

Britishvolt/Recharge Industries shows how the UK's strategic gap around cathode material production and large-scale cell manufacturing has, so far, been filled with speculative forms of private finance capital and commercial real estate development (underpinned by land and planning agreements with local councils) rather than by investment from leading international battery producers. In essence, this flagship gigafactory project – a state accumulation project at the convergence of research policy and industrial policy, combining battery development (FBC-funded) and battery manufacturing (ATF funded) – attracted speculative forms of capital seeking decarbonization using, in part, the green credentials of a comparative life-cycle analysis methodology for the envisaged battery product.

4.1.3. Tata Motors Group/Jaguar Land Rover

Tata Motors Group, owner of Jaguar Land Rover (JLR), announced plans (2023) to construct a 40 GWh battery manufacturing facility in Somerset. This will be Tata's first gigafactory outside India, and will be located on the Gravity industrial park near Bridgwater with power available from the Hinkley Point nuclear power station.[36] Tata/JLR was considering an alternative site in Spain and, to land the deal, the UK government is reported to have provided around £500 million in support including subsidies for energy use, a grant from the Automotive Transformation Fund, and state-funded infrastructural improvements (FT 2023a). The selection of the Gravity site is reportedly also linked to Tata's steel business in Port Talbot, south Wales, which has received around £300 million in government funding to improve and decarbonise the plant (BBC 2023). It is reported that Envision-AESC will supply the battery technology for manufacturing at JLR's Somerset site, including supplying batteries from AESC's Sunderland plant when it comes on stream and before the Somerset plant is commissioned (FT 2023c). Longer term, TATA is expected to design and produce batteries via its new global battery business, Agratas, located in Sanand, northern Gujarat, India (FT 2023b; InsideEVs 2023; Reuters 2023) The facility in India is being developed with 20 GWh capacity, via an investment of USD 1.58 billion (130 billion rupees) and an MoU between Tata Group subsidiary Agratas Energy Storage Solutions and the government of the western state of Gujarat under the latter's new 2022–28 Electronics Policy (TechSciResearch 2023). Tata/JLR is the UK's second largest auto-producer, accounting for around a quarter of all production, and the planned scale of the Somerset facility means it will have capacity to produce batteries for other auto manufacturers in the UK. Announcement of this gigafactory has been hailed by some as a potential turning point for onshoring battery production, with its scale anticipated to incentivize investment by other firms along the battery supply chain (The Guardian 2023d; UK GOV 2023).

[33] LCA stipulating GHG emission associated with production of NMC111 batteries (25kg CO_2/kWh) - compared to China (91 kg), Japan (89kg), South Korea (82kg), US (66kg), Europe (62kg).

[34] BV sent its first sample of batteries for testing in September 2022. Two niche automotive firms (Lotus and Aston Martin) had signed non-binding MOUs.

[35] Among these were DeaLab– a private equity firm with Indonesian roots; Greybull Capital; HSBC-backed Saudi British Bank; and Recharge Industries an Australian start-up backed by US capital (The Guardian 2023b; see also Financial Times 2023)

[36] The Gravity site was reportedly also under consideration by US SUV producer Rivian, and financially supported by e-commerce actor Amazon which had joint interest in electric delivery vans. However, Rivian's decision-making about future production sites turned in favour of Germany (Nasdaq 2023).

4.1.4. AMTE Power

AMTE Power currently has the second largest cell manufacturing capacity in the UK. Based in Thurso, Scotland, it was established in 2013 by technology engineers from the defence technology company QinetiQ although its origins trace back to a spin-off from the Atomic Energy Authority and two Japanese groups that inaugurated a lithium-ion battery plant in Thurso in the 1990s (Daily Business Group 2021a). AMTE owns a range of battery IP with a focus on high performance automotive and heavy goods applications where it works with partners such as Cosworth, Viritech, MAHLE Powertrain and BMW (AMTE Power 2022).[37] Its focus is on developing a UK supply chain "to support higher value, lower volume specialist automotive markets such as motorsport, sports car, long range commercial and off highway vehicles" (AMTE Power 2023). AMTE Power is looking to scale up its own cell manufacturing capacity via a 'mega-factory' (0.5 GWh) proposal in Dundee to commercialise the company's core products and produce around 8 million cells per year (Daily Business Group 2022). To that end, AMTE concluded a framework agreement in 2021 with UKBIC in Coventry to scale-up production of its Ultra High Power and Ultra Energy cells, generating sufficient cells to enable real-world testing by its customers.[38] Since 2021, AMTE Power is also invested with InfraNomics Technologies (a capital investment firm) in a 50/50 Australian joint venture – Bardan Cells – which is pursuing a similar upscaling route to commercialisation, developing a 'micro' cell-manufacturing facility for 200,000 cells in the Kwinana Industrial Area south of Perth, known as Australia's 'Lithium Valley' (AMTE Power, 2021; Daily Business Group 2021b).

4.1.5. Ilika

Ilika Plc is a UK-based battery start-up specializing in solid-state battery technology with applications to the health care sector and high-performance vehicles. It was originally spun out of Southampton University in 2004 and is now the UK's largest pure-play, publicly listed battery company. Ilika began developing its large format Goliath batteries in 2018 with Faraday Battery Challenge (FBC) support, and has led work on an FBC-funded feasibility project for a 50 MWh / year pilot-plant to manufacture solid state battery cells at the UKBIC (Ilika 2022a, b, 2023). It conducted this work in collaboration with Comau, a global corporate player in industrial automation headquartered in Turin and a member of Stellantis, producing a feasibility study for scaling up battery production for the automotive sector. Ilika has also been a partner in further FBC-funded projects, along with partners like JLR, AMTE, Warwick Manufacturing Group, BMW and Williams Advanced Engineering, to develop and apply solid-state cell and vehicle battery pack technology for use in passenger vehicles (FBC 2019; Fox 2023). Although solid state batteries do not use lithium-ion technology, Ilika is part of a broader cell and battery development ecosystem in the UK that harnesses government support (via APC, UKBIC and FBC) and private funding to develop and scale cell and battery technology. It is an example of how FBC has sought to combine scientific, technology development and manufacturing scale-up capability for batteries in the UK (Fox 2023).

4.1.6. The West Midlands Gigafactory

Finally, the West Midlands gigafactory is a public-private joint venture between Coventry Airport Ltd and Coventry City Council. It is anchored by a land parcel in the West Midlands close to several automotive manufacturing plants and UKBIC, and supported by an alliance that includes local and regional government, Warwick Manufacturing Group (Warwick University), Coventry University and the Manufacturing Technology Centre. Renewable energy is provided through the national grid, as well as through solar panel installations. Full capacity on the site would mean an operation of up to 60GWh (West Midlands Gigafactory 2021). As yet there are no anchor tenants for the site which is one of several potential gigafactory locations seeking inward investment. Like Britishvolt/Recharge Industries, it is an example of how much of the popular excitement in the UK around potential gigafactory development is driven not by proposals from Tier 1 battery suppliers, but by property development interests, capital funds and regional governments seeking to attract investment.

4.2. Cathode materials

The cathode is a key part of the battery cell, and most of a battery's material demand by value relates to the cathode. Cathode material production, therefore, is important to meeting the 'rule of origin' requirements of the EU-UK TCA which specify 65% UK/EU content for the cell from January 1st 2027 (Table 1).[39] Cathode material manufacturing is a specialised chemical business and a key 'midstream' step between refined materials and cell manufacture. It involves combining refined mineral-based materials into an intermediary form to be subsequently integrated into a battery cell (Bridge and Faigen 2022). Here we consider the case of EV Metals Group (EVM), an integrated battery chemicals company which entered the UK in 2022 with the purchase of midstream capacity previously owned by Johnson (2022).

EVM exemplifies the unfolding local and global dynamics of lithium in relation to the UK battery industry, illustrating how efforts to 'onshore' the global battery supply chain insert the UK into wider geographies of production and flows of capital in the context of geoeconomic competition for control over the battery mineral supply chain. EVM is a privately held, international battery materials company which integrates mining and refining of battery materials, battery chemical manufacturing, and cathode active material manufacturing. This 'resource to OEM' model is unusual in the battery minerals sector, although there are increasing moves towards vertical integration across different parts of the supply chain (Bridge and Faigen 2022). EVM is in a developmental phase across its suite of assets and not yet in production. Acquisition of Johnson Matthey's battery business included UK technology development centres (Oxfordshire and County Durham), a technical group and IP linked to cathode active material commercialisation, and a cathode active material plant being built in Poland. Acquisition integrates these UK and European assets into a corporate supply chain that also includes a major Battery Chemicals Complex being constructed in Yanbu Industrial City in Saudi Arabia. The Yanbu Battery Chemicals Complex, aligned with Saudi Arabia's Vision 2030 plan for economic diversification into renewables, aims to offer an alternative to China's control over battery mineral supply chains and will supply battery chemicals to UK/European cathode material manufacturers.[40] Locating cathode active material manufacturing capacity in

[37] This involves IP licensed from third parties which is being used for further development (AMTE Power, 2022). In addition to lithium-ion battery chemistries, AMTE is also developing sodium-ion battery chemistries (see Fig. 2).

[38] The agreement started in January 2023, covers 24 months, and stipulates production of up to 60,000 of AMTE Power's Ultra High Power cells per year for the high power automotive and fuel cell electric vehicle markets. In August 2022, AMTE Power announced that manufacturing trials for the Ultra High Power cell at UKBIC delivered AMTE Power's cell target specifications, including a six minute full-charge.

[39] The Chief Executive of AMTE Power recently testified that the UK and Europe are "playing catch-up" in relation to cathode active material, and that with the UK's lack of capacity in this area "it is going to be very difficult for us to comply fully with the rules of origin" (HoC 2023: Q49). An estimated 150,000 tonnes of cathode materials per year are needed to support EV battery production in the UK by 2030 (Marston 2023).

[40] The complex will include "a plant to produce lithium hydroxide monohydrate; a nickel chemicals plant to produce nickel, cobalt and manganese sulphate; and a pre-cathode active materials plant" with start-up planned for 2024 (Kallanish 2022).

Europe – such as EVM's Polish plant and potential developments in the UK – will help OEM and battery cell manufacturers in UK/Europe meet the TCA's 'rules of origin' requirement. EVM's integrated production network also extends to ownership of a nickel-cobalt project in Australia; and creation in 2022 of the Australian Lithium Alliance, a wholly owned subsidiary of EVM to partner in joint-ventures and lithium off-take agreements with Australian lithium mining and refining companies.[41]

In sum, EVM's entry into the UK via the purchase of Johnson Matthey's cathode active material assets anticipates demand for these materials from gigafactory development in both the UK and EU. While it maintains UK jobs in technology development, cathode active material manufacturing (like gigafactory development) may go to Europe. Overall, EVM integrates the UK into a wider geography of battery mineral materials that includes major battery chemical investments in Saudi Arabia and the expansion of lithium mining and refining in Australia.

4.3. Lithium extraction and processing

Efforts to onshore the battery supply chain extend to lithium extraction and processing.[42] Support for domestic lithium mining and refining has come from the Automotive Transformation Fund, outlined below, and supplements bilateral diplomatic initiatives aimed at securing reliable lithium supply (see Section 3.3).

4.3.1. Domestic mineral exploration and extraction, and processing

The Automotive Transformation Fund (ATF) is providing funds to three junior exploration firms exploring for and developing domestic lithium occurrences, although none are yet in commercial production.[43] In various jurisdictions across the world, including in established mining regions, the potential to extract lithium is being explored in relation to financial, socio-cultural and environmental factors (Ibarra-Gutiérrez et al., 2021; Chaves et al., 2021; Escosteguy et al., 2022). Cornwall, in the UK's southwest, has centuries of mining heritage, and geothermal lithium brines discovered in the 19th century within the region's copper mines have attracted renewed interest (BBC 2020). *Cornish Lithium*, a private firm with access to lithium from hard rock and geothermal brines, plans to produce battery grade lithium hydroxide using experimental Australian technology to extract lithium from these geothermal brines while also using conventional technology to recover lithium from granites at a former kaolin pit.[44] The company received ATF support in 2022 for a demonstration scale processing plant (SPG 2022). The company has a £2.3 m licensing agreement with the Australian ASX-listed firm Lepidico, providing access to 'an innovative and environmentally responsible metallurgical processing solution' that will extract lithium from zinnwaldite and polylithionite mica ores (Business Live 2020). *British Lithium*, also a private firm operating in Cornwall, is seeking to produce 20,000 tonnes a year of lithium carbonate from the mica in granite, at a former kaolin works in the St Austell region. The company received £2 m in government funding from the ATF's Scale-Up Readiness Competition in 2022 to move beyond pilot plant stage. At the other end of England, *Weardale Lithium* - located in County Durham's historic lead mining district - is proposing to extract lithium from geothermal brines using direct lithium extraction (DLE) technologies (North East Future Resources 2022).[45] This early phase development received a grant from the ATF to prepare a feasibility study and investment case, aiming for a pilot plant. There is the potential to use recovered geothermal brine heat for heat and/or power generation, and interest in marketing the lithium as 'green' (LSE 2022a).

4.3.2. Domestic refining initiatives

There are two substantial initiatives to establish large-scale lithium refineries in the UK. Unlike the EVM example above, where battery chemical production is part of an integrated supply chain, these are merchant/tolling operations that would receive mine output and generate battery-grade lithium products for onward delivery to the battery minerals supply chain. *Green Lithium* (2022), backed by the global metals trader Trafigura,[46] received ATF funding for a feasibility study to develop Europe's first large-scale lithium refinery, drawing on spodumene feed to produce lithium hydroxide (for NMC battery chemistries) and lithium carbonate (for LFP chemistries) on Teesside (NOF 2023).[47] Alkemy's wholly owned subsidiary *Tees Valley Lithium* (TVL) is also planning a refinery on Teesside (TVL 2022a). This refinery will receive primary lithium sulphate from Alkemy's planned lithium sulphate monohydrate refinery at Boodarie, close to Port Hedland in the Pilbara region of Western Australia, but with capacity to also take crude lithium carbonate from UK sources and, following EU 2027 legislative requirements, recycled material (SMH 2023; The Guardian 2022b; Kitco News 2023).[48] TVL UK will produce lithium hydroxide (for NMC), lithium carbonate (for LFP) and nickel sulphate (TVL 2022b). Alkemy's simultaneous investment in the Boodarie and Teesside refineries indicates formation of an inter-continental lithium supply chain, and a convergence of Australian interests in downstream processing with UK interests in onshoring. TVL is positioning its UK refinery to lithium miners in Africa, Australia and South America as a gateway to "the burgeoning European market" by exporting a high-value, low-carbon intermediate product (TVL 2022b:11). TVL's UK refinery received a first phase approval from the ATF in 2023, supporting its access to £1 billion in private capital (Shares 2023), and the refinery will be fed with electricity from the Equinor-owned Dogger Bank wind farm in the North Sea with power shifted from natural gas to hydrogen, in a trial with BP (LSE 2022b).[49]

Our goal in this section has been to illustrate some of the 'out workings' of efforts in the UK to onshore battery production and develop a domestic supply chain. Our empirical focus highlights the multifaceted role of the UK state in constituting battery production networks. It shows how a state accumulation project of green industrial transformation

[41] EVM describes the ALA as "an alternative to Chinese companies that currently dominate the purchase of spodumene concentrate (SC6) from Australia."

[42] The UK battery industry is expected to require around 80,000 tonnes of lithium carbonate per year by 2030, around 7% of global demand (Gifford 2023).

[43] The company has received funding from TechMet Limited worth £18 million since November 2021, raised £12 million via crowdfunding, and received 'additional funding from Innovate UK through the ATF Scale up Readiness Validation competition (IG 2019; Cornish Lithium 2021; SPG 2022)

[44] Pegmatitic occurrences might gain increasing exploration interest for high-quality lithium occurrences, and potentially diversify the geographies of lithium extraction (Gruber et al 2011, in Narins 2017)

[45] DLE processes have been assessed as consuming less water and less waste than conventional processing techniques for alternative lithium sources (LSE, 2022a).

[46] Trafigura provides bankability through long-term supply contracts to finance the debt (NOF 2023).

[47] Green Lithium estimates annual imports of 340,000 t of spodumene, 60,000 t of soda ash, and 60,000 t of quick lime for 50,000 tpa battery grade lithium output which amounts to about 70% of estimated UK demand by 2030 (NOF 2023).

[48] TVL has been allocated land along with BP, POSCO, Fortescue Metals and Alinta Energy with the aim of making Boodarie part of an A$70 billion globally competitive Pilbara green industrial precinct hosting the Asian Renewable Energy Hub (AREH), an 11 GW intercontinental renewable energy project (7.5 GW wind, 3.5 GW solar power project, with possibility for conversion to hydrogen and ammonia) to be led by BP.

[49] TVL and Green Lithium supplement an existing lithium chemical manufacturer and distributor, Leverton Lithium (2022), that recently concluded an agreement with a German chemical marketing company to scale up its manufacturing capacity to 20,000 tonnes per year.

directs and selects targets for state support, the role of local institutional capacity in creating alignments between regional assets and firms in GPNs, and the reliance of TNCs on the innovative capacity of SME suppliers (Rutherford and Holmes 2008; Rutherford et al., 2018). We have shown efforts to onshore LiB production and construct a battery production network to be a differentiated state accumulation project: the UK government is seeking to assemble several previously discrete elements into a coherent sector, including automobile manufacturing, battery R&D, materials chemistry, minerals exploration and mining, and green finance. We have highlighted the UK's progress and limits (at the time of writing) in attracting gigafactory investment at the scale and pace required to support automotive incumbents in navigating the transition to electrification and a post-Brexit environment. We have focussed on state efforts to align regional assets with firms in GPNs and create strategic coupling; the significance of cathode materials in the overall equation of battery manufacturing under the EU-UK TCA's rules of origin requirements and, by contrast, the UK's limited capacity to do this at scale; and 'upstream' efforts to support domestic lithium mining and refining capacity, and boost geological knowledge and its nexus with mining finance which – compared to cell and battery assembly – are less directly tethered to the specific needs of the UK automotive sector.

5. Concluding discussion

This paper has explored local and global lithium dynamics arising out of strategic concerns in the UK for the fate of its automotive manufacturing sector, in the context of a structural shift towards EVs and the UK's exit from the EU. Our grounded case of the lithium-ion battery/automotive nexus is an atypical perspective on lithium dynamics, as GPN research tends to focus on zones of lithium extraction and their integration into production networks as suppliers of battery mineral materials. Yet the automotive sector's nexus with lithium-ion battery production is a major driver of lithium's geographies and organisational networks (Bridge and Faigen 2022), so that exploring this dynamic from the battery-consumer end of the chain can offer a valuable and complementary perspective. Our primary aim has been empirical: to document this nexus from the perspective of the UK at a critical moment in its evolution; and to understand how it is driving efforts to onshore battery production and develop a domestic supply chain. We adopted a GPN perspective and, within that, focused on how the UK state has sought to onshore different elements of the battery value chain and shape the intersection of global lithium-ion production networks with the UK. We deployed the notion of 'strategic coupling' to explore different outcomes (modes and types) of coupling, and the concept of 'coupling creation' to shed light on the antecedents to strategic coupling. We deployed the notion of a 'state accumulation project' (Rutherford and Holmes 2008) to reflect the centrality of the automobile-battery nexus to green industrial transformation in the UK. We used the concept of the 'entrepreneurial state' (Mazzucato 2015) to capture the directive, risk-taking and yet selective role of the state within this project. This combined conceptual perspective has allowed us to show three things.

First, we showed (in both Sections 3 and 4) the significant power of incumbent transnational automotive OEMs in garnering support from state institutions to promote a lithium economy that is responsive to their needs. This speaks to Rutherford and Holmes (2008) argument about how TNCs are privileged within GPNs by state accumulation projects. Automotive sector incumbents have sought to steer industrial and research policy along technological trajectories in a bid to ensure continuity of UK automotive production. The Automotive Deal and the ATF highlight an important material basis for battery industrialisation policy in the UK that actively shapes the LiB-automotive nexus. Here the state's actions are primarily defensive, in the sense they are designed by and respond to incumbent actors (as shown on the cases of Envision-AESC and Nissan, and Tata Motors / Jaguar Land Rover) and they configure institutional funding and R&D in support of the automotive industry (e.g., APC, Faraday Institution/FBC). We demonstrated how the state accumulation project of green industrial transformation has been selective and tailored towards these OEM incumbents (and key arms of material processing, such as the case of Tata's steel), while being discursively packaged as narratives of 'greening' and 'transition'. There is some evidence, for example, that government's focus on automotive applications (via the APC) has deflected support from other, long-term growth areas such as alternative forms of e-mobility and energy storage.[50] The example of the Gravity industrial land parcel, which was considered by a couple of automotive OEMs (Rivian with Amazon, and Tata Motors/JLR) in their search for European production sites, demonstrates how coupling creation is challenging when government signals are inconsistent or missing.[51] Industrial policy in the UK has been characterised by limited duration, changing objectives, competitive bidding among regions and, ultimately a limited scale of support (in the face of the substantial structural and financial challenge of automotive restructuring, and the 'game-changing' scale of the US Inflation Reduction Act). These features of industrial policy attest to the relative power of the UK Treasury over other organs of the state, and to the prevalence of a neoliberal approach to industrial policy that constrains full manifestation of the entrepreneurial state. Together these have limited the state's overall capacity to address the challenges of automotive restructuring.

Second, we have shown how the state's efforts to localise battery production in the UK and develop a domestic supply chain are plural. They include trying to converge two distinct political economies and areas of policy – battery science and industrial manufacturing; harnessing national sources of mineral expertise and green finance; and strategically coupling territorial assets (including land parcels and port sites) to firms within GPNs. The differentiated character of the state accumulation project around lithium-ion batteries becomes visible here, as does the role of localised institutional capacity in negotiating power asymmetries in GPNs (Rutherford and Holmes 2008) and creating the conditions for strategic coupling (Dawley et al., 2019). The development of institutional capacities in relation to battery production are a visible manifestation of this state accumulation project, such as establishing the Advanced Propulsion Centre (APC) as a co-investment platform and inaugurating the Faraday Institution's Faraday Battery Challenge, UKBIC, and the UK Critical Minerals Centre. This institutional capacity works to balance out power asymmetries in GPNs by developing 'critical mass': the FBC's research on batteries, for example, develops a depth and concentration of research capacity that helps position UK researchers alongside their peers i.e., battery research in the US and the EU.

Institutional capacity also facilitates coupling creation, via undertaking joint research and/or seeking out synergies for R&D in battery GPNs as explored, for example, by the academic and industry experts from UK Innovate Global Expert Mission Programme visiting Canada and the US in 2022. Coupling creation here refers to episodes of harnessing and matching regional R&D assets, as well as the state's capacity for brokering coupling and negotiating its terms (see Dawley et al., 2019). Furthermore, battery research (facilitated by the FBC) may

[50] "Batteries go into cars, but they also go into what are now called vertical take-off and landing aeroplanes, for want of a better explanation, and into energy storage. My experience…(as) a potential inward investor, is that those different sectors were not recognised. We were constantly pointed at APC and told, "Because you have orders with a vertical take-off and landing company, that does not count" … Looking at this through the lens of automotive is, frankly, ridiculous. You have to look at the bigger picture, which is looking particularly at energy storage, which is mission-critical… Funding batteries through the APC is, in my humble opinion, a mistake. That is one of the issues that gets in the way" (Andy Palmer, Chairman of InoBat (HoC 2023).

[51] "(…)it's really difficult to land those investments without a demand signal" (Ian Constance, Chief Executive of the APC (The Guardian 2023d)).

advance battery chemistry development at a pace which allows UK researchers to seek patents and participate in bargaining, negotiating, and setting international performance benchmarks for particular battery chemistries. Coupling creation also involves an episode of valorisation and materialisation: in manufacturing this typically occurs at the onset of production but, in an R&D context, it occurs through patenting and standardization. A purpose of UKBIC, although it does not pursue patenting, is to facilitate production partnerships which may lead to more balanced (less asymmetric) outcomes for UK battery start-ups pursuing novel cross-sector battery technologies when they seek to integrate into GPNs (in Section 4 we presented the case of Ilika collaborating with Comau, a member of Stellantis, in preparing a feasibility study for scaling up battery production). Coupling creation is also a mandate of the UK Critical Minerals Intelligence Centre which harnesses and matches regional assets: the Critical Minerals Strategy helped establish this institution, which benchmarks and positions UK mineral knowledge and expertise within global mining and refining networks, especially around the critical minerals used in energy technologies associated with global energy system transformation (as charted by the IEA, IRENA, G7 and G20).

Furthermore, the state has sought to do this in a context where growing UK battery production capacity serves several different economic and political ends: securing inward investment and maintaining jobs; addressing regional inequalities and 'levelling up'; and positioning 'Global Britain' post-Brexit within alternative global production networks to China and the EU. One consequence has been that an established pathway of 'home-grown' research in relation to lithium-ion batteries (anchored in Universities, research organisations and long-standing battery technology developers like AMTE Power) has increasingly had to reckon with the urgency of commercialising and scaling battery production for the automotive sector. In this context, technology development in relation to lithium-ion batteries has been a focal point of state support, with a view to moving promising technologies from research through to commercialisation. UKBIC's facility for scaling up battery technology is a notable instance of converging research policy and industrial policy – and an illustrative case of risk-taking characteristic of an entrepreneurial state, that may facilitate coupling creation. UKBIC features prominently in FBC projects with key incumbent actors (e.g., Ilika with Comau; AMTE Power with William Blythe, Williams Advanced Engineering, Delta Motorsport, Cosworth), including where external IP is licensed to progress battery developments (see EVM and US OnToTechnologies' IP for cathode healing, or AMTE Power's IP to Bardan Cells, in a joint venture with Australian company InfraNomics, to scale cell manufacturing).

However, there remains a substantial gap in relation to full-scale lithium-ion battery manufacturing. In this sense there is not yet a domestic 'supply chain' but, instead, a series of segments of the battery chain that are co-located in the UK. While these segments are increasingly connected and integrated at the research and commercialisation end (with state support) and provide a battery research ecosystem from which fully scaled cell and battery manufacturing for a range of uses may emerge over time, there remains some gap in relation to the specific needs of the UK automotive sector (the recent Tata/JLR announcement, if fulfilled, goes some way towards closing this gap). The structure of the EU-UK Trade Agreement's rules of origin means these remaining gaps are particularly significant in the cathode materials segment (our discussion of EVM shows how lithium economies are forming faster around cathode material production in Europe) and in cell and battery assembly. Britishvolt/Recharge Industries shows how this strategic gap has been filled with speculative forms of finance capital and commercial real estate development, underpinned by land and planning agreements with local councils, instead of investment from leading international battery producers. A notable exception is Envision-AESC's investment with Nissan, as a Tier 1 global battery producer, and the Tata Motors/JLR commitment of July 2023, an automotive OEM with its energy technology subsidiary in Gujarat, India, to develop plants in the UK to manufacture batteries at scale.[52] Yet, these are commitments by incumbents and their GPNs touching ground, rather than coupling creation from the materialization of the convergence of innovation and industrial policy by a UK entrepreneurial state. A similar instance is how metallurgical process technology in the Cornish Lithium project is being licensed from Australian ASX-listed Lepidico.

Third, our lithium lens identifies some of the global production networks for lithium that now intersect the UK, converging UK interests with that of other states, and highlights their geographical and organisational forms. It shows how efforts to 'onshore' battery production and develop a domestic supply chain have, in practice, embedded the UK in GPNs that span Australian hard rock lithium occurrences mining and refining (e.g. Zenith Minerals and EVM; Alkemy's TVL with access to lithium-containing minerals and plans for refining), US finance capital (Scale Facilitation, backer of Recharge Industries), Saudi Arabian chemicals production (e.g. via the planned EVM Battery Chemicals Complex), and several EU counterparts (e.g. EVM's pilot plant for cathode active materials in Poland). Networks like these are a material manifestation of political claims for a 'Global Britain', exemplified by growing synergies between state policy towards battery supply chain development in the UK and Australia, which extends to mining, minerals processing, cell manufacturing and technology licensing.[53]

To conclude, we have offered a largely empirical perspective on contemporary dynamics of onshoring lithium-ion battery production to the UK and have foregrounded the role of the UK state in this process. We supplemented a general GPN perspective, attentive to the governance and organisational dynamics of cross-border networks, by showing how these networks intersect in the UK with a state accumulation project of green industrial transformation. This combined perspective allowed us to spotlight the existential challenge faced by automotive OEMs in the UK in the context of a state-mandated transition away from petrol and diesel engines, and where electric drive from lithium-ion batteries has become the mobility platform of choice; and to identify how these challenges have been exacerbated by the UK's exit from the EU, where Rules of Origin under the EU-UK TCA reinforce geographies of localisation for battery production and automotive manufacturing. We demonstrated how the UK government exhibits features of the mission-led, 'entrepreneurial state' in its efforts to secure a functioning EV manufacturing sector; how its actions are shaping new lithium geographies and production networks, and embedding the UK in wider geographies of lithium mining and refining, battery chemical production, technology development and finance; and how, at the same time, the scale and scope of state support is limited in significant ways. While government support for battery research and technology commercialisation within the UK is creating new horizontal linkages – a battery 'ecosystem' – with some capacity to scale, there remains a substantial gap when it comes to the specific needs of the mass market automotive sector for battery production. Although primarily an empirical paper, our approach has revealed the differentiated and plural character of lithium-ion batteries as a state accumulation project, in which the state has increasingly framed the trajectory of (automotive) transformation and acted as a risk-taker. Specifically, it has shown how the UK state's efforts to localise battery production and develop

[52] At the time of writing (July 2023) there is limited information on the Tata/JLR plans but, should Tata design, build and operate the facility with Agratas alone (i.e., not with Envision), this pattern of localising battery manufacturing capacity without Tier 1 battery producers will continue.

[53] e.g., Alkemy's lithium refineries in Australia and UK; AMTE Power's Bardan Cells JV in Australia; Recharge's interest in Britishvolt – reportedly attracted by IP – and battery production plans in Geelong; Cornish Lithium licensing technology from ASX-listed Lepidico.

domestic capacities in the value chain have sought to align innovation and industrial policy (around batteries for automotive EVs). This has involved supporting and integrating multiple value chain elements that, hitherto, have been embedded in different production networks and have largely operated independently of one another, such as battery science, chemical and industrial manufacturing capacity, automotive manufacturing and green finance.

Declaration of Competing Interest

This research was undertaken as part of the UK Energy Research Centre Phase 4 Theme 1 research programme and was funded by the UK Research and Innovation Energy Programme under grant number EP/S029575/1.

Acknowledgments

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 Lithium-Ion Battery production networks contributes. We thank our anonymous informants and respondents for generously allocating their time to speak with us and for sharing their knowledge and insight; Tiago Alves-Teixeira and Charanjeet Singh for engaging with a pre-submission draft; the Economic Geography Working Group at the University of Vienna for comments on a presented draft; Chris Orton for his assistance in preparing the figures; and the Reviewers and Editor for their comments and suggestions on the submitted paper.

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