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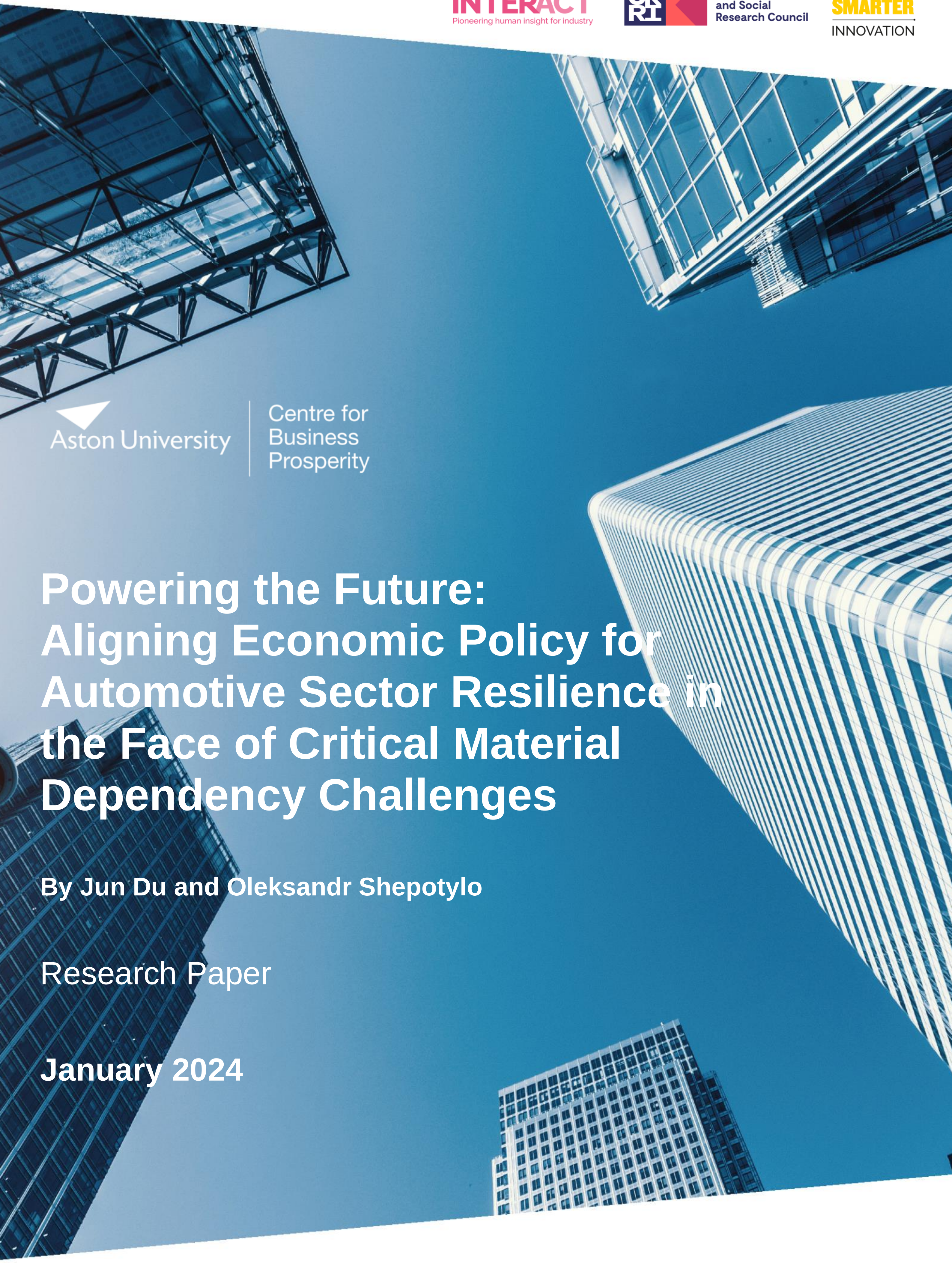

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Powering the Future: Aligning Economic Policy for Automotive Sector Resilience in the Face of Critical Material Dependency Challenges

By Jun Du and Oleksandr Shepotylo

Research Paper

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ABSTRACT

This paper provides a comprehensive analysis of the UK's electric vehicle (EV) industry within the framework of economic policy and global value chains. It delves into the intricate dynamics of supply chains, industrial policy, and critical dependencies.

The UK's automotive sector faces various challenges arising from technological advancements, socioeconomic transformations, and geopolitical intricacies. This necessitates the development of agile and responsive economic policies. The UK's exit from the EU, as outlined in the Trade and Cooperation Agreement, adds complexity, especially in navigating non-tariff measures and rules of origin that impact EV exports. In a world marked by increased global competition and expanding industrial policies, the need for swift responses is evident.

Insights from the analysis of EV global value chains (GVCs) and the UK's dependencies highlight the EU as a strong EV market, with Germany leading in EV exports by value and China dominating in volume. The UK's diversified export portfolio and limited reliance on GVCs position it favourably. Short-term concerns in EV battery supply chains can be traced to trade policy issues, potentially evolving into medium-term dependencies on battery materials and production.

The recommendations in this study strategically target opportunities in the EV revolution, advocate for optimizing trade policy, call for strategic investments in EV battery production, emphasize the need for a future-ready industrial strategy, and underscore the importance of continuous monitoring of global value chains. Implementing these recommendations can solidify the UK's leadership in electric mobility, ensuring sustainable growth, competitiveness, and innovation.

JEL Codes: F14, L62, O33, Q42, Q55

Keywords: Electric Vehicles (EVs), Global Value Chains (GVCs), Trade Policy, Rules of Origin (RoO), Industrial policies, Net Zero Transition, UK, EU, Trade and Cooperation agreement (TCA), Supply Chain Resilience, Critical Dependencies, Network Analysis

Executive Summary

This paper offers a comprehensive analysis of the UK's electric vehicle (EV) industry within the framework of economic policy and global value chains. It delves into the intricate dynamics involving supply chains, industrial policy, and critical dependencies.

The UK's automotive sector confronts multifaceted challenges stemming from technological advancements, socioeconomic transformations, and geopolitical intricacies, necessitating the formulation of agile and responsive economic policies. The UK's departure from the EU, as stipulated in the Trade and Cooperation Agreement, amplifies the complexities, particularly in navigating non-tariff measures and rules of origin that exert influence on EV exports. Within a landscape marked by heightened global competition characterized by escalating industrial policies on a global scale, the urgency of nimble responses becomes evident.

The insights derived from the analysis of EV global value chains (GVCs) and the UK's dependencies underscore the resilience of the EU as a formidable EV market, with Germany leading in EV exports by value and China dominating in terms of volume. The UK's diversified export portfolio and its modest reliance on GVC position it favourably in this context. Short-term concerns within the EV battery supply chains can be attributed to trade policy issues, potentially evolving into medium-term dependencies on battery materials and production.

To ensure long-term viability and competitiveness, the UK must proactively embrace this transformation. Our policy recommendations lay out a strategic roadmap for the UK automotive sector in the midst of the EV revolution, aiming to position it as a global leader, driving innovation and growth in the dynamic landscape of electric mobility:

I. Seizing EV Revolution: Capitalizing on Market Opportunities

The shift to EVs presents opportunities for growth and innovation while aligning with global sustainability goals. Investing in cutting-edge research and development positions the UK as a leader in EV technologies. Leveraging proximity to the EU market and exploring emerging markets like China further enhances the industry's global competitiveness.

II. Optimizing Trade Policy for Global Success

A well-crafted and adaptable trade policy is crucial for navigating international markets. Swift action is needed to extend the deadline for rules of origin under the EU-UK TCA,

preserving tariff advantages. Long-term solutions should be pursued to ensure sustained competitiveness and foster international collaborations.

III. Mitigating Rising Material Costs and Boosting Self-Reliance

Strategies to mitigate the effects of rising material costs include diversifying suppliers, investing in domestic EV battery production, and integrating circular economy principles into supply chains. Developing an integrated charging infrastructure alongside battery production supports EV adoption.

IV. Pioneering a Future-Fit UK Industrial Strategy

A well-defined industrial strategy aligns policies with sector goals, incentivizing research and development. An agile approach anticipates evolving technologies and market conditions. Foreign investment is vital, and the UK should create an attractive environment for global investors. Continuous monitoring of the UK's position in global EV value chains ensures resilience and competitiveness.

1. Introduction

The automotive sector holds a distinctive and pivotal position within the UK economy. Beyond its substantial contributions to national outputs, employment, and value addition, the sector embodies a catalyst for future growth, aligning with the levelling up agenda and propelling the Net Zero transition. In 2022, automotive-related manufacturing injected £78 billion turnover and contributed £16 billion in value added to the UK economy. The sector's impact extends to the employment of over 208,000 individuals directly in automotive manufacturing and a total of 800,000 across the broader sector. Noteworthy within this context is the diversity epitomized by more than 25 manufacturing brands, collectively producing over 70 distinct vehicle models, complemented by the presence of specialized small-volume manufacturers. This intricate ecosystem is further supported by approximately 2,500 supply chain businesses, housing some of the world's most skilled engineers.[1]

With an annual investment of approximately £3 billion in Research and Development (R&D), the UK automotive manufacturing sector is an integral component of the interconnected European Automotive cluster and innovation ecosystem, which remarkably lays claim to over 30% of the world's patents related to automotive technologies (Cornet et al., 2023). The sector's technological and productivity advances not only enhance its own capabilities but also catalyse spillover effects, fostering growth and prosperity in related industries.

The automotive sector is arguably one of the most globalized industries. Its competitiveness depends on the international production networks, global supply chains and distribution to reach global customers. Cross border collaborative R&D efforts are of paramount importance for automotive sectors to access global talent and expertise (Hagedoorn, 2002), share risks and costs for innovation (Rose-Anderssen et al., 2008), reach regulatory compliance (van den Broek and van Veenstra, 2018) and conduct eco-innovation which tackle more complex problems (Maldonado Guzmám and Pinzón Castro, 2023). This is particularly the case for the UK automotive sector. In 2022, the UK Automotive sector was the country's largest exporting sector in goods, contributing £94 billion in exports and constituting over 10% of UK trade in goods. [2] In every 10 cars manufactured in the UK, eight are for exporting (SMMT, 2023a), highlighting the sector's pivotal role in the country's trade and global market presence. Further, the ownership structure of the UK automotive sector involves a significant

[1] The statistics are provided by Anand Dossa at the SMMT, November 2023.
[2] The statistics are provided by Anand Dossa at the SMMT, November 2023.

presence of multinational companies. A substantial portion of the industry consists of multinational corporations, both in terms of automakers and suppliers.

As one of the most successful automotive industries in the UK and worldwide, the prevailing landscape is being vigorously contested, as the sector grapples with formidable challenges and undergoes substantial transformations driven by technological, socio-economic, and geopolitical forces. First, transportation accounts for a significant share of greenhouse gas emissions in Europe and the US. The global push for sustainable transport has fuelled the rapid growth of the electric vehicle (EV) industry, a crucial part of the broader shift to cleaner energy. Nations worldwide are committed to reducing carbon emissions in line with the Paris Agreement, speeding up the transition to sustainable mobility to achieve carbon neutrality by 2050. This imperative drives the shift from Internal Combustion Engines (ICE) to EV technology. While significant progress has been made, challenges persist, including EV battery production, capacity, material supply, charging infrastructure, and recycling. These areas need focused attention for the sustainable growth of the EV industry.

Second, globalization and geopolitical factors add complexity. The UK's exit from the European Union, along with the Trade and Cooperation Agreement (TCA), brings new challenges. Although the TCA eliminates tariffs and quotas, non-tariff measures (NTMs) and rules of origin (RoO) create formidable export barriers, particularly for EVs, given the substantial value of batteries. The challenge intensifies with rising prices of critical raw materials for EV batteries in 2023, driven by post-pandemic demand and geopolitical tensions. While immediate EV sales tariffs between the UK and the EU seem to be delayed, the threat persists.

The emergence of global players, such as China dominating EV exports, threatens the UK's competitiveness. A comprehensive assessment of the UK's position in the evolving landscape compared to peers is necessary, considering the impact of global industrial policies like the US Inflation Reduction Act (IRA), the EU's Green Deals, and China's Made in China 2025 initiative on automotive sectors and supply chains. Increasing global competition for private investments adds to challenges, jeopardizing the long-term viability of the UK automotive industry. A comprehensive strategy addressing internal dynamics and external policies is vital to secure the industry's position in the evolving global automotive arena.

The complex and dynamic environment highlights the importance of decision-makers' ability to adapt quickly. Stakeholders play a critical role in creating conditions for businesses to thrive in reshaped global value chains. Urgent policies and support are essential to anchor and boost the sector in the age of industrial policy.

This paper aims to provide evidence for policy discussions and decisions, focusing on the resilience of electric vehicle global value chains (GVCs) and the UK's dependencies as it exits an economic integrated area (EIA). The study examines the impact of disintegration on GVCs, highlighting the UK's vulnerability to new trade barriers, rising raw material prices, and protectionist policies from global players like China, the EU, and the US.

Specifically, the study assesses the resilience and critical dependencies of value chains in the top 10 electric vehicle-producing countries, analysing trends in raw materials, batteries, and EV trade. It traces the UK's EV supply chain from materials to batteries to EVs, evaluating critical dependencies and comparing them with other leading EV exporters. The analysis follows the European Commission methodology. Key findings reveal varying supply chain lengths across countries, with China's participation being crucial. Disruptions could lead to substantial economic losses, particularly in materials and EV trade. We draw four key policy recommendations.

The rest of the paper has the following structure. Section 2 sets the global and policy background. Section 3 discusses the existing literature and identifies the gaps. Section 4 compares the global value chains of the main EV exporting countries. Section 5 looks at their critical dependencies. Section 6 offers a network analysis of key players in the EV global supply chains. Section 7 discusses the key findings and provide policy recommendations. Section 8 concludes.

2. Global and Policy Context

The UK automotive industry is heavily reliant on external markets, particularly the EU. Currently, it exports 78.3% of produced cars and nearly 70% of EVs in value to EU countries.[3] However, the UK's departure from the EU and the subsequent implementation of the EU-UK TCA have introduced new challenges.

While the TCA maintains zero tariffs and quotas, non-tariff measures and RoO have become significant barriers to exports. Compliance with RoO under the TCA is particularly challenging due to the high value of EV batteries. Batteries constitute 30-40% of the overall value of EVs (Harrison and Ludwig, 2021), and many raw materials essential for battery production are sourced externally, leading to a higher proportion of non-originated materials in automobile valuation.

[3] Authors' calculations based on COMTRADE data for 2019-2022.

The TCA regulations stipulate that for tariff-free trade in EVs, a minimum of 40% value added must originate from the UK or EU countries, increasing to 55% by 2027. Similarly, for batteries and battery cells, a minimum of 30% value added is required from the UK or EU countries, with expectations of reaching 65-70% by 2027. These rules apply to exporters in both the UK and EU, posing significant challenges, especially given the dominance of China in providing critical raw materials and battery cells.

Furthermore, a notable surge in the relative prices of critical raw materials for electric battery production occurred in 2023 due to increased demand and geopolitical conflicts. While the immediate threat of EV sales tariffs between the UK and the EU seems to be on the verge of a three-year delay, it does not eliminate the persistent threat to the industry.

The EV industry faces fierce global competition for market share and technological dominance. Major players, including the EU, China, and the US, have introduced government subsidies to promote electric vehicles, sometimes at the expense of multilateral trade liberalization principles. For instance, the US introduced the Inflation Reduction Act (IRA) in August 2022, offering consumer tax credits for domestically produced EVs, but later adjusted the rules to be less discriminatory after negotiations with the EU and Republic of Korea EV producers.

In contrast, EU industrial policies like the EU Green Deal policy include carbon taxes and carbon border adjustment mechanisms (CBAM) to encourage sustainable practices without discriminating against foreign producers. Most EU countries offer consumer tax credits for EV purchases, which are non-discriminatory towards foreign producers. However, the EU's ad valorem MFN tariff is higher at 10%, compared to the US's 2.5%, making the US market less protected against foreign competition.

In March 2023, the EU unveiled the European Green Deal Industrial Plan to counter the potential negative effects of the IRA and develop green technologies, including EVs and EV batteries.

Overall, the combination of TCA value-added requirements, rising raw material prices, and EU and US industrial policies poses significant challenges to the UK automotive industry. These developments raise concerns about its sustained viability in both domestic and international contexts, particularly within the EU and US markets. The UK's separation from the EU single market has disrupted its close ties with the European automotive industrial ecosystem. Additionally, the absence of a robust industrial strategy and manufacturing plan in the UK hampers its ability to effectively address the substantial hurdles confronting the automotive sector. Therefore, industry stakeholders must consider strategic adjustments, policy changes, and potential collaborations to safeguard the UK's position in the evolving automotive market.

Table 1 MFN tariffs on EV for top importing countries

Reporter Name	MFN tariff, %	Reporter Name	MFN tariff, %
European Union	10	New Zealand	6.67
United Kingdom	10	Turkey	10
Norway	0	United Arab Emirates	5
United States	2.5	Ukraine	4
Canada	6.1	Iceland	0
Japan	0	Brazil	35
China	15	Russian Federation	5
Korea, Rep.	8	Bangladesh	25
Australia	5	Luxembourg	10
Israel	7	Slovak Republic	10
Taiwan, China	17.5	Pakistan	50
Hong Kong, China	0	India	125

Source: WITS
Note: Countries/regions are sorted in value of import in 2021.
EU countries all have the same MFN tariff.

3. Literature

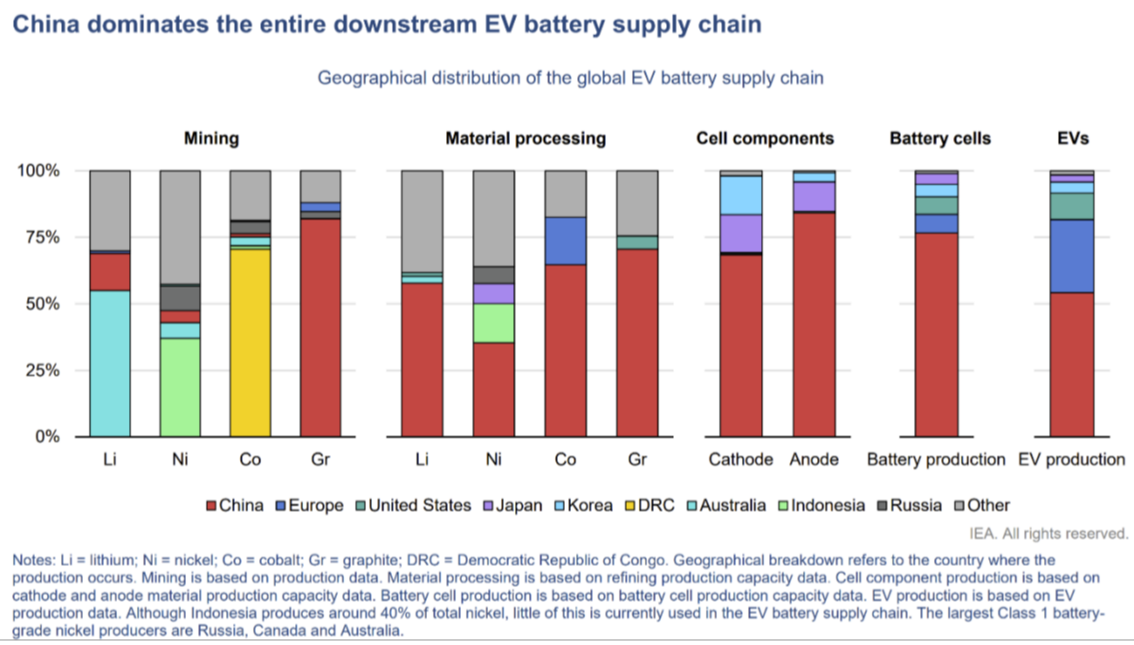
Development of GVCs has been extensively studied. Antràs and Chor (2022) give an overview of the literature on modelling and empirical research on GVCs. Trade costs in interaction with the first nature geography shape GVCs and determine the locations of different stages of production (Antràs and De Gortari, 2020). Trade policy plays an important role in the formation of GVCs. It amplifies the effect of ad valorem tariffs on trade, as the tariff is applied each time a product or intermediate good is crossing the border, which leads to even small levels of tariff protection having a strong effect on the GVC formation (Goldberg and Pavcnik, 2016). The role of NTMs in this regard cannot be overestimated, as they can disrupt trade flows and production, due to having much higher ad valorem equivalent as compared to MFN tariffs (Kee et al., 2009).

The literature on the EV GVS is also emerging. It mainly focuses on the role of critical minerals in GVCs (Eggert et al., 2016; Tisserant and Pauliuk, 2016; Olivetti et al., 2017). Research also points out at the central role of China in GVCs. According to IAE (2023), the main producers of raw materials for EV battery production are Australia (lithium), Indonesia (nickel), Democratic Republic of Congo (cobalt), and China (graphite). Moving further along the supply chain, China dominates processing of raw materials and is essentially a monopolist in production of battery cells and other components (Figure 1). Jones et al. (2023) considered implications of the surge in production of EVs on developing countries who are the main suppliers of raw materials from the environmental and political economy point of view.

To estimate critical vulnerabilities of EV GVC, Arjona et al. (2023) developed a methodology for identifying the critical dependencies and vulnerabilities of the EU bound GVCs. It identifies the critical dependencies based on 3 criteria: high geographical concentration, import to export ratio above 1, and share of non-EU imports above 50%. As a step forward in improving the methodology, Korniyenko et al. (2017) suggest using the network analysis to analyse the resilience of GVCs.

There is however no research on the EV GVC critical dependencies using the network economics approach. This paper fills the gaps in the literature by looking at the resilience of EV GVCs and also critical dependencies of the UK as a country that has chosen to exit an economic integrated area (EIA), which contributes to understanding on the role of disintegration on GVCs by studying the UK and its vulnerability to new trade barriers after the introduction of TCA and new protectionism of the key players – China, EU, and US.

Figure 1 Geographical distribution along the EV battery supply chain



Source: IEA (2023)

4. The Landscape of EV Global Value Chains

This section provides an overview of the global trend of the EV production during 2017-2022, highlighting the leading players in the supply chain and their respective strengths. We compare the supply chains of EV production in the UK with that of the top nine global automakers.[4] It sets out the context in which the UK Automotive seeks to navigate and position itself within this competitive market.

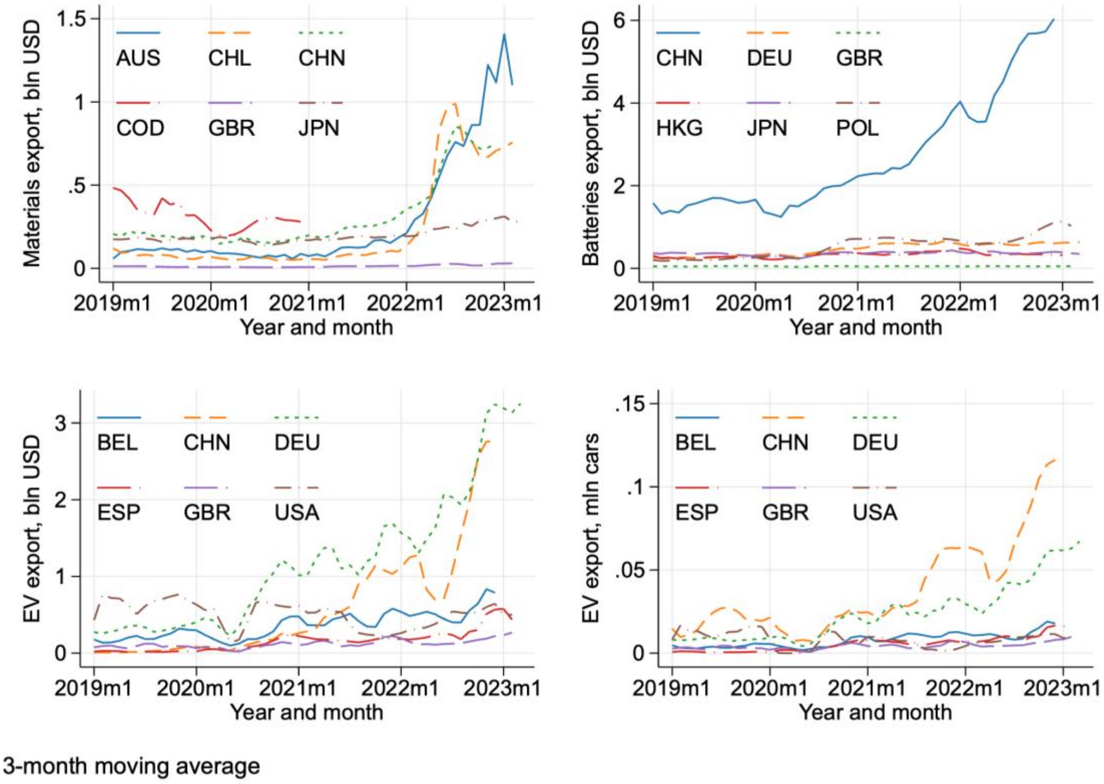
4.1. Exports

Figure 2 illustrates the trends in the value of exports of materials, batteries, and EVs. The graph highlights a significant surge in the value of exports for materials, batteries, and electric vehicles since the beginning of 2022. It also identifies the key players in the EV GVCs. Notably, Australia, Chile, and China have emerged as the leaders in the production of raw and processed materials required for EV battery production in recent years. China holds the dominant position in EV battery exports, while Germany and China lead in exporting EVs to other countries.

The competition to become the top exporter of electric vehicles is fierce, with Germany leading in terms of export value. However, in 2021 China surpasses Germany and other countries in terms of the number of cars exported per month. Despite that fact, Germany retains the title of the top exporter based on value in US dollars. These differences in export numbers reflect disparities in EV production between China and Germany, including variations in quality, size, and marketing strategies.

[4] Notably, South Korea is missing from this analysis as we do not have monthly trade data for the investigated period.

Figure 2 Leading exporters of materials, batteries, and electric vehicles in 2019-2022



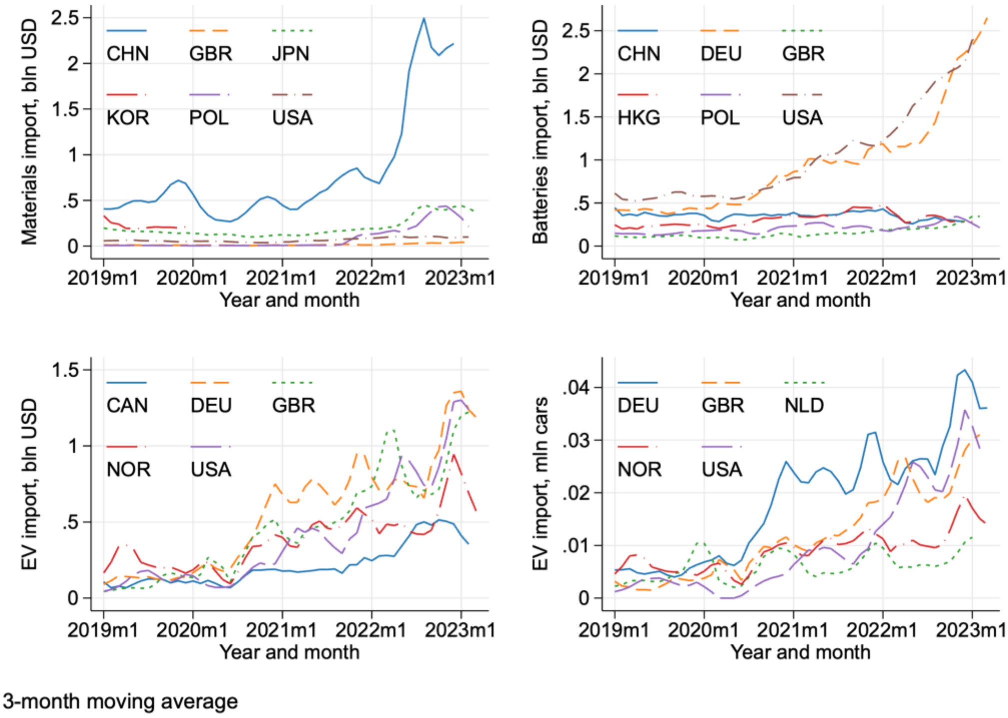
Data: COMTRADE

4.2. Imports

Figure 3 displays the primary importers of materials, batteries, and electric vehicles. This information provides insights into the demand side of these three parts of the EV GVC. Notably, China stands out as the largest consumer of raw materials for batteries, with its import value experiencing a dramatic surge in 2022, reaching nearly 2.5 billion USD by mid-2022. Poland has become the leading consumer of the materials for production of EV batteries since the middle of 2021.

When it comes to battery imports for EV production, the US and Germany are the major importers. These countries play a significant role in acquiring batteries from international markets to support their domestic EV manufacturing. In terms of EV consumption, consumers are concentrated in North America and Western Europe, including Norway, the Netherlands, UK, Germany, Canada, and US. The demand for EVs is primarily driven by the leading countries in Green Technology transformation, as measured, for example by the Green Future Index 2022 published by MIT Technology Review. The top 10 countries of the index features all major EV importers, including Norway, the Netherlands, Sweden, and the UK.

Figure 3 Leading importers of materials, batteries, and electric vehicles in 2019-2022



Data: COMTRADE

5. Analysis of Critical Dependencies and Market Diversification

We measure geographical concentration of exports and imports for each country and product along the production value chain of the electric vehicles by calculating the Herfindahl-Hirschman Index (HHI) which is a commonly used measure to quantify market concentration or the degree of competition within an industry. It is calculated as

$$HHI_{pit} = \sum_{j=1}^{N} (S_{pijt}^2)$$

where S_{pijt} represents the market share (expressed in percent) of partner country j in export/import of product p to country i at time t. In this case, with the number of countries in the chains (N=245), the lower bound of the index is 41 and the theoretical upper bound is 10000. The HHI below 1,500 generally suggests a highly geographically diversified trade. In the case of medium concentration, HHI values ranging from 1,500 to 2,500 indicate moderate geographical concentration. High concentration is typically associated with an HHI above 2,500.

5.1. Global Exports of EVs

We report geographical concentration indices of EV exports in Table 2, which presents information on the exports of electric vehicles by the top 10 EV exporters. The first panel of

Table 2 displays the concentration ratio of exports over time. According to the table, the concentration ratio has generally declined for most countries during the four years between 2019-2022, with the exceptions of the United States. In 2021, the United States reported the highest concentration ratio in its main export markets, which may be explained by its more remote location relative to the mass of consumers, who were primarily located in Europe. The situation further was exacerbated by the COVID-19 crisis, which led to global disruption in value chains and increase in transportation costs, which increased advantages of shipping locally. The US EVs were mainly exported to Canada. By contrast, Germany has the most diversified export portfolio, capitalizing on its central location relative to the major EV consumers located in Europe. Interestingly, the United Kingdom has a diversified export portfolio, comparable to countries with medium level of export diversification such as China, Belgium, and Japan.

Examining the prices of electric vehicles globally, presented in Panel B of the table, we observe significant heterogeneity. Germany, the United States, and Belgium offer higher-priced electric vehicles, whereas countries like the Czech Republic, France, Japan, Slovakia, Spain, and the United Kingdom provide cars in the medium price range. China, on the other hand, exports cheaper cars with an average price below $20,000 USD.

Moving to the third panel, we systematically examine the primary market destinations for car exports originating from the top 10 global exporters. This analytical focus entails a categorization into three distinct regions: China, the EU, and the remainder of the world (ROW). The tabulated data reveals that the predominant market for the UK's electric vehicles is the EU, with approximately 72% of its EV exports directed towards EU member countries.

Table 2 Exports of EV, 2019-2022

A: Geographical concentration: Herfindahl-Hirschman Index (HHI) of exports										
Year	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
2019	4675	2348	2497	1824	1628	4188	3188	2052	3875	1970
2020	3317	1995	4005	-	1148	2274	2079	1857	3993	1354
2021	2236	1817	1758	-	906	1333	3236	1606	6163	1456
2022	1128	1184	1503	2577	804	1283	2672	2102	5808	1240
B: Export Price, thousand USD										
	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
2019	54.9	-	-	33.0	39.2	30.4	27.5	29.3	39.0	29.5
2020	50.2	9.1	27.7	-	52.5	26.6	26.0	29.9	38.5	24.6
2021	42.8	16.8	36.1	-	49.3	26.2	26.4	26.9	42.8	30.2
2022	46.1	19.8	33.6	24.6	50.9	26.1	23.9	27.8	53.5	27.5
C: Main export destinations for top EV exporters in 2019-2022										
	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
China										
% of total export	0.00	-	-	0.02	5.53	4.12	-	0.00	2.32	0.01
Value, bln USD	0.00	-	-	0.00	1.41	0.08	-	0.00	0.12	0.00
EU										
% of total export	54.49	46.91	70.38	70.14	36.70	29.29	84.82	84.19	10.05	71.71
Value, bln USD	3.69	9.39	1.98	1.69	9.32	0.60	1.32	3.18	0.54	1.25
ROW										
% of total export	45.50	53.09	29.62	29.84	57.77	66.59	15.18	15.81	87.64	28.28
Value, bln USD	3.08	10.62	0.84	0.72	14.67	1.36	0.24	0.60	4.69	0.49

Note: Panel A presents geographical Herfindahl-Hirschman Index (HHI) for each country. Panel B reports the unit price of EV, calculated as the reporter total value of exports divided by the number of EVs exported. Finally, Panel C reports % and value of exports from the reporter country to China, EU, and the rest of the world. Calculated by the authors using the COMTRADE data. The reporter countries are top EV exporters in 2019-2022.

5.2. Global Import of Battery Materials

We now delve into the analysis of the supply value chains of major EV producers, focusing on materials such as lithium, nickel, cobalt, and their composites, including lithium oxide and other combinations, with the full list of materials and corresponding HS product codes presented in Table A1 in Appendix B. According to the first panel of Table 3, the UK exhibits one of the most diversified import portfolios of materials suitable for EV production. However, EU countries like the Czech Republic, France, Spain, and Germany, as well as the United States, possess even more diversified imports.

Furthermore, there is a noticeable trend of increasing concentration in the UK's material imports. Regarding the prices of imported materials for EV battery production, China and Germany have the most affordable inputs. However, China experienced a significant price surge in imported materials in the past year, while before 2022, it had access to considerably cheaper imported materials. France, according to the chart, currently offers the most favourable prices for imported materials. In contrast, countries like the UK have seen nearly double growth in the prices of imported materials, posing challenges in terms of production costs for electric vehicles and compliance with regional rules.

Examining the sources of materials for EV battery production, the UK heavily relies on the rest of the world, which falls outside the scope of regional regulations, potentially impacting preferential access to EU markets. In contrast, EU countries engage in substantial trade within the EU markets for raw materials, while China and the US primarily source their materials from the rest of the world. The issue for the UK lies in the fact that, unlike China, this sourcing strategy does not provide a price advantage.

These findings highlight the complexities faced by the UK in terms of material imports, production costs, and adherence to regional regulations. Addressing these challenges is crucial for the UK to enhance its competitiveness in the EV industry and ensure sustainable access to global and EU markets.

Table 3 Imports of EV batteries materials 2019-2022

	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
A: Geographical concentration: Herfindahl-Hirschman Index (HHI) of imports										
Year										
2019	1788	1912	1697	1052	1409	2181	2413	1896	1189	1531
2020	1870	2220	1603		1653	2251	2082	1655	1228	1363
2021	2566	2106	1501		1390	2584	2030	1878	1137	1626
2022	2624	2632	1629	1699	1311	3252	2962	1548	1449	1893
B: Import Price, USD per kg										
	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
Year										
2019	0.775	0.117	0.319	0.078	0.391	0.435	0.674	1.864	1.099	1.147
2020	0.609	0.122	0.361		0.415	0.504	0.772	1.691	1.283	0.962
2021	0.974	0.173	0.544		0.384	0.514	0.721	2.125	1.636	1.746
2022	1.956	0.481	0.570	0.128	0.481	0.967	1.070	2.294	7.325	2.979
C: Source of materials										
	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
China										
% of total import	4.75	0.16	9.66	11.50	16.19	54.93	0.97	27.27	27.59	14.76
Value, bln USD	0.02	0.03	0.01	0.04	0.10	2.25	0.00	0.06	0.32	0.05
EU										
% of total import	61.50	0.23	56.53	68.82	51.59	1.87	68.10	42.65	12.24	14.66
Value, bln USD	0.27	0.05	0.03	0.22	0.31	0.08	0.01	0.09	0.14	0.05
ROW										
% of total import	33.76	99.62	33.80	19.68	32.23	43.20	30.94	30.08	60.17	70.57
Value, bln USD	0.15	21.36	0.02	0.06	0.19	1.77	0.00	0.07	0.70	0.24

Note: Panel A presents geographical Herfindahl-Hirschman Index (HHI) for each country. Panel B reports the unit price in USD per kilogram, calculated as the reporter total value of imports divided by the mass in kilograms. Finally, Panel C reports % and value of imports to the reporter country from China, EU, and the rest of the world. Calculated by the authors using the COMTRADE data. The reporter countries are top material importers in 2019-2022. Calculated by the authors using the COMTRADE data.

5.3. Global Imports of Batteries

Turning to imports of batteries for the top ten EV exporters in Table 4, Panel A reveals that China has the most diversified battery imports among all major EV producers, with a growing balance in the sourcing countries. By contrast, many European EV producing countries demonstrate an increase in concentration of sourcing countries to a varying extent. This might show a tendency of EU countries shifting towards closed cycle of production for materials, batteries, and electric vehicles within the European market such as from neighbouring countries such as Poland and Hungary, less dependent on China.

The UK displays a moderately diversified range of battery imports, but in 2022, there has been an increase in concentration, primarily driven by a surge of imports from China. Panel B highlights that the UK has access to the most affordable batteries, which likely corresponds to the types of electric vehicles being produced in the lower price range, as indicated in Table

1. In comparison, countries like the US, Germany, and Belgium produce electric vehicles in higher price ranges. Additionally, there is a general trend of increasing battery prices among major car producers. China is the only country that has seen importing batteries more cheaply than before.

In terms of sourcing strategies, the UK imports over 40% of its batteries from China, around a quarter from the EU, and another 30% from the rest of the world. This is arguably more diversified basket of imports which help resilience. However, heavy reliance on non-EU countries will create a problem for tariff-free exports of the UK produced EVs to EU, due to the requirement that not more than 45% of the vehicle value are allowed to originate from non-EU countries by 2027. EU countries such as Belgium and Germany attempt to source more batteries within the EU, but some countries like the Czech Republic, Slovakia, and Spain still rely on imports from China. Both Japan and the US source their batteries from China, while China itself has a diverse range of battery sources from the rest of the world.[5]

These findings highlight the diverse sourcing strategies and battery import patterns among the major EV exporters, with China playing a significant role as a global battery supplier. Understanding these dynamics is crucial for assessing supply chain resilience, market competitiveness, and the impact on pricing and production strategies in the EV industry.

[5] These stats are strongly affected by the vehicle segment. For example, none of the SUV or High-Capacity batteries are coming from the UK. The UK, (Envision) provides, until their new factory is ready (end 2025) only small arrays (30Kw), resulting in a car battery capacity of 40 to 60 kw, whereas Tesla or any SUV need at least 90 to 170 to function. As a result, all those batteries are supplied by China, LG in Eastern Europe and soon by Samsung in Hungary that is taking off the ground with a €1.2 b grant from the EU. The bigger batteries will be provided soon by Envision in Germany and later in France. To analyse highly heterogeneous flows within each EV type and battery type would require more fine-grained trade data, which is not available at COMTRADE HS 6-digit level.

Table 4 Imports of EV batteries materials 2019-2022

A: Geographical concentration: Herfindahl-Hirschman Index (HHI) of imports

Year	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
2019	3770	1616	2786	1757	1782	3492	2484	1342	2082	1535
2020	3174	1546	3210		1818	4320	4963	2535	1928	1584
2021	3505	1437	2576		2322	5151	4377	2701	2443	1428
2022	2603	1246	3787	2095	2822	4565	3842	4531	3084	2381

B: Import Price, USD per kg

	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
2019	15.036	39.574	12.393	11.440	13.223	30.379	19.581	7.143	13.536	10.937
2020	17.351	34.224	17.976		16.604	25.821	28.955	11.881	14.329	12.031
2021	21.299	35.738	20.103		17.509	25.076	30.741	13.237	12.282	14.705
2022	24.017	34.759	23.356	14.759	22.362	26.935	29.721	18.906	33.281	14.058

C: Source of imports

	Belgium	China	Czechia	France	Germany	Japan	Slovakia	Spain	USA	UK
China										
% of total import	27.12	12.77	57.52	40.53	46.75	64.74	55.35	67.02	51.00	43.50
Value, bln USD	0.75	0.46	2.18	0.94	8.76	1.69	0.97	1.84	10.84	1.17
EU										
% of total import	69.04	24.39	37.08	37.51	43.42	2.08	33.48	26.39	7.88	27.53
Value, bln USD	1.91	0.88	1.41	0.87	8.13	0.05	0.59	0.72	1.67	0.74
ROW										
% of total import	3.84	62.83	5.40	21.96	9.83	33.18	11.17	6.60	41.12	28.97
Value, bln USD	0.11	2.27	0.20	0.51	1.84	0.87	0.20	0.18	8.74	0.78

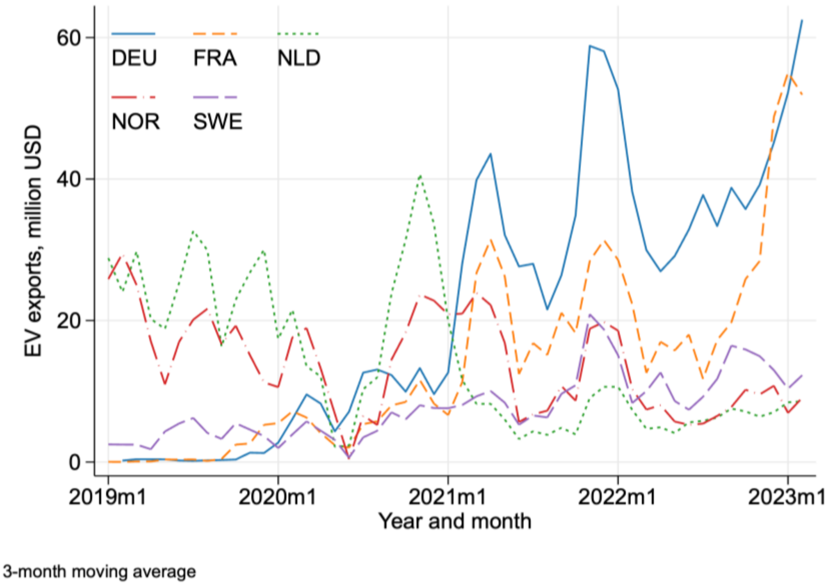
Note: Panel A presents geographical Herfindahl-Hirschman Index (HHI) for each reporting country. Panel B reports the unit price in USD per kilogram, calculated as the reporter total value of imports divided by the mass in kilograms. Finally, Panel C reports % and value of imports to the reporter country from China, EU, and the rest of the world. Calculated by the authors using the COMTRADE data. The reporter countries are top battery importers in 2019-2022. Calculated by the authors using the COMTRADE data.

5.4. UK Trade of EVs, Batteries and Battery Materials

We finally look at the UK supply chain in more detail, in terms of the main destinations for the UK produced EVs, main sources of materials and batteries, as well as unit prices. This gives us a view of the current global profile of UK EV supply chains.

Based on Figure 4, in 2019, Norway and the Netherlands emerged as the primary destinations for UK-produced electric vehicles. However, the year 2020 witnessed a notable decline in exports across all countries due to COVID-19 measures, hitting a minimum level. The recovery of the UK's electric vehicle exports commenced in 2021, marked by a substantial surge in shipments to Germany in the latter half of 2022. Furthermore, there was a sharp uptick in exports to France toward the end of 2022. Notably, all major customers for UK electric vehicles are within the EU, underlining the significance of this market for the country.

Figure 4 Top destination of the UK exports of EV

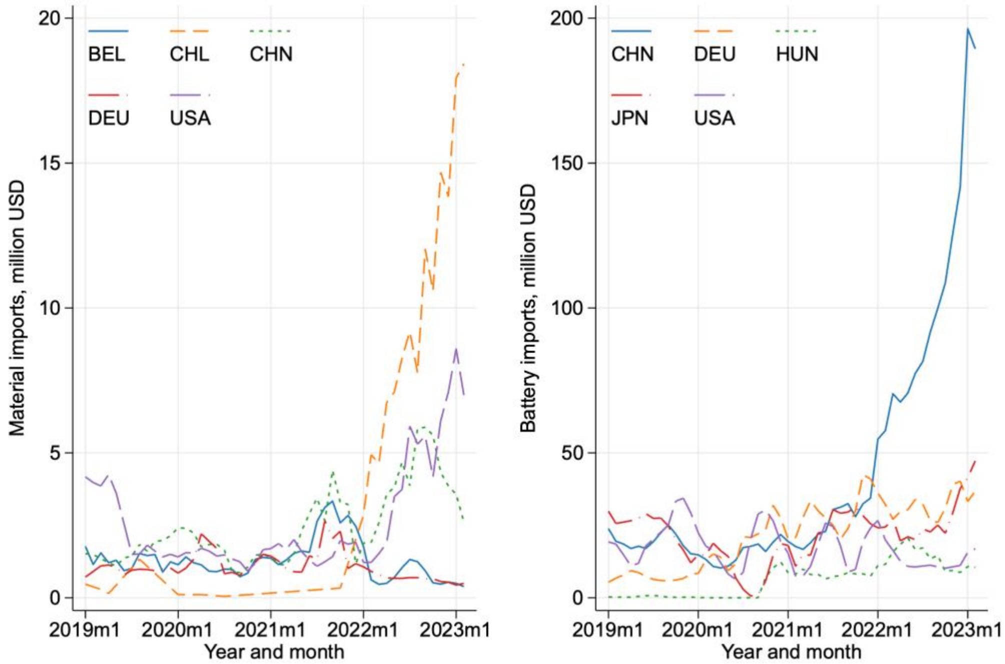


Data: COMTRADE

Figure 5 delineates the primary sources of materials and batteries imported to the UK from 2019 to 2022. Initially, materials imports were dominated by the United States. However, throughout 2020 and 2021, material imports decreased significantly from all countries. In 2022, material imports surged, with China, Chile, and the United States emerging as the top three sources for battery production materials.

The figure's right panel portrays the value of battery imports to the UK. From 2022 onward, China became the predominant source of batteries, witnessing a nearly tenfold increase in imports. The growing reliance on Chinese-built batteries raises concerns, especially if UK automakers fall short of the 55% threshold required for tariff-free EU exports of electric vehicles. Given that batteries constitute around 40% of a car's cost, sourcing materials from Chile and batteries from China may impede major automakers from meeting crucial rules of origin requirements.

Figure 5 Top sources of the UK imports of material and batteries



3-month moving average
Data: COMTRADE

5.5. UK vulnerabilities and critical dependency

To study UK's critical dependencies of EV production and exports more systematically, we further performed the analysis of the diversification, import dependency, and EU dependency of the UK trade flows for the automotive industry.

Table 5 presents the UK critical dependency measures. Panel A looks at concentration measures for exports and imports. The least diversified parts of the supply chain are imports of batteries and EV. Exports of the UK are well diversified geographically along all products, including export of vehicles, batteries, and auto parts.

Panel B of the table reports import to export ratio for each product category. It indicates how much more in value the UK imported compared to what it exported for each product. For most products, the UK imported more than it exported. For batteries and EVs, the import was 4.6 and 5.9 times higher than the export. The only product where the UK has exported more are hybrids, where the import to export was 0.9.

Panel C gauges the proportion of exports and imports to the EU within the overall exports or imports for each product category. Notably, 26.9% of the imports for batteries originate from the EU, whereas only 14.6% of materials are imported from the EU. Given that a substantial 68% of electric vehicles exported by the UK are destined for EU countries, there exists a pronounced risk of losing access to EU markets for EVs. This risk stems from exceeding the agreed-upon shares of value added to UK-produced EVs that originate from outside both the EU and the UK.

Table 5 Critical dependency for UK trade in automotive industry in 2022

	Product						
	Batteries	EV	Hybrid	ICE	Materials	Parts	Total
A: Concentration							
Geographical import concentration, HHI	**2249**	**2401**	933	1352	1729	990	1534
Geographical export concentration, HHI	903	1048	823	1223	1103	636	933
B: Import to export ratio							
Import to export ratio	**4.622**	**5.906**	0.871	1.463	1.282	2.231	2.729
C: EU exposure							
Import (%)	26.9	50.0	60.5	72.7	14.6	62.4	47.9
Export (%)	51.7	**68.4**	43.2	19.3	40.2	55.8	46.4

Note: the table reports HHI index, ratio of value of import to export, and share of UK imports and exports to EU. Data is COMTRADE in 2022.

The problem is further exacerbated by the increase in the relative price of materials and batteries in 2022, while price of exported EV has declined as shown in Table 6. The relative export price of car to import price of materials in the UK has declined by 59.6 percent in 2023, which made it increasingly difficult to satisfy the TCA RoO requirements.[6]

[6] In 2019, ratio of the price of export of EV to price of import of material was 30.838/23.052= 1.338. By 2023, the ratio declined to 28.469/52.726=0.540.

Table 6 UK prices of automotive industry products

A: Import prices						
year	Batteries	EV	Hybrid	ICE	Materials	Parts
2019	30.273	49.800	26.541	23.8	23.052	11.105
2020	28.459	47.707	25.587	25.6	9.460	10.681
2021	27.436	41.283	29.293	43.8	17.211	11.261
2022	20.520	41.844	29.354	33.9	31.713	11.300
2023	21.630	39.167	29.814	25.8	52.726	11.526
Average	25.113	42.798	28.304	30.1	26.459	11.105
B: Export prices						
year	Batteries	EV	Hybrid	ICE	Materials	Parts
2019	21.464	30.838	32.932	41.889	10.137	14.155
2020	41.553	29.949	48.984	43.295	9.708	13.307
2021	33.897	35.036	53.255	53.640	27.435	13.762
2022	53.736	28.433	45.533	113.891	33.739	15.834
2023	44.130	28.469	57.610	81.523	36.693	15.722
Total	37.756	30.962	47.778	58.602	25.379	14.304

Data: UK unit price based on COMTRADE data in 2019-2023. Price is in USD per kilogram for batteries, materials and part. Price is in thousand USD per vehicle for EV, hybrid, and ICE.

We further preform analysis at more granular HS6 product level to identify the most vulnerable products with the results presented in Table 7. We identified products as having critical dependency if they are concentrated geographically (HHI>2500), reply on trade with EU by more than 50%, and have imports exceeding exports.

Table 7 Assessment of the UK critical dependencies and vulnerabilities for EV supply chains

Product	Type	HHI		Import to export ratio	UK Share, %		Critical dependency on		
		Import	Export		Import from EU	Export to EU	Export to EU	Import from EU	Imports
250410	Materials	1670	1653	1.7	9.7	26.5			
253090	Materials	1492	818	2.0	52.5	40.6			
260400	Materials	10000	3360	0.0	.	93.3	Yes		
260500	Materials	6892	1203	0.0	.	51.2			
280519	Materials	5017	2276	48.6	1.6	32.9			Yes
282010	Materials	5928	2617	1.9	1.1	48.3			
282200	Materials	3871	6313	0.2	73.7	13.0		Yes	
282520	Materials	7229	3696	1.0	2.0	18.1			
282540	Materials	2841	2683	7.8	27.6	82.9	Yes		
282690	Materials	4583	2934	13.9	2.1	36.6			Yes
282739	Materials	1704	1600	0.6	35.4	53.2			
283529	Materials	1620	1377	1.8	77.0	52.2			
283691	Materials	8077	1943	1.7	3.4	52.2			Yes
284190	Materials	2034	2091	0.1	23.3	49.9			
284530	Materials	10000		.	.				

850720	Batteries	938	1112	1.3	35.3	56.7			
850730	Batteries	2717	777	1.6	38.7	60.1			
850760	Batteries	2829	1154	10.5	27.7	52.7			Yes
850790	Batteries	4657	994	2.6	5.7	64.7			Yes
854511	Batteries	2161	1232	2.7	64.3	43.2			Yes
854519	Batteries	7883	4670	0.5	4.5	0.5			
870321	ICE	1453	912	9.9	58.5	57.4			
870322	ICE	1439	1025	5.5	83.0	49.2			
870323	ICE	2292	1533	1.6	78.0	15.0			
870324	ICE	1959	1595	0.1	50.0	13.2			
870331	ICE	3652	2576	4.1	96.4	52.3	Yes	Yes	Yes
870332	ICE	1838	1006	9.7	72.1	64.7			
870333	ICE	2527	697	10.8	50.2	22.4		Yes	Yes
870340	HEV	1185	1081	0.6	49.1	39.4			
870350	HEV	4570	1030	0.5	81.7	42.7			
870360	PHEV	1288	839	2.5	73.7	66.6			
870370	PHEV	3735	6321	23.0	51.7	88.9	Yes	Yes	Yes
870380	EV	2401	1048	5.9	50.0	68.4			
870810	Parts	1244	1009	1.7	70.0	37.6			
870830	Parts	1260	880	1.7	49.3	65.0			
870840	Parts	2452	1499	3.3	65.0	36.8			
870850	Parts	1094	796	4.0	62.2	73.3			
870870	Parts	973	1014	2.4	41.7	52.5			
870880	Parts	1413	1291	1.7	75.9	55.9			
870891	Parts	958	1258	1.9	64.7	49.9			
870892	Parts	1746	860	1.5	74.7	69.2			
870893	Parts	1825	1648	2.2	69.6	78.0			
870894	Parts	1353	1806	3.8	69.4	73.0			
870895	Parts	1539	6930	1.4	84.8	5.2			
870899	Parts	837	606	2.1	62.0	54.6			
Average	All	2056	1426	4.6	49.3	49.1			

Note: Full name of products is listed in Table A1 in Appendix B. We follow the definition of critical values adopted by Arjona et al. (2023). The red shaded areas indicate the areas of UK's critical dependence. These include: HHI above 2500, Import to export ratio exceeds 1, share of trade with EU more than 50%;

Critical dependency on Export to the EU is when Export HHI > 2500 and the EU share in UK exports is > 50%;

Critical dependency on Import from the EU is when Import HHI > 2500 and the EU share in UK imports is > 50%;

Critical dependency on imports is defined as Import HHI > 2500 and Import to export ratio is greater than 1.

According to the results, the UK critically depends on the import of batteries for EVs (HS850760). The UK imports of EV batteries exceeds exports by 10.5 times, coming from China. While there is low dependency on EU imports, it is not necessarily beneficial for the UK EV producers, since this configuration of the EV GVC will prevent them to export cars to the EU tariff free after the new RoO comes in action in 2027. The UK is also vulnerable in trade of diesel plug-in cars (HS870370) and traditional petrol cars with high engine volume (HS870331). For EV, the UK dependence on exports to EU is mitigated by the reasonably high geographical diversification of customers withing the EU, as the UK exports to a large number of the EU countries. However, this high diversification may be deceptive as the common trade policy of the EU pose high risk to the UK exporters who are exposed to the risk of losing tariff free access to the EU market for 68.4% of its exports of EV.

6. Network Analysis of the EV Global Value Chains

6.1. Network characteristics

Long-distance trade has been an integral part of global economy. Despite its numerous benefits, long-distance trade has historically posed greater risks and incurred higher costs compared to local trade. Trade costs that include freight, insurance and customs duties, as well as longer time of moving parts and final products (Anderson and Van Wincoop, 2004; Djankov et al., 2010). Long-distance trade is susceptible to political risks and uncertainty. Military conflicts, geopolitical tensions, and piracy along trading routes pose threats to the security and stability of trade operations. Unforeseen political events, such as trade disputes or changes in government policies, can disrupt supply chains and create uncertainty for businesses engaged in long-distance trade. Engaging in trade with foreign business entities introduces legal uncertainties. Differences in legal systems, contract enforcement mechanisms, and dispute resolution processes can complicate commercial relationships (Greif, 1993; Levchenko, 2007).

Recent trends towards outsourcing tasks and long-distance global supply chains, motivated by economic efficiency but not always by pricing externalities associate with them, as well as risks of natural disasters and global pandemics, pose new challenges that have prompted discussions around the regionalization and localization of supply chains. In recent years, growing environmental concerns have highlighted the impact of long-distance trade on pollution and carbon dioxide emissions. The environmental bias in trade policy creates incentives to locate dirty industries in developing countries (Shapiro, 2021; Copeland et al. 2021). Excessive shipping of intermediate goods along global trading routes and outsourcing dirty stages of production to developing countries contributes to the carbon footprint of supply chains. The externalities associated with increased pollution and emissions are not always adequately priced into the market system, creating a pressing need for sustainable practices and environmentally conscious alternatives (World Bank, 2020).

It is important to analyse the GVC networks in terms of distance along the routes and the dynamics. We use monthly data for 2017-2022 exports of materials of EV batteries, batteries and EVs, supplemented with the mirror imports in cases where direct exports are not available and investigate the weighted average length per product k, given by

$$Distance_{kt} = \frac{1}{N_{kt}} \sum_i \sum_j w_{ij,kt} d_{ij}$$

where w is the share of exports from i to j of product k at time t in the total export of good k at time t. d is distance from i to j (Mayer and Zignago, 2011) and N_{kt} is total number of positive exports of product k at time t. Table 8 reports length of trading routes per product and its dynamics for the EV GVCs.

The calculations are shown in Table 8. The data provided in columns 2017-2022 of the table allows for a detailed analysis of the dynamics and comparison of trends in the supply chains distances for materials, batteries, and EVs, as well as their comparison with the length of the supply chains of traditional vehicle. The length of the trading routes in materials varies substantially from 1.2 (Other Inorganic Compounds, HS282540 in 2017) to 15.9 (Lithium Carbonate, HS283691 in 2022) thousand kilometres. Importantly, there is a trend of an increase of the length of the trading routes, which was particularly strongly featured in 2022.

The length of trading routes for lithium-ion batteries, which valued about 5.4% of total exports, in 2017-2021 has been stable, fluctuating around 5.2 thousand kilometres, which sharply increased to 5.7 in 2022. These fluctuations in the length of trading routes for lithium-ion batteries could be attributed to various factors. Changes in the sourcing strategies of battery manufacturers, shifts in global production centres, and the establishment of new trade relationships can impact the distances involved in the supply chains. Additionally, geopolitical factors, trade policies, and regional demand patterns can also contribute to the dynamics observed.

For electric vehicles, the length of trading routes was shorter and appeared to take a U-shaped pattern over time, which is consistent with moving the centre of EV vehicles production and trade from the US to Germany, closer to the consumers of EVs, primarily located in Europe. The increase in 2022, however, represents the rise of China as the main EV producer. Comparing to the length of the trading routes for ICE vehicles, EVs export length is higher than for small ICE (HS870321, 870322, 870331, 870332), but shorter than for large ICE (HS870323, 870324, 870333, 870332). It is also comparable with the length of the trading routes of HEV and PHVE vehicles, except for Diesel PHVE (HS870370) having shorter trading routes of 2.0-3.9 thousand kilometres. Overall, however, there was a trend towards longer EV GVCs, increasing from 4.8 thousand kilometres in 2018 to 5.3 thousand kilometres in 2022.

Table 8 Length of trading routes for EV GVCs and passenger cars in 2017-2022

HS6	Type	Product description	Year						Share of
			2017	2018	2019	2020	2021	2022	Exports, %
250410	Materials	Natural Graphite	3.5	3.9	4.8	3.5	4.8	6.2	0.04
253090	**Materials**	**Unprocessed Lithium Mineral**	**7.4**	**7.4**	**7.4**	**7.1**	**8.0**	**8.6**	**0.46**
260400	Materials	Nickel Ores and Concentrates	5.9	5.9	5.3	5.4	5.9	6.6	0.45
260500	Materials	Cobalt Ores and Concentrates	6.1	5.5	9.6	9.4	9.6	9.3	0.04
280519	Materials	Lithium Metal	4.6	5.3	3.6	4.0	3.0	4.5	0.03
282010	Materials	Manganese Dioxide	5.4	4.5	4.1	5.1	5.1	4.8	0.01
282200	Materials	Cobalt Oxides and Hydroxides	4.2	4.2	5.1	5.8	4.1	5.1	0.67
282520	Materials	Lithium Oxide and Hydroxide	7.0	5.7	4.8	3.5	4.0	3.5	0.21
282540	Materials	Other Inorganic Compounds	4.3	1.2	1.3	1.7	1.7	3.5	0.07
282690	Materials	Lithium Fluoride	7.9	8.2	8.1	7.7	5.6	6.0	0.05
282739	Materials	Lithium Chloride	5.5	4.6	4.4	5.1	5.1	4.9	0.04
283529	Materials	Phosphates	8.2	6.1	6.9	2.1	5.6	2.1	0.01
283691	**Materials**	**Lithium Carbonate**	**14.6**	**13.8**	**13.0**	**14.9**	**15.1**	**15.9**	**0.41**
284190	Materials	Salts of oxometallic acids	2.6	3.7	4.6	6.2	6.6	7.4	0.48
850720	Batteries	Lead-acid batteries	5.3	5.5	5.5	5.8	5.7	6.0	0.73
850730	Batteries	Nickel-cadmium batteries	5.3	4.9	5.5	5.7	6.2	7.0	0.04
850760	**Batteries**	**Lithium-ion batteries**	**5.2**	**5.2**	**5.2**	**5.0**	**5.1**	**5.7**	**5.36**
850790	Batteries	Primary battery cells	3.5	4.3	4.5	5.3	5.9	7.1	0.60
854511	Batteries	Graphite Electrodes	5.8	5.5	4.9	4.7	4.7	5.3	0.58
854519	Batteries	Other Electrodes	5.3	5.4	5.2	5.7	5.8	6.4	0.23
870321	ICE	Petrol Car, less than 1000 cm3	3.0	2.9	2.7	2.9	3.2	2.9	4.38
870322	ICE	Petrol Car, 1000 to 1500 cm3	3.9	3.8	3.6	3.7	4.1	4.5	12.49
870323	ICE	Petrol Car, 1500 to 3000 cm3	6.3	6.1	6.0	6.1	6.1	6.3	30.74
870324	ICE	Petrol Car, more than 3000 cm3	5.8	5.8	5.9	6.2	6.2	6.0	10.93
870331	ICE	Diesel Car, less than 1500 cm3	1.7	1.4	1.4	1.4	1.5	1.7	2.25
870332	ICE	Diesel Car, 1500 to 2500 cm3	2.7	2.7	2.7	2.5	2.5	2.8	12.33
870333	ICE	Diesel Car, more than 2500 cm3	4.5	4.5	5.1	5.5	5.7	5.8	3.58
870340	HEV	Petrol HEV	5.5	5.0	5.1	5.0	5.0	5.1	5.49
870350	HEV	Diesel HEV	1.7	1.4	1.5	3.0	3.5	3.7	0.72
870360	PHEV	Petrol PHEV	5.2	5.4	5.5	4.2	4.0	4.4	2.40
870370	PHEV	Diesel PHEV	2.0	2.1	2.2	2.9	3.0	3.9	0.14
870380	**EV**	**EV**	**5.6**	**4.7**	**5.2**	**4.2**	**4.1**	**4.7**	**4.03**
Average			**4.9**	**4.8**	**4.8**	**4.8**	**4.9**	**5.3**	100.00

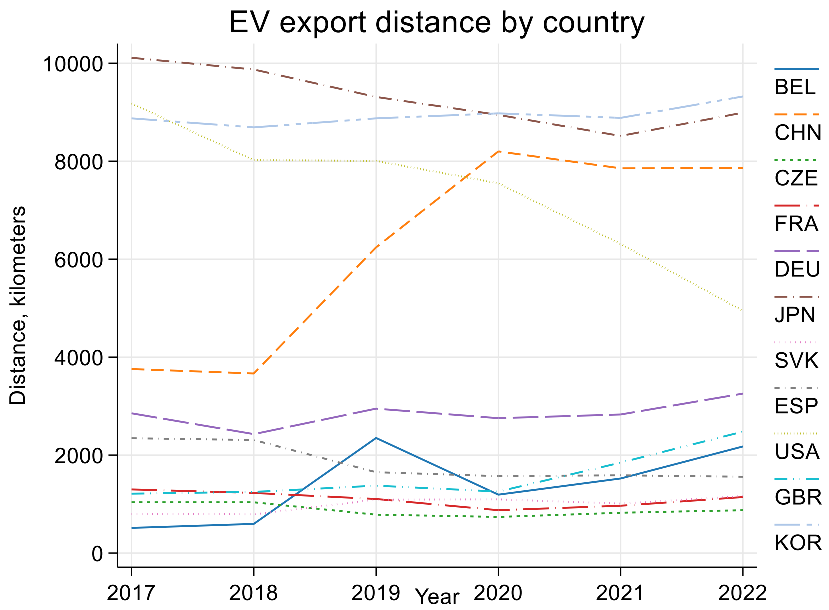
Source: COMTRADE data and author's calculations.
Note: Distance is measured as the weighted average distance between reporter and partner weighted by export value. We use mirror data to fill the missing exports, using the mirror import values as reported by trading partners. Share of export in percent is given for the whole period as the percentage of the total export generated by EV and passenger car GVC.

Figure 6 illustrates significant variability in the length of supply chains across countries.[7] European nations exhibit notably shorter EV export routes, such as 0.9 thousand

[7] Table A3 in the appendix provides data on GVC distances for each component of the value chain for major participating countries.

kilometres for the Czech Republic, 3 thousand kilometres for the UK, and 3.3 thousand kilometres for Germany in 2022. In contrast, non-European EV exporters contend with considerably longer routes: the US ships EVs to destinations 6.2 thousand kilometres away, China covers 7.8 thousand kilometres, Japan spans 9.0 thousand kilometres, and South Korea extends to 9.3 kilometres in 2022. While European countries show no distinct trends, the US has reduced its export routes by 35% from 2017 to 2022, whereas China has globally expanded its exporting routes by 61%. This evolution of EV export distances over time is further visualized in Figure 6.

Figure 6 Distance of export of EV (HS870380) for top 10 EV producers in 2022



Note: this figure reports length of the supply of EV (HS870380) for selected countries, calculated as the average distance of reporting country to its partner countries weighted by the export value. Data on export values of EVs are from COMTRADE. Data on distances between countries is from CEPII Gravity Dataset.

6.2. GVCs properties and vulnerabilities

Analysing the stability and resilience of EV Global Value Chain GVC is best achieved through the network analysis, a focal point in theoretical and applied research in the network economics. A crucial aspect is understanding the stability of a network and identifying key players whose removal would most disrupt network activities. Ballester et al. (2006) propose a theory characterizing the key player as the agent whose removal optimally changes the aggregate activity level in equilibrium, considering both network topology and social interaction intensity. In what follows we provide a brief and intuitive explanation for each measure of the key players in a network. For more formal exposition, please refer to Appendix A.

Measures of networks

Methods for identifying key players have evolved significantly. Direct or local centrality measures, counting incoming (**indegree** centrality) or outgoing (**outdegree** centrality) links, may not pinpoint key players, even when considering the importance of each connection measured by import (**weighted indegree** centrality) or export (**weighted outdegree** centrality) value. For more local connectivity, the Local **Clustering Coefficient** proves effective, capturing the density of connections in a node's immediate neighbourhood. While adept at identifying tightly connected clusters, it doesn't consider the global network structure and may overlook nodes connecting different clusters.

The local measures often overlook non-local effects, such as nodes with small degrees acting as vital bridges between network segments. It's crucial not only to have numerous direct links but to be centrally located, influencing trade flow, akin to the strategic significance of the Panama Canal or Molucca Strait for the global trade. In this context, a widely used metric for node centrality is **betweenness centrality** (BC), which quantifies the fraction of shortest paths between pairs of nodes passing through a given node. **Closeness Centrality** takes a more comprehensive stance by incorporating both direct and indirect connections, spotlighting nodes close to all others. However, its sensitivity to network size and disconnected components is a notable drawback.

For centrality with a focus on connection quality, **Eigenvector Centrality** (Ballester et al., 2006) distinguishes itself by capturing both quantity and quality of connections, accentuating nodes linked to well-connected nodes. Although more computationally involved, it offers valuable insights into a node's influence. In sum, each centrality measure brings a unique perspective, contributing to a comprehensive understanding of a node's importance within a network. The choice ultimately hinges on research goals and the specific network characteristics under scrutiny.

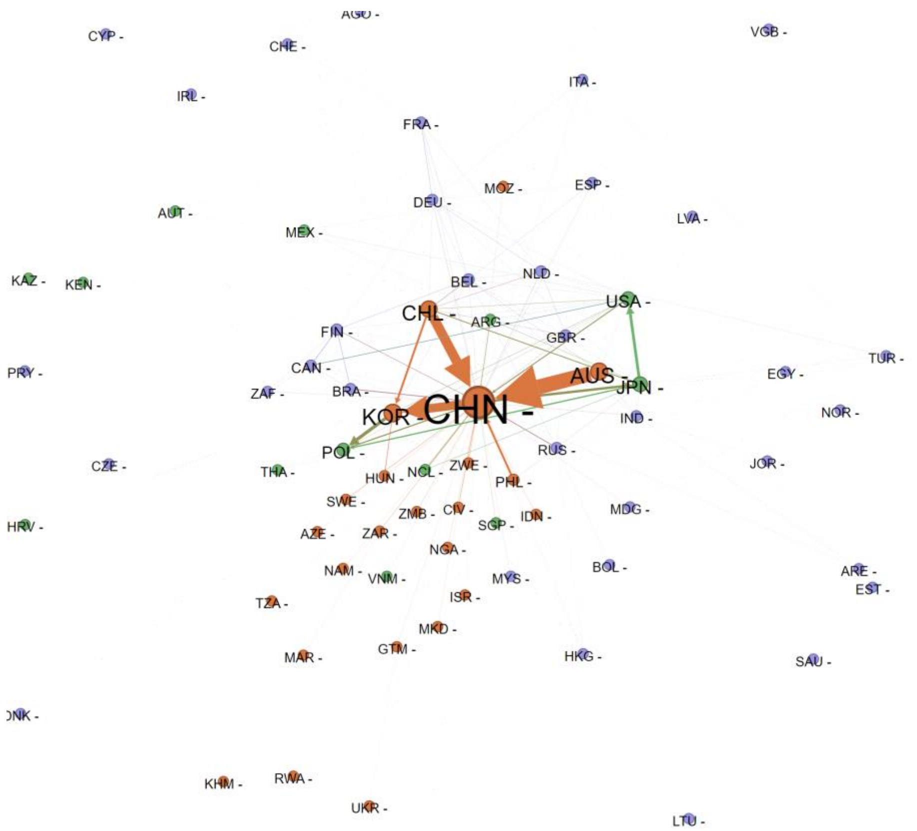
Because of strength and weaknesses of different measures of centrality, we report a wide range of measures, including indegree and outdegree, weighted indegree and outdegree, closeness, betweenness, clustering and eigenvector centrality. The definitions and formal discussion of the measures is presented in Appendix A. The analysis is performed using Gephi, with betweenness centrality using Brandes (2001) and modularity (or regional clusters) based on Blondel et al. (2008).

Evolution of EV batteries materials networks

Figure 7 shows the global EV batteries supply chains at country level. Each node indicates a country, participating in the supply chain. The size of the node is proportional to its weighted degree (sum of indegree and outdegree), identifying the nodes that are better connected with other countries. China holds the central place in the network of materials for the EV batteries in 2022, while three clusters can be identified in the network (marked with nodes of different colours). The China-centred cluster is marked in orange, the US-centred cluster is marked in green, and the EU based one is marked in purple. The linked nodes indicate positive trade with the direction of trade shown with the arrows. The width of the arrow is proportional to the value of exports.

The main suppliers of raw materials are Australia and Chile, which ship lithium and other metals to China as the central hub of processing and production of the semi-processed intermediate inputs to produce battery cells and battery packages. Another substantial flow shown on the figure is the shipment of materials from China to South Korea, which has become one of the leading centres of the EV battery and EV production.

Figure 7 Network of EV battery materials in 2022



Note: Links with value of trade below 1 mln USD are excluded.

Table 9 presents the characteristics of the materials network nodes for top 10 participants in 2022 (Panel A) and in 2017 (Panel B). Each panel also shows the network average and network total for all participants. Panels C and D present absolute and relative changes between 2017 and 2022. In terms of characteristics, the table includes in and out degrees, both simple count and weighted. The weighted outdegree is approximately the value of the node exports in billion USD, while the weighted indegree is the value of the node imports in billion USD.[8] Centrality measures, standard for the network analysis, are further presented.

Between 2017 and 2022, the network expanded in terms of the number of links and generated value per node on average by 30% and 179% consequently: 84 new links were created with the value of trade increasing by 27 bln USD. The US was more central to the network in 2017 according to the eigencentrality measure, while this has shifted in 2022 with betweenness and eigencentrality pointing to China being the key player in this network, both as the well connected directly and also as a bridge between producers of raw materials, such as Australia and Chile and consumers of processed materials for the batteries in Asia and Europe.

[8] Links with the annual value below 1 mln USD are excluded from the analysis.

Table 9 Battery materials network: comparison of 2017 and 2022

Country	Indegree	Outdegree	Weighted Indegree	Weighted Outdegree	Centrality measures: Closeness	Betweenness	Clustering	Eigen
A: EV materials network in 2022								
CHN	44	32	20.483	8.682	0.763	1371	0.101	1.000
KOR	12	12	6.692	3.214	0.529	155	0.295	0.509
AUS	3	6	0.012	9.156	0.484	1	0.625	0.167
CHL	0	14	0.000	8.346	0.560	0	0.484	0.000
JPN	21	10	3.258	2.957	0.517	97	0.220	0.701
USA	27	17	2.680	1.518	0.584	422	0.174	0.835
POL	9	3	3.573	0.063	0.459	14	0.633	0.524
PHL	1	5	0.004	1.286	0.479	0	0.950	0.051
BEL	17	17	0.696	0.498	0.608	231	0.248	0.635
GBR	13	12	0.398	0.190	0.556	142	0.333	0.604
Average	4.4	4.4	0.556	0.556	0.399	48	0.401	0.178
Total	338	338	42.3	42.3	30.3	3614	30.5	13.6
B: EV materials network in 2017								
CHN	26	21	4.212	1.556	0.603	986	0.099	0.970
ZAR	0	8	0.000	5.171	0.458	0	0.214	0.000
ZAF	3	9	4.087	0.247	0.490	35	0.255	0.014
KOR	12	7	1.823	0.730	0.461	59	0.267	0.639
JPN	15	6	1.086	0.693	0.456	49	0.268	0.834
AUS	5	10	0.028	1.249	0.495	26	0.382	0.317
USA	18	19	0.555	0.606	0.580	504	0.165	1.000
CHL	0	12	0.000	0.857	0.521	0	0.432	0.000
PHL	2	4	0.022	0.571	0.398	50	0.567	0.221
GBR	5	6	0.040	0.044	0.427	61	0.422	0.478
Average	3.4	3.4	0.199	0.199	0.318	52	0.207	0.200
Total	254	254	14.7	14.7	23.6	3828	15.3	14.8
C: Difference, 2017-2022								
Average	1.0	1.0	0.357	0.357	0.081	-4	0.194	-0.021
Sum	84	84	27.5	27.5	6.8	-214	15.2	-1.2
D: Difference in %, 2017-2022								
Average	29.6	29.6	179.2	179.2	25.3	-8.1	93.7	-10.7
Sum	33.1	33.1	186.7	186.7	28.7	-5.6	99.0	-8.3

Note: Indegree and outdegree count the number of positive incoming and outgoing positive trade links respectively. The weighted indegree and outdegree count the positive trade links using the value of imports and exports between the linked nodes as weights. The centrality measures take into account the configuration of the network, including direct and indirect links. The closeness measure incorporates both direct and indirect connections, spotlighting nodes close to all others. The betweenness centrality quantifies the fraction of shortest paths between pairs of nodes passing through a given node. Clustering coefficient calculates the density of connections in a node's immediate neighbourhood. Finally, eigenvector centrality summarizes importance of each node by counting direct links, links of neighbours, links of neighbours of neighbours and so on. It assigns higher centrality scores to nodes that are connected to other highly central nodes. It assumes that nodes with high centrality scores can influence the network more strongly. For more formal presentation of centrality measure, look at Appendix A. Data: Comtrade monthly export data, with mirror data used when the direct export data is not available. Links with value of trade below 1 mln USD are excluded.

Evolution of EV batteries networks

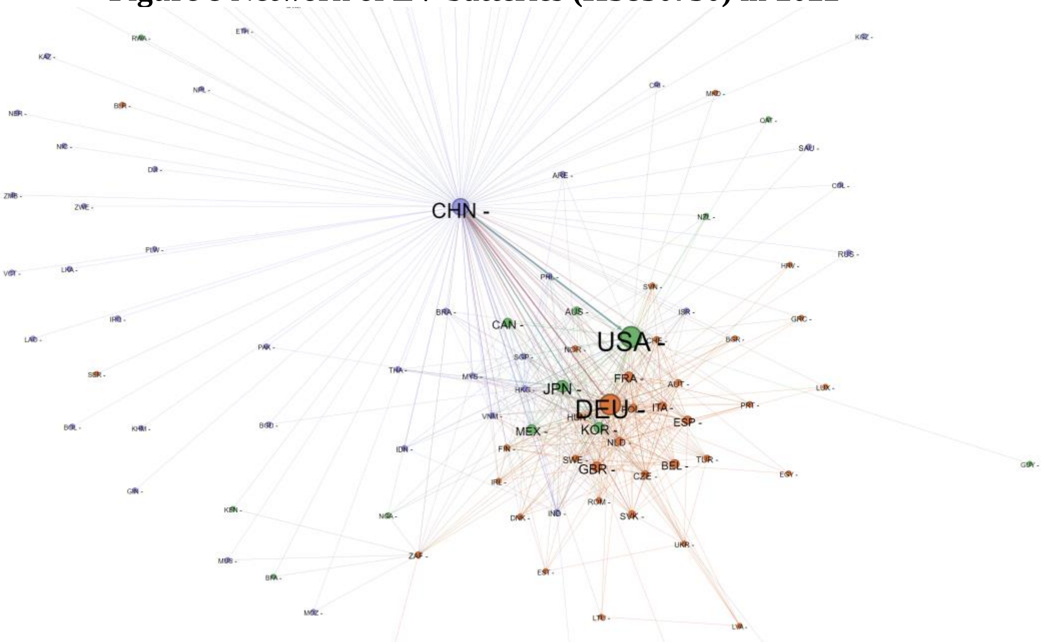
Figure 8 presents a visual description of the EV batteries network in 2022. The main centres around which other countries are clustered are China, Germany and the US. The EV batteries network is much denser than the network of materials, having more nodes and links. According to Table 10, which shows the characteristics of the nodes, the network expanded by 92% over the period of 2017-2022 in the number of connections per average node and by 340% in terms of the average value generated by a link. It also became less dense, as indicated by 15% decline in clustering and 65% decline in betweenness centrality. The growth of the network combined with its becoming less centralized is a natural process as new countries joining the network are on average less connected and are less centrally located. It is especially pronounced for the hub and spoke type of network formed around China, with many countries connected to China, but isolated from the other participants of the network. This observation is confirmed by a highly negative coefficient of the assortativity of the EV battery network, -0.496, which indicates that the nodes with many connections tend to connect to nodes with few connections. It also mean that the countries do not diversify their supplies of batteries but tend to concentrate on a single supplier.[9]

Germany has been the key player in the battery network according to both betweenness and eigencentrality measures in 2017, while in 2022 it remains the key player according to eigencentrality, but China is firmly in the lead according to betweenness measure. Comparison of the clustering coefficient for China and Germany explains why this is the case, since China supply batteries to more markets (116), which are on average are not very central to the network. Germany, on the other hand, supply batteries to 47 markets, which are themselves located at the core of the network. Comparing 2017 and 2022 also demonstrate emergence of the new important participants of EV batteries GVC – Poland and Hungary.

UK is not at the top of the battery network in terms of in and out-degree, as it exports 160 mln USD worth of batteries in 2022. At the same time, it is located quite favourably in the network, well-connected to the main players of the network, which is shown by its high values of clustering and eigencentrality. It indicates that if the UK had a capacity to produce EV batteries, it could have expanded and increased its value in the network.

[9] For more detailed data on assortativity of the EV GVC networks, please look at Table A4 in the appendix.

Figure 8 Network of EV batteries (HS850750) in 2022



Note: Links with value of trade below 1 mln USD are excluded.

Table 10 EV Battery network: comparison of 2017 and 2022

Country	Indegree	Outdegree	Weighted Indegree	Weighted Outdegree	Closeness	Betweenness	Clustering	Eigen
A: EV battery network in 2022								
CHN	19	116	4.219	50.743	0.960	2756	0.042	0.650
DEU	31	47	18.764	5.764	0.622	945	0.129	1.000
USA	28	36	16.872	1.857	0.585	672	0.158	0.885
POL	18	23	2.380	8.844	0.548	192	0.234	0.669
KOR	9	36	6.233	4.845	0.588	77	0.195	0.357
HUN	14	22	1.829	7.044	0.545	107	0.196	0.520
HKG	11	35	2.210	3.929	0.585	248	0.149	0.337
NLD	25	27	4.654	0.982	0.558	264	0.173	0.856
JPN	12	33	2.395	3.101	0.577	169	0.190	0.372
CZE	14	19	2.476	2.034	0.414	23	0.229	0.572
GBR	24	14	2.600	0.160	0.522	249	0.206	0.841
Average	3.6	3.6	0.546	0.546	0.128	36	0.453	0.136
Total	645	645	96.7	96.7	22.6	6417	80.1	24.1
B: EV battery network in 2017								
CHN	13	70	3.584	8.534	0.709	2432	0.054	0.656
HKG	10	29	2.981	2.142	0.539	237	0.104	0.530
USA	19	28	3.831	1.222	0.709	1695	0.124	0.911
KOR	8	27	0.615	3.474	0.723	684	0.168	0.487
JPN	9	26	0.756	2.658	0.796	1828	0.154	0.519
DEU	19	27	2.095	0.890	0.738	3312	0.151	1.000
VNM	6	15	1.214	0.382	0.526	4	0.237	0.303
MYS	7	15	0.359	0.978	0.523	26	0.229	0.444
NLD	15	15	1.033	0.201	0.583	441	0.142	0.800
IND	6	0	0.838	0.000	0.632	844	0.267	0.308
GBR	8	8	0.428	0.106	0.664	660	0.196	0.526
Average	1.9	1.9	0.124	0.124	0.258	104	0.523	0.111
Total	344	344	22.5	22.5	46.7	18788	94.7	20.0
C: Difference, 2017-2022								
Average	1.7	1.7	0.422	0.422	-0.130	-68	-0.071	0.026
Sum	301	301	74.2	74.2	-24.1	-12371	-14.6	4.1
D: Difference in %, 2017-2022								
Average	91.7	91.7	339.5	339.5	-50.5	-65.1	-13.5	23.3
Sum	87.5	87.5	329.8	329.8	-51.6	-65.8	-15.4	20.6

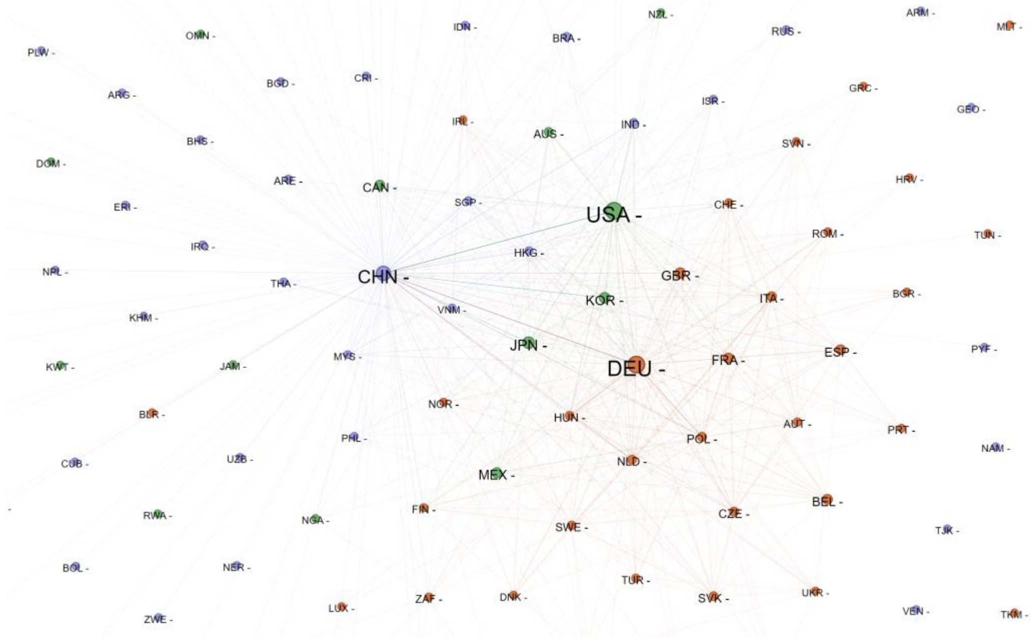
Note: Indegree and outdegree count the number of positive incoming and outgoing positive trade links respectively. The weighted indegree and outdegree count the positive trade links using the value of imports and exports between the linked nodes as weights. The centrality measures take into account the configuration of the network, including direct and indirect links. The closeness measure incorporates both direct and indirect connections, spotlighting nodes close to all others. The betweenness centrality quantifies the fraction of shortest paths between pairs of nodes passing through a given node. Clustering coefficient calculates the density of connections in a node's immediate neighbourhood. Finally, eigenvector centrality summarizes importance of each node by counting direct links, links of neighbours, links of neighbours of neighbours and so on. It assigns higher centrality scores to nodes that are connected to other highly central nodes. It assumes that nodes with high centrality scores can influence the network more strongly. For more formal presentation of centrality measure, look at Appendix A. Data: Comtrade monthly export data, with mirror data used when the direct export data is not available. Links with value of trade below 1 mln USD are excluded.

Evolution of EV networks

Figure 9 shows the network of EVs in 2022, while Table 11 presents the main characteristics of the EV network in 2017 and 2022 and its evolution. It is striking that the network grew in value 1020% in 5 years. The number of links per node has increased by 330% on average. The betweenness and eigencentrality have also increased, indicating a better connectivity of the network. Despite being more connected, the network also appears less clustered, indicating that EVs are reaching to the most parts of the worlds, even to countries which have poor connections with the rest of the network.

Germany is the central player of the network in 2022 according to betweenness and eigencentrality. China, despite having second highest weighted degree, has a low value of eigen centrality, indicating that is does not export to the key markets of EU and US where the most consumers of the EV are located. China has a high value of outdegree, but primarily serving the markets which are located at the periphery of the EV network.

Figure 9 Network of EV (HS870380) in 2022



Note: Links with value of trade below 1 mln USD are excluded.

Table 11 EV network: comparison of 2017 and 2022

Country	Indegree	Outdegree	Weighted Indegree	Weighted Outdegree	Centrality measures Closeness	Betweenness	Clustering	Eigen
A: EV network in 2022								
DEU	24	76	9.238	25.836	0.852	1305	0.00515	1.000
CHN	6	76	1.641	20.224	0.852	534	0.00452	0.283
USA	15	32	11.452	5.906	0.601	373	0.00463	0.627
BEL	20	51	7.763	6.780	0.687	443	0.00624	0.844
GBR	17	43	10.580	1.756	0.609	208	0.00735	0.679
KOR	8	41	2.244	7.650	0.643	55	0.00510	0.388
FRA	16	34	5.171	2.589	0.568	58	0.00776	0.711
ESP	18	34	2.738	3.945	0.575	142	0.00830	0.790
NOR	20	4	5.669	0.017	0.357	10	0.00544	0.916
NLD	18	17	4.043	1.010	0.511	89	0.00924	0.834
Average	3.8	3.8	0.518	0.518	0.121	23	0.30659	0.175
Total	669	669	91.7	91.7	21.4	4056	54.3	30.9
B: EV network in 2017								
USA	7	17	1.067	3.170	0.589	184	0.00000	0.489
DEU	12	24	0.753	1.475	0.694	329	0.00000	0.922
CHN	2	6	1.458	0.086	0.402	66	0.00000	0.233
NLD	7	17	0.191	1.169	0.558	126	0.00181	0.633
NOR	13	0	1.348	0.000	0.000	0	0.00000	1.000
FRA	9	15	0.353	0.501	0.558	106	0.00000	0.638
GBR	8	12	0.577	0.228	0.506	131	0.00000	0.697
JPN	3	11	0.105	0.634	0.518	76	0.00000	0.272
KOR	3	15	0.080	0.409	0.566	45	0.00000	0.335
CAN	3	0	0.483	0.000	0.000	0	0.00000	0.288
Average	0.9	0.9	0.045	0.045	0.080	7	0.47644	0.077
Total	159	159	8.2	8.2	14.5	1207	86.2	13.9
C: Difference, 2017-2022								
Average	2.9	2.9	0.473	0.473	0.041	16	-0.170	0.098
Sum	510	510	83.5	83.5	6.9	2849	-32.0	17.0
D: Difference in %, 2017-2022								
Average	330.3	330.3	1045.1	1045.1	50.6	243.6	-35.6	126.9
Sum	320.8	320.8	1019.8	1019.8	47.3	236.0	-37.1	121.9

Note: Indegree and outdegree count the number of positive incoming and outgoing positive trade links respectively. The weighted indegree and outdegree count the positive trade links using the value of imports and exports between the linked nodes as weights. The centrality measures take into account the configuration of the network, including direct and indirect links. The closeness measure incorporates both direct and indirect connections, spotlighting nodes close to all others. The betweenness centrality quantifies the fraction of shortest paths between pairs of nodes passing through a given node. Clustering coefficient calculates the density of connections in a node's immediate neighbourhood. Finally, eigenvector centrality summarizes importance of each node by counting direct links, links of neighbours, links of neighbours of neighbours and so on. It assigns higher centrality scores to nodes that are connected to other highly central nodes. It assumes that nodes with high centrality scores can influence the network more strongly. For more formal presentation of centrality measure, look at Appendix A. Data: Comtrade monthly export data, with mirror data used when the direct export data is not available. Links with value of trade below 1 mln USD are excluded.

6.3. Testing short-run disruption

The pivotal role of China within EV Global Value Chains (GVCs) has experienced significant growth in the past five years, particularly in the supply of materials and batteries, solidifying its position as a key player. Concurrently, rising political and economic tensions between China and the United States, along with a notable policy shift within the European Union towards strengthening regional supply chains, accentuate the need for a comprehensive risk assessment. It is imperative to scrutinize the stability of the network in response to the hypothetical scenario of removing China from the EV GVCs.

This risk assessment is crucial given the intricate interdependencies and China's pronounced influence on the supply chain. The potential consequences of such a scenario necessitate thorough exploration, taking into account the multifaceted impacts on material supply, battery production, and overall network stability. Examining the network's resilience to the absence of China becomes paramount for strategic decision-making in the face of evolving geopolitical dynamics and shifting global economic landscapes.

Table 12 presents the results of removing China from the network of EV battery materials, revealing a reduction in the value generated by the network by 29 billion USD (69%). Among exporting countries, Australia, Chile, and the Philippines would incur the most significant losses. On the receiving side, Korea, Japan, and Poland would be the most affected.

Table 12 Materials network disruption

Country	Degree		Weighted degree		Centrality			
	In	Out	In	Out	Closeness	Betweenness	Clustering	Eigen
				A: Absolute change				
KOR	-1	-1	-5.145	-0.450	-0.023	19.8	-0.064	0.058
AUS	-1	-1	-0.004	-8.887	-0.018	1.8	-0.101	-0.073
CHL	0	-1	0.000	-5.786	-0.010	0.0	-0.067	0.000
JPN	-1	-1	-1.456	-0.356	-0.035	138.7	-0.043	0.129
USA	-1	-1	-0.266	-0.583	-0.007	145.9	-0.030	0.165
POL	-1	-1	-0.697	-0.035	-0.053	-4.6	-0.050	0.089
PHL	0	-1	0.000	-1.205	-0.038	0.0	-0.033	0.020
BEL	-1	-1	-0.060	-0.002	0.004	66.1	-0.037	0.120
GBR	-1	-1	-0.060	-0.045	-0.009	175.3	-0.049	0.107
Average	-0.64	-0.64	-0.366	-0.366	-0.027	1.2	-0.108	0.014
All network	-75	-75	-29.1	-29.1	-4.7	-247	-10.2	-0.3
				B: Difference in %				
KOR	-8.33	-8.33	-76.88	-14.00	-4.39	12.79	-21.84	11.39
AUS	-33.33	-16.67	-34.47	-97.07	-3.71	130.98	-16.19	-43.73
CHL	0.00	-7.14	0.00	-69.33	-1.70	0.00	-13.83	0.00
JPN	-4.76	-10.00	-44.69	-12.05	-6.75	142.73	-19.70	18.41
USA	-3.70	-5.88	-9.91	-38.44	-1.19	34.57	-17.38	19.76
POL	-11.11	-33.33	-19.52	-55.72	-11.60	-31.75	-7.89	16.91
PHL	0.00	-20.00	0.00	-93.72	-7.91	0.00	-3.51	39.62
BEL	-5.88	-5.88	-8.69	-0.33	0.63	28.64	-14.97	18.85
GBR	-7.69	-8.33	-15.06	-23.77	-1.60	123.04	-14.71	17.73
Average	-14.30	-14.30	-65.75	-65.75	-6.82	2.62	-26.86	7.57
All network	-22.19	-22.19	-68.91	-68.91	-15.40	-6.83	-33.60	-2.34

Note: Table presents changes in 2022 network properties as a result of counterfactual removal of China from the export of batteries for selected countries, on average, and for the whole network. The results are valid for the short-run when the network has not adjusted yet and new links have not been formed. The countries are sorted by their weighted degree in 2022

Table 13 presents the short-run effect of disrupting the EV batteries network. The removal of China from the network would reduce value generated by 4.6 billion USD, with Germany, USA and Korea most effected as importers, while the losses of exporters are not very pronounced.

Table 13 Batteries network disruption

Country	Degree		Weighted degree		Centrality			
	In	Out	In	Out	Closeness	Betweenness	Clustering	Eigen
A: Absolute change								
DEU	-1	-1	-0.644	-0.042	0.159	-213.7	-0.137	0.000
USA	-1	-1	-0.845	-0.004	0.074	-55.7	-0.147	-0.009
KOR	-1	-1	-0.440	-0.028	0.100	7.6	-0.197	-0.025
POL	-1	-1	-0.112	-0.020	0.018	-97.4	-0.276	-0.005
HUN	-1	-1	-0.052	-0.002	0.031	-54.0	-0.295	-0.018
HKG	-1	-1	-0.142	-0.083	0.095	-63.9	-0.206	-0.034
NLD	-1	-1	-0.280	-0.001	0.034	-100.0	-0.206	-0.003
JPN	-1	-1	-0.138	-0.016	0.063	-51.8	-0.194	-0.032
CZE	-1	0	-0.044	0.000	0.107	1.9	-0.327	-0.009
GBR	-1	-1	-0.114	-0.001	-0.006	-156.5	-0.280	0.000
Average	-0.66	-0.66	-0.025	-0.025	0.011	-19.7	-0.145	-0.022
All network	-134	-134	-4.6	-4.6	1.1	-3594	-28.6	-4.6
B: Difference in %								
DEU	-3.23	-2.13	-40.59	-8.36	25.53	-22.61	-51.07	0.00
USA	-3.57	-2.78	-59.48	-2.07	12.71	-8.29	-47.19	-1.00
KOR	-11.11	-2.78	-83.69	-6.33	16.99	9.78	-48.52	-6.91
POL	-5.56	-4.35	-52.73	-2.69	3.36	-50.67	-51.84	-0.69
HUN	-7.14	-4.55	-31.68	-0.26	5.71	-50.37	-58.82	-3.39
HKG	-9.09	-2.86	-73.69	-23.97	16.31	-25.74	-56.27	-10.22
NLD	-4.00	-3.70	-67.41	-1.12	6.17	-37.93	-53.37	-0.35
JPN	-8.33	-3.03	-67.15	-5.84	10.93	-30.71	-48.88	-8.60
CZE	-7.14	0.00	-19.81	0.00	25.75	8.36	-57.17	-1.65
GBR	-4.17	-7.14	-48.50	-4.00	-1.08	-62.93	-55.33	0.04

Note: Table presents changes in 2022 network properties as a result of counterfactual removal of China from the export of batteries for selected countries, on average, and for the whole network. The results are valid for the short run, when the network has not adjusted yet and new links have not been formed. The countries are sorted by their weighted degree measure in 2022.

Finally, Table 14 shows the impact of removal of China from the network of EV. It would be associated with 21.9 bln USD loss in value, with the most affected countries including Belgium, UK, and Spain.

Table 14 EV network disruption

Country	Degree		Weighted degree		Centrality			
	In	Out	In	Out	Closeness	Betweenness	Clustering	Eigen
				A: Absolute change				
DEU	-1	-1	-0.970	-1.405	0.069	-58.7	0.000	0.000
USA	-1	-1	-0.460	-0.122	0.011	-62.7	0.000	-0.009
BEL	-1	-1	-4.193	-0.019	0.026	-70.8	0.000	-0.005
GBR	-1	0	-3.323	0.000	0.063	7.5	0.000	-0.008
KOR	-1	-1	-0.197	-0.006	0.018	-11.8	0.000	-0.011
FRA	-1	0	-0.347	0.000	0.049	2.2	0.000	-0.006
ESP	-1	0	-1.701	0.000	0.051	8.2	0.000	-0.005
NOR	-1	0	-0.544	0.000	0.018	0.1	0.000	-0.001
NLD	-1	0	-0.337	0.000	0.032	-6.3	0.001	-0.001
Average	-0.35	-0.35	-0.110	-0.110	0.004	-2.9	-0.302	-0.001
All network	-82	-82	-21.9	-21.9	-0.1	-625	-53.4	-1.2
				B: Difference in %				
DEU	-4.17	-1.32	-10.51	-5.44	8.16	-4.50	0.06	0.00
USA	-6.67	-3.13	-4.01	-2.07	1.77	-16.83	9.21	-1.47
BEL	-5.00	-1.96	-54.01	-0.28	3.86	-15.98	5.93	-0.59
GBR	-5.88	0.00	-31.41	0.00	10.32	3.62	-0.53	-1.18
KOR	-12.50	-2.44	-8.80	-0.07	2.79	-21.41	8.78	-2.94
FRA	-6.25	0.00	-6.71	0.00	8.56	3.87	4.17	-0.90
ESP	-5.56	0.00	-62.15	0.00	8.86	5.79	3.99	-0.67
NOR	-5.00	0.00	-9.59	0.00	5.00	1.16	9.09	-0.13
NLD	-5.56	0.00	-8.32	0.00	6.25	-7.11	6.06	-0.15
Average	-9.18	-9.18	-21.18	-21.18	2.97	-12.44	-98.35	-0.55
All network	-12.26	-12.26	-23.85	-23.85	-0.52	-15.41	-98.41	-3.92

Note: Table presents changes in 2022 network properties as a result of counterfactual removal of China from the export of electric vehicles for selected countries, on average, and for the whole network. The results are valid for the short run, when the network has not adjusted yet and new links have not been formed. The countries are sorted by their weighted degree measures in 2022.

7. Discussion and Policy Recommendations

The automotive industry stands as one of the most globally integrated sectors, characterized by extensive global supply chains and a corresponding global demand. The ability to procure intermediate inputs on a global scale and access consumers worldwide has been paramount to sustaining the competitiveness of automotive industries on a global scale. However, in the contemporary landscape, the imperative for resilience against disruptions, spanning technological, socioeconomic, and geopolitical dimensions, has introduced a layer of complexity to business decision-making. This necessitates the formulation and implementation of economic policies that provide essential support. This study specifically delves into the case of the UK Automotive sector, scrutinizing the challenges posed by the electrification paradigm.

The UK automotive sector, a pivotal contributor to the national economy, confronts substantial challenges and undergoes a profound transformation amid global shifts towards sustainable transportation, particularly the accelerated growth of the EV industry. The UK's withdrawal from the EU and subsequent implementation of the TCA introduces additional hurdles. Non-tariff measures and rules of origin significantly impact the export of EVs.

Furthermore, the sector faces intensified global competition, manifested in the rising industrial policies in the major economies around the world. This complex and dynamic environment necessitates agile responses from decision-makers and stakeholders to safeguard the sector's prosperity. In this context, our analysis of the resilience of EV global value chains and the critical dependencies encountered by the UK in the context of its economic disintegration from the EU have yielded the following key findings.

UK

- The UK’s EV battery supply chains exhibit a **moderate to high dependence** on global value chains. Critical dependencies are identified in a limited number of products within the battery materials, EV batteries, and EV cars categories.
- The UK exhibited a **diversified import portfolio,** positioned relatively more favourably than its European counterparts and the USA.
- The UK demonstrated a **diversified export portfolio**, comparable to countries with a medium level of export diversification.
- But The UK EV exports, while well-diversified across customers in different EU countries, remains highly exposed to the common EU trade policy shock stemming from reliance on non-originating supply of batteries and potentially highly stringent RoO.
- In sum, the challenge in the UK's EV battery supply chains in the short term is a trade policy concern, and in the medium term, it transforms into a critical dependence problem on battery materials and production.

Global market

- The global landscape in EV production revealed the leading players in the supply chain and their respective strengths. Germany emerged as the top exporter in terms of value, while China surpassed others in terms of the number of cars exported.
- The European Union demonstrates a robust demand for electric vehicles, presenting substantial market opportunities. The world leading adopters of EVs are Norway, Iceland, Sweden, Netherlands, and China.
- Global EV GVCs are expanding towards new countries, but exhibit lower density and negative assortativity, indicating that countries with many connections tend to form links

with countries that have few connections. It leaves a potential opportunity for tightened competition between major players in the future.

- Global EV GVC is highly dependent on China and, as a result, may experience highly disruptive breakdown in case of the withdrawal of China. The UK is exposed to the loss of sources of batteries and imported EVs.

It is useful to note that certain limitations of these stylised facts and empirical findings. The analysis is based on available data up until 2022, and the rapidly evolving nature of the industry may have led to subsequent changes. Additionally, the study focused on specific aspects such as supply chains, trade patterns, and market concentration, leaving room for further exploration of factors such as technological advancements, policy dynamics, and consumer preferences.

These findings underscore the necessity for comprehensive industrial and trade policies and measures to preserve, boost and invest in the future of UK automotive industries. We have four **policy recommendations**:

I. Seizing EV Revolution: Capitalizing on Market Opportunities

Recognizing the challenges confronting the automotive sector, it is imperative to embrace the expansive array of opportunities presented by the EV revolution. The paradigm shift towards EVs not only signifies a pivotal moment for growth and innovation but also aligns with global imperatives for sustainable transportation, positioning the sector as a driving force in the Net Zero transition. A strategic and proactive investment in cutting-edge research and development is essential to position the industry as a trailblazer in EV technologies, enhancing global competitiveness.

Leveraging Proximity to the EU Market

Huge market opportunities also manifest in the close neighbour that has shown steep demand in EVs. Recognizing that the European Union (EU) stands as the predominant market for EV demand, particularly in close proximity to the UK, it is prudent to expedite the development of EV capacity. Given the familiarity of UK car producers with the EU market, expediting capacity building will strategically position the UK to meet and capitalize on the burgeoning demand for EVs in the EU. This approach not only enhances economic outputs and job creation but also aligns with broader environmental objectives.

Winning emerging markets, especially China

Acknowledging China as the future powerhouse of the automotive market, it is imperative to view it not merely as a chokepoint in EV supply chains but as a dynamic arena full of considerable opportunities. China offers prospects beyond sales, including the intermediate inputs supplies from Original Equipment Manufacturers (OEMs), collaborations in research and development, and knowledge creation. Additionally, the increasing outward Foreign Direct Investment (FDI) from China presents a ripe avenue for mutually beneficial opportunities that extend beyond traditional market dynamics.

In short, a comprehensive policy strategy should encompass seizing the opportunities presented by the EV revolution, strategically leveraging proximity to the EU market, and actively pursuing opportunities in emerging markets like China. This multifaceted approach positions the UK's automotive sector as a global player, not just adapting to change but driving innovation and growth in the dynamic landscape of electric mobility.

II. Optimising Trade Policy for Global Success

In the facilitation of optimal conditions, a well-crafted and adaptable trade policy stands as a linchpin for the automotive sector's prosperity. A clear and flexible trade policy is crucial for navigating international markets and addressing challenges posed by evolving geopolitical landscapes. Streamlined negotiations can mitigate barriers like non-tariff measures and rules of origin, boosting the sector's export capabilities for EVs and associated components.

Addressing Immediate Trade Priorities

Given the current lack of industry policy guidance in the UK, swift action on trade policy is essential (Henig, 2023). Urgently, negotiations with the EU to extend the deadline (31 December 2023) for the three-year phase-in period for rules of origin, particularly for batteries and EVs under the Trade and Cooperation Agreement (TCA), is paramount. This adjustment, maintaining a 40% 'regional content value' (instead of 45%), preserves tariff advantages and safeguards UK automotive competitiveness.

Pursuing Long-Term Solutions

Recognizing that postponement is not a sustainable solution, seek opportunities to delay changes to the rules of origin provision in the EU-UK TCA. This strategic move allows for the gradual establishment of self-reliance, ensuring sustained competitiveness for auto manufacturers on both sides.

Fostering Global Collaboration

A forward-thinking trade policy should actively foster international collaborations. This approach ensures the automotive sector remains integrated into global supply chains, leveraging diverse expertise from partner nations. Particularly post-Brexit, strategic trade policy decisions are imperative, offering a pathway to mitigate disruptions and capitalize on emerging opportunities in the dynamic global automotive landscape.

III. Mitigating Rising Material Costs and Boosting Self-Reliance

Recognizing the challenges linked to battery production dependence, the UK must deploy strategic and multifaceted approach to mitigate the effects of rising import costs of materials in the context of a reliance on battery imports. The measures to be considered include ***Diversifying suppliers*** to reduce dependency and establish ***long-term contracts*** with suppliers to provide stability and potentially lock in prices.

Strategic Investment in EV Battery Local Production

The recent support of UK government to Toyota and Nissan carmakers shows positive movements. Further targeted investment into domestic EV battery production facilities is key not only to improve self-reliance through domestic supply of advanced and sustainable batteries including battery recycling but could also catalyse private investment into the industry.

Integrate circular economy principles into battery supply chains

Use regenerative principles should not be a preference but a necessity to enhance sustainability, resource efficiency, and overall resilience of battery supply chains.

Strategic investments in cutting-edge battery production not only fortify industry self-sufficiency but also contribute to environmental sustainability by reducing reliance on external sources. Cultivating a robust domestic battery manufacturing ecosystem ensures a stable and resilient supply chain, thereby mitigating risks associated with geopolitical uncertainties and fluctuations in raw material prices.

Integrated Charging Infrastructure

The UK has made substantial efforts to expand its electric vehicle charging infrastructure. Initiatives include government funding and partnerships with private companies to increase the number of charging points across the country. In this rapid development, it is key to invest in integrated charging infrastructure alongside battery production. The development of a comprehensive charging network is vital for supporting the surge in EV adoption. A symbiotic approach ensures that the UK not only produces cutting-edge batteries but also fosters an environment conducive to seamless EV utilisation, addressing challenges related to charging accessibility.

IV. Pioneering a Future-Fit UK Industrial Strategy

Recognizing its role as a catalyst within facilitating conditions, an overdue industry policy emerges as a crucial driver for resilience and innovation in the automotive sector. A meticulously crafted industry policy becomes the guiding framework, directing the industry towards sustainable growth and enhanced competitiveness.

Strategic Alignment for Incentivizing Innovation

Governments, by strategically aligning policies with the sector's goals, can incentivize research and development initiatives, ensuring a continuous influx of cutting-edge technologies. Notably, estimates from the Advanced Propulsion Centre (APC) underscore a £24 billion opportunity within the EV supply chain, underscoring the potential impact of a well-defined industrial strategy (SMMT, 2023b).

Forward-Looking Vision and Agile Adaptation

Beyond addressing immediate needs like battery production for current EV demand, a forward-looking industrial strategy anticipates and adapts to rapidly evolving technologies and market conditions. It is imperative to sustain support for industries prioritizing and investing in research and development (R&D) within the automotive sector. Additionally, fostering collaborative efforts across industries and technological domains is vital, ensuring the UK remains a global leader in automotive technologies.

Strategic Alignment for foreign investment

Unlocking the transformative potential of the UK's EV sector hinges on a strategic embrace of foreign investment. Not only foreign investment is an indispensable financial catalyst, meeting the substantial requirements for the EV industry's development, it can accelerate the sector's technological advancements by infusing capital, expertise, and cutting-edge innovations from global markets.

Adding the benefit of global market access, inward investment opens avenues for UK-produced EVs to integrate into global supply chains and markets. This further can help risk mitigation and investment diversification, reducing vulnerability to domestic economic fluctuations, enhancing the sector's resilience and long-term viability. The recent Lord Harrington's Review emphasizes the importance of ensuring the UK's attractiveness as an investment destination in Europe within a globally competitive environment. Despite the chilling effect of the EU exit on inward investment since the 2016 Referendum, [10] automotive industries remain key growth sectors for attracting investment. Positive developments, such as

[10] Also see mainstream news agencies reports, *e.g.* https://www.ft.com/content/bdc9f940-bb92-11e9-b350-db00d509634e.

recent additional investment decisions by carmakers like Nissan and BMW in UK EV production, underscore the potential of the sector.

To chart a visionary course for the UK's EV sector and attract investors to contribute to this trajectory, the industrial policy should set out agile and bespoke regulatory processes tailored for the dynamic EV sector. Introducing targeted incentives and initiatives exclusively crafted for the industry, along with articulating clear and transparent investment protocols, solidifies the UK's reputation as a secure and attractive long-term investment destination. A substantial investment in tailored skills development programs for the EV manufacturing and technology sectors becomes pivotal. By actively promoting the UK as a leading global hub for foreign investment in the EV sector, the economy can leverage its openness, adaptability, and innovation prowess, ensuring sustained growth and competitiveness.

Finally, it is important to institute robust mechanisms for the continuous monitoring and evaluation of the United Kingdom's position in the Global Value Chains (GVCs) within the EV industry. This entails a systematic assessment of critical dependencies, vulnerabilities, and the adaptation of policies in response to the ever-evolving global dynamics, geopolitical shifts, and supply chain disruptions. By establishing these proactive monitoring frameworks, the UK can enhance its resilience, maintain a competitive edge, and strategically navigate the complexities of the global EV landscape. This iterative evaluation process ensures that policies remain agile and responsive to emerging challenges, safeguarding the stability and sustained growth of the UK's position within the global EV value chains.

8. Conclusion

In summary, this paper has meticulously examined the economic policy and global value chain of the UK electric vehicle (EV) industry, specifically delving into the intricate interplay between supply chains, industrial policy, and critical dependencies. The discussion on the UK automotive sector within the electrification paradigm has brought to light multifaceted challenges and transformative shifts. As a cornerstone of the national economy, the industry grapples with disruptions arising from technological advancements, socioeconomic shifts, and geopolitical complexities, necessitating the formulation of responsive economic policies.

The UK's withdrawal from the EU, as delineated in the Trade and Cooperation Agreement (TCA), magnifies challenges, especially in navigating non-tariff measures and rules of origin that impact EV exports. A landscape of global competition, characterized by escalating industrial policies worldwide, underscores the imperative for agile responses.

Insights gleaned from the analysis of EV global value chains (GVCs) and UK dependencies underscore the EU's standing as a robust EV market, with Germany leading in EV exports by value and China excelling in volume. The UK's diversified export portfolio and moderate dependence on global value chains position it favourably. Short-term concerns in EV battery supply chains are ascribed to trade policy issues, evolving into medium-term dependencies on battery materials and production.

The recommendations outlined in this study strategically target opportunities in the EV revolution, advocate for the optimization of trade policy, call for strategic investments in EV battery production, emphasize the need for a future-fit industrial strategy, and stress the importance of continuous monitoring of global value chains. Implementing these recommendations can solidify the UK's position as a global leader in electric mobility, ensuring sustained growth, competitiveness, and innovation.

As avenues for future research, exploring the implications of emerging technologies on the EV industry and conducting a more in-depth analysis of the policy landscape, including the impact of regulatory frameworks, incentives, and innovation policies, could provide invaluable insights into the necessary industrial strategies that can propel the UK into a leadership role in the evolving global EV market.

References

Anderson, J.E. and Van Wincoop, E., 2004. Trade costs. *Journal of Economic literature, 42*(3), pp.691-751.

Antràs, P. and Chor, D., 2022. Global value chains. *Handbook of International Economics*, *5*, pp.297-376.

Antràs, P. and De Gortari, A., 2020. On the geography of global value chains. *Econometrica*, *88*(4), pp.1553-1598.

Arjona, R, W Connell and C Herghelegiu 2023. An enhanced methodology to monitor the EU's strategic dependencies and vulnerabilities, *Single Market Economy Papers WP2023/14*, Publications Office of the European Union.

Baldwin, R.E., 2017. Multilateralising regionalism: spaghetti bowls as building blocs on the path to global free trade. In *Global Trade* (pp. 469-536). Routledge.

Ballester, C., Calvo-Armengol, A. and Zenou, Y. (2006). Who ís who in networks. Wanted: the key player, *Econometrica* 74: 1403-1417.

Blondel, V.D., Guillaume, J., Lambiotte, R., Lefebvre, E., Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment* 2008 (10), P1000

Bown, C.P., 2023. Industrial policy for electric vehicle supply chains and the US-EU fight over the Inflation Reduction Act. *Peterson Institute for International Economics Working Paper*, (23-1).

Brandes, U., 2001. A Faster Algorithm for Betweenness Centrality. *Journal of Mathematical Sociology* 25(2):163-177, (2001)

Copeland, B.R., Shapiro, J.S. and Taylor, M.S., 2021. Globalization and the environment. *NBER Working Paper No. 28797.*

Cornet Andreas, Heuss Ruth, Schaufuss Patrick and Tschiesner Andreas, 2023, A Road Map for the Automotive Industry in Europe, McKinsey and Company.

Djankov, S., Freund, C. and Pham, C.S., 2010. Trading on time. *The Review of Economics and Statistics*, *92*(1), pp.166-173.

Eggert, R., Wadia, C., Anderson, C., Bauer, D., Fields, F., Meinert, L. and Taylor, P., 2016. Rare earths: market disruption, innovation, and global supply chains. *Annual Review of Environment and Resources*, 41, pp.199-222.

Goldberg, P.K. and Pavcnik, N., 2016. The effects of trade policy. In *Handbook of Commercial Policy* (Vol. 1, pp. 161-206). North-Holland.

Greif, A., 1993. Contract enforceability and economic institutions in early trade: The Maghribi traders' coalition. *The American Economic Review*, pp.525-548.

Hagedoorn, J., 2002. Inter-firm R&D partnerships: an overview of major trends and patterns since 1960. Research policy, 31(4), pp.477-492.

Harrison, D. and Ludwig, C., 2021. Electric Vehicle Battery Supply Chain Analysis—How Battery Demand and Production Are Reshaping the Automotive Industry. *Automotive from Ultima Media*.

Henig, David, 2023, Perspectives: How precedent and politics are stalling the UK trade policy agenda, Borderlex, 15/11/2023

IEA (2023). Global supply chains of EV batteries. *IEA Publications.* International Energy Agency.

Jones, B., Nguyen-Tien, V., & R. Elliott, R. J. (2023). The electric vehicle revolution: Critical material supply chains, trade and development. *The World Economy*, *46*(1), 2-26.

Kee, L. H., Nicita, A. and Olarreaga, M., 2009. Estimating trade restrictiveness indices. *The Economic Journal*, *119*(534), pp.172-199.

Korniyenko, M.Y., Pinat, M. and Dew, B., 2017. Assessing the fragility of global trade: The impact of localized supply shocks using network analysis. International Monetary Fund.

Levchenko, A.A., 2007. Institutional quality and international trade. *The Review of Economic Studies*, *74*(3), pp.791-819.

Maldonado Guzmám, G. and Pinzón Castro, S.Y., 2023. Collaboration, eco-innovation and economic performance in the automotive industry. International Journal of Industrial Engineering and Operations Management.

Mayer, T. and Zignago, S., 2011. Notes on CEPII's distances measures: The GeoDist database.

Olivetti, E.A., Ceder, G., Gaustad, G.G. and Fu, X., 2017. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule*, *1*(2), pp.229-243.

Rose‐Anderssen, C., Baldwin, J.S., Ridgway, K., Allen, P.M. and Varga, L., 2008. Aerospace supply chains as evolutionary networks of activities: innovation via risk‐sharing partnerships. Creativity and innovation management, 17(4), pp.304-318.

Shapiro, J.S., 2021. The environmental bias of trade policy. *The Quarterly Journal of Economics*, *136*(2), pp.831-886.

SMMT, 2023a, SMMT Motor Industry Facts 2023, The Society of Motor Manufacturers and Traders (SMMT)

SMMT, 2023b, Race to Zero: Powering Up Britain's EV Supply Chains, The Society of Motor Manufacturers and Traders (SMMT)

Tisserant, A. and Pauliuk, S., 2016. Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, *5*, pp.1-19.

van den Broek, T. and van Veenstra, A.F., 2018. Governance of big data collaborations: How to balance regulatory compliance and disruptive innovation. Technological Forecasting and Social Change, 129, pp.330-338.

World Bank, 2020. Trading for development in the age of global value chains. *World Development Report 2020*.

Appendix

Appendix A Measures of centrality

1. Closeness Centrality:
Closeness centrality measures how close a node is to all other nodes in a network. It is defined as the inverse of the sum of the shortest path distances from a node to all other nodes in the network. Nodes with higher closeness centrality are closer to all other nodes and can reach them more efficiently.

The formula for closeness centrality of a node "i" in a network with "N" nodes is given by:

$$C(i) = \frac{N-1}{\sum_j d(i,j)}$$

where $d(i,j)$ represents the shortest path distance between nodes i and j.

Reference: Freeman, L. C. (1979). Centrality in social networks: Conceptual clarification. Social Networks, 1(3), 215-239.

2. Betweenness Centrality:

Betweenness centrality identifies nodes that act as bridges or intermediaries in a network. It quantifies the extent to which a node lies on the shortest paths between pairs of other nodes. Nodes with higher betweenness centrality have more control over the flow of information or resources within a network.

The formula for betweenness centrality of a node i in a network is given by:

$$C_B(i) = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}}$$

where σ_{st} represents the total number of shortest paths between nodes s and t, and $\sigma_{st}(i)$ represents the number of those paths that pass-through node i.

Reference: Freeman, L. C. (1977). A set of measures of centrality based on betweenness. Sociometry, 40(1), 35-41.

3. Clustering Coefficient:
The clustering coefficient measures the extent to which the neighbors of a node are connected to each other. It quantifies the level of local clustering or the presence of tightly interconnected groups or communities within a network.

The formula for clustering coefficient of a node i in a network is given by:

$$C_c(i) = \frac{2E_i}{k_i(k_i - 1)}$$

where E_i represents the number of edges among the neighbors of node i, and k_i represents the degree (number of neighbors) of node i.

Reference: Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. Nature, 393(6684), 440-442.

4. Eigenvalue Centrality:

Eigenvalue centrality determines the importance of a node based on the concept of eigenvector centrality. It assigns higher centrality scores to nodes that are connected to other highly central nodes. It assumes that nodes with high centrality scores can influence the network more strongly.

The formula for eigenvalue centrality of a node i in a network is given by solving the eigenvector equation:

$$Ax = \lambda x$$

where A is the adjacency matrix of the network, x represents the eigenvector associated with the largest eigenvalue λ, and the centrality score of node i is given by x_i.

Reference: Bonacich, P. (1987). Power and centrality: A family of measures. American Journal of Sociology, 92(5), 1170-1182.

Appendix B Types of goods

Table A1 Supply chain of automotive industry

HS code	Type	Sub-type	Description	Source
250410	Materials		Natural Graphite	
253090	Materials		Unprocessed Lithium Mineral	LaRocca (2020)
260400	Materials		Nickel Ores and Concentrates	
260500	Materials		Cobalt Ores and Concentrates	
280519	Materials		Lithium Chloride	LaRocca (2020)
282010	Materials		Manganese Dioxide	
282200	Materials		Cobalt Oxides and Hydroxides	
282520	Materials		Lithium Oxide and Hydroxide	LaRocca (2020)
282540	Materials		Other Inorganic Compounds	
282690	Materials		Lithium Fluoride	LaRocca (2020)
282739	Materials		Lithium Chloride	LaRocca (2020)
283529	Materials		Phosphates	
283691	Materials		Lithium Carbonate	LaRocca (2020)
284190	Materials		Salts of oxometallic or peroxometallic acids	
284530	Materials		Lithium enriched in lithium-6 and its compounds	
850720	Batteries		Lead-acid batteries	
850730	Batteries		Nickel-cadmium batteries	
850760	Batteries		Lithium-ion batteries	
850790	Batteries		Primary battery cells	
854511	Batteries		Graphite Electrodes	
854519	Batteries		Other Electrodes	
870321	Cars	ICE	Petrol Car, less than 1000 cm3	
870322	Cars	ICE	Petrol Car, 1000 to 1500 cm3	
870323	Cars	ICE	Petrol Car, 1500 to 3000 cm3	
870324	Cars	ICE	Petrol Car, more than 3000 cm3	
870331	Cars	ICE	Diesel Car, less than 1500 cm3	
870332	Cars	ICE	Diesel Car, 1500 to 2500 cm3	
870333	Cars	ICE	Diesel Car, more than 2500 cm3	

870340	Cars	HEV	Petrol HEV
870350	Cars	HEV	Diesel HEV
870360	Cars	PHEV	Petrol PHEV
870370	Cars	PHEV	Diesel PHEV
870380	Cars	EV	EV
870810	Car parts		Bumpers
870830	Car parts		Brakes
870840	Car parts		Gear Boxes
870850	Car parts		Drive-axles
870870	Car parts		Road wheels
870880	Car parts		Suspension systems
870891	Car parts		Radiators
870892	Car parts		Silencers
870893	Car parts		Clutches
870894	Car parts		Steering wheels
870895	Car parts		Safety airbags
870899	Car parts		Other parts

Appendix C TCA Rules of origin

A2 Rules of origin

HS Code	Type	Provisonal RoO, Annex 5, sec 1 Until Dec 31, 2023	Provisional RoO, Annex 5 sec 2 Until Dec 31, 2026	RoO, Annex 2
25.01-25.30	Materials			CTH; or MaxNOM 70 % (EXW).
26.01-26.21	Materials			CTH
28.01-28.53	Materials			CTSH; A chemical reaction, purification, mixing and blending, production of standard materials, a change in particle size, isomer separation, or biotechnological processing is undergone; or MaxNOM 50 % (EXW)
85.07	Battery packs and battery cells	CTSH; Assembly of battery packs from non-originating battery cells or battery modules; or MaxNOM 70 % (EXW)	CTH except from non-originating active cathode materials; or MaxNOM 50 % (EXW)	CTH except from non-originating active cathode materials; or MaxNOM 35 % (EXW)
85.07	Accumulators containing battery cells	CTSH; Assembly of battery packs from non-originating battery cells or battery modules; or MaxNOM 70 % (EXW)	CTH except from non-originating active cathode materials; or MaxNOM 40 % (EXW)	CTH except from non-originating active cathode materials; or MaxNOM 30 % (EXW)

87.03	EV	MaxNOM 60 % (EXW)	MaxNOM 55 % (EXW)	MaxNOM 45 % (EXW) and battery packs of heading 85.07 of a kind used as the primary source of electrical power for propulsion of the vehicle must be originating

Notes:

1. "CTH" means production from non-originating materials of any heading, except that of the product; this means that any non-originating material used in the production of the product must be classified under a heading (4-digit level of the Harmonised System) other than that of the product (i.e. a change in heading);
2. "CTSH" means production from non-originating materials of any subheading, except that of the product; this means that any non-originating material used in the production of the product must be classified under a subheading (6-digit level of the Harmonised System) other than that of the product (i.e. a change in subheading).
3. "EXW" or "ex-works price" means: (i) the price of the product paid or payable to the producer in whose undertaking the last working or processing is carried out, provided that the price includes the value of all the materials used and all other costs incurred in the production of the product, minus any internal taxes which are, or may be, repaid when the product obtained is exported; or (ii) if there is no price paid or payable or if the actual price paid does not reflect all costs related to the production of the product which are actually incurred in the production of the product, the value of all the materials used and all other costs incurred in the production of the product in the exporting Party:
   (A) including selling, general and administrative expenses, as well as profit, that can reasonably be allocated to the product;
   (B) excluding the cost of freight, insurance, all other costs incurred in transporting the product and any internal taxes of the exporting Party which are, or may be, repaid when the product obtained is exported;

   iii) for the purposes of point (i), where the last production has been contracted to a producer, the term "producer" in point (i) refers to the person who has employed the subcontractor.

4. "MaxNOM" means the maximum value of non-originating materials expressed as a percentage and shall be calculated according to the following formula: VNM MaxNOM (%) = × 100 EXW (d) "VNM" means the value of the non-originating materials used in the production of the product which is its customs value at the time of importation including freight, insurance if appropriate, packing and all other costs incurred in transporting the materials to the importation port in the Party where the producer of the product is located; where the value of the non-originating materials is not known and cannot be ascertained, the first ascertainable price paid for the non-originating materials in the Union or in the United Kingdom is used; the value of the non-originating materials used in the production of the product may be calculated on the basis of the weighted average value formula or other inventory valuation method under accounting principles which are generally accepted in the Party.
5. Originating products

The Trade and Cooperation Agreement contains provisions allowing the UK and the EU to cumulate origin. This means materials originating from the:

EU (as well as production carried out within the EU on non-originating materials) may be considered as originating in the UK

UK (as well as production carried out within the UK on non-originating materials) may be considered as originating in the EU

This process is known as bilateral cumulation.

Once a product has gained originating status, it is considered 100% originating. This means that if that product is incorporated in the production of a further product:

its full value is considered originating

no account is taken of the materials from a different country that have been used

For example, if a UK-manufactured engine contains 30% of materials from a different country but meets its rule of origin, if that engine is used in the production of a car in the UK or EU, 100% of the value of that engine can be counted towards the originating content of the car.

There are 2 ways a product can be considered originating.

6. Wholly obtained

These are goods that have been exclusively obtained or produced in the territory of one country, without using materials from any other country. The goods must not have been manipulated or changed in another country, apart from certain minimal processes to keep them in good condition, examples of wholly obtained goods include:

minerals extracted from the soil of a single country

live animals born and raised in a single country

goods produced in a single country from materials sourced exclusively from there — that is, all materials used in a product are wholly obtained

7. Substantially worked or processed

These are goods that have been substantially worked or processed in line with the relevant product-specific rule. There are 3 basic rules used to decide if goods are sufficiently transformed worked or processed:

the ad-valorem, or 'value added' rule

the change of commodity code used to classify your goods

manufacture from certain products or through specific processes

Annex 3 of the Trade and Cooperation Agreement sets out the rule that applies for the product you're importing.

8. Claiming preferential treatment under the Trade and Cooperation Agreement

To benefit from preferential tariffs (a reduced rate of Customs Duty) when importing into the UK or EU, you will need to:

claim preference on your customs declaration

declare you hold proof that the goods meet the rules of origin

A proof of origin is used by the importer to show that the goods qualify as originating and are eligible to claim preference. In the Trade and Cooperation Agreement this proof can be either:

a statement on origin completed by the exporter on an invoice, or any other document including a commercial document

knowledge obtained and held by the importer that the goods are originating

Read more about the different proof of origins for the Trade and Cooperation Agreement.

Appendix D Additional tables and results

Table A3 Length of EV GVC for top 10 EV exporters in 2022

HS6	Exporter										
	BEL	**CHN**	**CZE**	**DEU**	**ESP**	**FRA**	**GBR**	**JPN**	**KOR**	**SVK**	**USA**
250410		4.7		0.7				8.9	8.0		10.7
253090	0.5	6.4		0.8	6.1	0.8		9.6			10.6
260400				0.9							2.1
260500				0.4							
280519		5.9		3.0		0.8					7.7
282010		4.9	0.8		1.4			6.6			
282200	5.8	3.8					6.5				
282520	4.7	1.5				0.8	7.5	1.0			9.6
282540	7.8	1.8						3.7			7.3
282690	7.3	5.8		9.1				7.4	3.2		8.9
282739	0.9	5.1		2.2	1.0	1.6	3.9		4.7		8.4
283529		7.1		1.9		4.4	1.1		1.2		
283691	1.6	1.8		1.0		6.5	4.6	2.4	1.2		9.7
284190	3.7	5.9		4.6			9.4	8.8	6.7		4.9
850720	0.4	7.8	0.8	2.4	1.4	2.5	3.3	1.9	10.0	2.3	5.5
850730		8.2	1.0	5.9		6.0		10.3			7.8
850760	6.9	7.1	0.6	3.9	1.4	2.8	3.5	9.0	8.0	0.5	7.2
850790		6.7	0.6	5.4	1.6	5.0	1.1	6.8	9.7	1.7	5.0
854511	0.4	6.9		2.2	3.5	3.7		6.9			3.0
854519		6.7		6.6		6.5	7.8	11.4	10.7		11.4
870321	0.7	9.8	0.9	1.1	2.2	0.8	2.4	9.9	9.6	1.1	5.0
870322	0.9	9.7	1.4	2.2	1.8	1.5	4.0	9.6	10.2	1.3	5.3
870323	2.8	8.4	3.0	6.4	4.3	2.5	7.0	8.8	10.0	3.3	8.0
870324	0.9	4.1	0.6	5.1	1.7	2.8	6.4	8.8	10.5	3.5	6.3
870331	0.9	11.4	0.4	1.2	2.1	1.7	4.8	8.5	12.5	2.3	7.3
870332	0.8	8.0	0.9	1.6	2.1	1.2	3.7	9.1	9.1	1.4	8.9
870333	0.9	4.6	0.7	2.5	4.4	1.4	8.2	8.6	8.8	3.4	8.5
870340	1.3	7.4	0.9	6.0	1.4	0.8	4.3	7.4	9.9	4.9	6.7
870350	0.7	8.0	1.2	1.6	1.0		3.2			3.3	7.7
870360	1.1	8.9	0.9	2.7	1.7	1.5	3.0	9.2	9.3	3.3	7.6
870370	0.2			0.9		0.7	4.7	4.5	10.7	0.7	7.6
870380	2.2	7.9	0.9	3.3	1.6	1.1	2.5	9.0	9.3	1.2	4.9

Note: Distance is measured as the weighted average distance between reporter and partner weighted by export value. We use mirror data to fill the missing exports, using the mirror import values as reported by trading partners. Share of export in percent is given for the whole period as the percentage of the total export generated by EV and passenger car GVC.

Source: COMTRADE data and author's calculations.

Table A4 Assortativity

HS6	Type	Description	Assortativity	
			Degree	**Weighted degree**
250410	Materials	Natural Graphite	-0.092	-0.120

253090	Materials	Unprocessed Lithium Mineral	-0.358	-0.012
260400	Materials	Nickel Ores and Concentrates	-0.338	0.003
260500	Materials	Cobalt Ores and Concentrates	.	0.730
280519	Materials	Lithium Metal	-0.471	-0.254
282010	Materials	Manganese Dioxide	-0.355	-0.419
282200	Materials	Cobalt Oxides and Hydroxides	-0.054	-0.072
282520	Materials	Lithium Oxide and Hydroxide	-0.238	0.042
282540	Materials	Other Inorganic Compounds	-0.457	-0.020
282690	Materials	Lithium Fluoride	-0.522	-0.483
282739	Materials	Lithium Chloride	-0.338	-0.194
283529	Materials	Phosphates	0.144	0.211
283691	Materials	Lithium Carbonate	-0.389	-0.094
284190	Materials	Salts of oxometallic acids	-0.369	0.155
850720	Batteries	Lead-acid batteries	-0.470	-0.336
850730	Batteries	Nickel-cadmium batteries	-0.245	-0.243
850760	Batteries	Lithium-ion batteries	-0.496	-0.222
850790	Batteries	Primary battery cells	-0.419	-0.145
854511	Batteries	Graphite Electrodes	-0.347	-0.294
854519	Batteries	Other Electrodes	-0.434	-0.084
870321	ICE	Petrol Car, less than 1000 cm3	-0.150	-0.105
870322	ICE	Petrol Car, 1000 to 1500 cm3	-0.289	-0.101
870323	ICE	Petrol Car, 1500 to 3000 cm3	-0.260	-0.061
870324	ICE	Petrol Car, more than 3000 cm3	-0.397	-0.126
870331	ICE	Diesel Car, less than 1500 cm3	-0.239	-0.230
870332	ICE	Diesel Car, 1500 to 2500 cm3	-0.176	-0.144
870333	ICE	Diesel Car, more than 2500 cm3	-0.306	-0.207
870340	HEV	Petrol HEV	-0.328	-0.123
870350	HEV	Diesel HEV	-0.385	-0.204
870360	PHEV	Petrol PHEV	-0.362	-0.195
870370	PHEV	Diesel PHEV	-0.414	-0.332
870380	EV	EV	-0.420	-0.208

Assortativity is a property of networks that describes the tendency of nodes with similar characteristics to be connected to each other. In other words, it measures the correlation between the degrees of neighbouring nodes in a network. The degree of a node in a network is the number of connections it has.