THESIS

INTERNATIONAL TRADE OF ELECTRIC VEHICLE BATTERIES AND LITHIUM: A NETWORK APPROACH TO TRADE STRUCTURE AND STRUCTURAL INEQUALITY

Submitted by

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ABSTRACT

INTERNATIONAL TRADE OF ELECTRIC VEHICLE BATTERIES AND LITHIUM: A NETWORK APPROACH TO TRADE STRUCTURE AND STRUCTURAL INEQUALITY

As international efforts toward clean energy transition and climate mitigation have been made, the international trade of emission-reducing technologies and their necessary materials has grown. Few technologies have seen as much growth as electric vehicles and their lithium-ion batteries; and few materials have seen as much growth as lithium. Research on international battery and lithium trade is extensive but has yet to examine the *formation* of the trade *structure* and its *structural inequality*. This study uses bilateral trade data from the UN COMTRADE database and country attribute data from the World Bank database to (1) measure the overall structure of and structural inequality in international electric vehicle battery and lithium trade *networks*; and (2) analyze determinants of the trade networks' formation. Results indicate that the international trade of electric vehicle batteries and of lithium are characterized by a core-periphery pattern—by which certain countries occupy the center of trade, and by which certain countries occupy the margins—and therefore, that there is an inequality in the distribution of trade relationships among countries participating in battery and lithium trade. The results also indicate that differences in countries' GDP and country's structural position in the networks largely determine the likelihood of trade-relationship formation. Inferentially, the results provide some evidence for (ecologically) unequal exchange in the trade of commodities that ostensibly support clean energy transition and sustainable economic development, like electric vehicle batteries and lithium.

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DEDICATION

To my parents,

For their love and unceasing support.

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CHAPTER 1: INTRODUCTION

The 2015 Paris Agreement marks the first time a legally binding treaty was adopted by 196 nations to avert climate change with the primary goal to hold global average temperature increases to 2°C (35.6°F) above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (34.7°F) above pre-industrial levels (UNFCCC 2015:3). To do so, the emission of heat-trapping greenhouse gases (GHGs) must be reduced. Approximately 75 percent of global GHG emissions come from the burning of fossil fuels (e.g., coal, gas, and oil) for energy (EIA 2022; UNDP 2023).

As such, (inter)national efforts to reduce GHG emissions and, thereby, to fulfill international agreements, often center on *clean energy transition*. Here, "clean energy transition" refers to *the (inter)national restructuration of energy supplies, storage, distribution, and consumption* (Smil 2017) *in accordance with international agreements and sustainable development goals* (SDGs) (IEA 2021; UN 2022). Requisites for this transition include emission-reducing technologies (e.g., photovoltaic solar power generation, carbon sequestration, etc.) and the "energy transition metals" and minerals (ETMs) (Boer, Pescatori, and Stuermer 2021) (e.g., cobalt, copper, graphite, nickel) necessary for the production and function of those technologies. Of these technologies, few have seen as much growth as electric vehicles (EVs) and the lithium-ion batteries on which EVs run (EV-LIBs); of these ETMs, few have seen as much growth as lithium.

In other words, as countries have made (inter)national efforts toward clean energy transition, the international EV-LIB and lithium trade has grown. Research on the international trade EV-LIB and lithium trade is extensive but has yet to examine the *formation* of the trade's *structure* and *structural inequality*.

This study intervenes by taking a network approach to examine the formation of international EV-LIB and lithium trade networks—their structure and their structural inequality. A network approach sees the study of international trade structure as the study of *networks* or of the "*relationships among entities that make up* [a] *system* [emphasis added]" (Borgatti et al. 2022:2). As such, an "international trade network" is conceptualized as the trade relationships among countries that make up an international trade system; "trade structure" is conceptualized as the overall pattern of trade relationships that determines the position of countries in the international trade system (Burt 1980); and "structural inequality" is conceptualized as the extent to which all trade relationships in the system involve a single country (Burt 1980). I argue that trade structure, structural inequality, and their formation are important because they facilitate and constrain countries' acquisition of EV-LIBs and lithium and, thereby, countries' pursuit of climate action and (sustainable) economic development in accordance with international agreements and national policy. Furthermore, I argue that trade structure, structural inequality, and their formation are important because—as research and theory on ecologically unequal exchange argues—asymmetrical trade relationships between differently positioned countries, such as "core" and "peripheral" countries, shape the distribution of economic and environmental benefits and detriments of EV-LIBs and lithium.

The research gap and the network approach prompt two research questions:

Research Question 1. What do the structures of and the structural inequality in international EV-LIB and lithium trade networks look like?

Research Question 2. What determines the formation of international EV-LIB and lithium trade network structures and structural inequality?

To address the first question, I use bilateral trade data on EV-LIBs from 2012 to 2020 and lithium from 2000 to 2020 (UN COMTRADE 2022). I then construct two directed networks of international EV-LIB trade (a 2012-2014 trade network; a 2015-2020 trade network) and four directed networks of international lithium trade (a 2000-2004 trade network; a 2005-2009 trade network; a 2010-2014 trade network; and a 2015-2020 trade network). I describe the networks' structure and structural inequality in two ways. First, I graph the networks. Second, I measure the extent to which all trade relationships in the networks involve a single country using the following measurements: betweenness centralization; closeness centralization; outdegree centralization; indegree centralization; eigenvector centralization; and core-periphery correlation. These steps constitute Stage 1 of the analysis.

To address the second question, I estimate exponential random graph models (ERGMs) using the bilateral trade data; attribute data on countries' regional classification, income classification, and GDP from the World Bank; and attribute data on countries' structural (core and peripheral) position in the networks. ERGMs are probability models for social networks that estimate the highest possible likelihood that a given set of parameters generates an observed network structure. I show the likelihood of trade-relationship formation between countries within the same region, within the same income group, with different GDPs, and with the same structural position in the networks. These steps constitute Stage 2 of the analysis.

The results of Stage 1 indicate that the international trade in EV-LIBs and international trade in lithium are characterized by a core-periphery pattern—by which certain countries occupy the center of EV battery and lithium compound trade, and by which certain countries occupy the margins—and, therefore, structural inequality among countries participating in EV battery and lithium trade. The results of Stage 2 indicate that differences in countries' GDP and countries' structural position in the networks largely determine the likelihood of trade-relationship formation. The results inferentially suggest that the international trade of commodities that ostensibly support "clean" and "green" transition, like EV-LIBs and lithium, may be characterized as an ecologically unequal exchange.

The rest of this chapter is organized into three sections. The first section provides background information about the relationship between clean energy transition and the increase in demand for lithium. The second section provides background information on the EV-LIB supply chain, from raw material extraction to recycling and reuse. The concluding section provides an overview of subsequent chapters.

CLEAN ENERGY TRANSITION & DEMAND FOR LITHIUM

Clean energy transition and related SDGs specifically aim to *decrease* the total energy intensity of the international economy;[1] the carbon intensity of power generation;[2] and the carbon intensity of final energy consumption[3] (IEA 2019; UN n.d.). Additionally, clean energy transition and related SDGs specifically aim to *increase* investment in the research and development of clean energy; the share of renewable electricity in final energy consumption; and the proportion of the global population with access to renewable electricity and clean fuels (IEA 2019; UN n.d.). Key sectors to which clean energy transition and related SDGs apply include

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[1] A measure of the total primary energy demand per unit of GDP, or "how much energy is required to produce an area's economic output in a given country or region" (IEA 2019).

[2] A measure of the total energy-related carbon emissions in tCO_2 per unit of total electricity generation (IEA 2019).

[3] A measure of the total energy-related carbon emissions in tCO_2 per unit of total final energy consumption (IEA 2019).

power generation, industrial production, buildings (specifically heating and cooling systems), and transportation; that is, energy-intensive sectors that significantly contribute to global GHG emissions (IEA 2021). According to the International Energy Agency (IEA),[4] transportation—which accounts for 16 percent of global GHG emissions (2022a)—has seen some of the most transition progress, particularly in the development of electric vehicles (EVs), and the growth of EV markets.[5] EVs can contribute to the reduction of the carbon intensity of final energy consumption because, unlike internal combustion engine vehicles, EVs run on battery engines and, therefore, do not require fossil fuels and do not produce tailpipe emissions.[6]

Stakeholders recognize the potential of EVs to reduce emissions and contribute to sustainable economic development. Stakeholders use pledges, financial investment, and (inter)national policy as instruments to support the development and distribution of EVs. For example, over 100 "representatives of governments, businesses, and organizations with an influence over the future of the automotive industry and road transport" signed a declaration to work toward "all sales of new cars and vans being zero emission globally by 2040" during the twenty-sixth Conference of Parties (UK Gov 2022). The European Union is working toward a ban on new CO_2-emitting vehicle sales which would take effect after 2035 (European Parliament 2022). And in the US, the Clean Energy for America Act, introduced in 2021, would provide tax

[4] The IEA is an intergovernmental organization based in Paris that provides research on and policy recommendations for the global energy sector.

[5] An indication of this progress: of the 55 fuels and emission-reducing technologies that the International Energy Agency (IEA) tracks, electric vehicles (EVs) are one of two—the other being lights and lighting—"on track" with the IEA's Net Zero Emissions by 2050 Scenario (IEA 2022a). The IEA considers infrastructure, policy, investment, and market trends when determining whether a technology is "on track." The other 53 fuels and technologies are classified "more efforts needed" and "not on track". The IEA's Net Zero Emissions by 2050 Scenario is a scenario that tracks energy transition progress by "[showing] what is needed across the main sectors by various actors, and by when, for the world to achieve net-zero energy-related and industrial process CO2 emissions by 2050" (2021:48).

[6] That said, the generation of electricity for EV-charging would still produce GHG emissions if done with fossil fuels like coal. Even though accounting for electricity used for charging shows that EVs have a smaller carbon footprint than internal combustion engine vehicles (EPA 2023), decarbonized, renewable power generation systems such as photovoltaic solar and wind can reduce emissions from electricity generation for EV-charging.

credits for investment in clean electricity generation, clean transportation, clean fuel production, and energy efficiency if signed into law (U.S. Congress 2021); and the 2022 Inflation Reduction Act includes the investment of 369 billion dollars in Energy Security and Climate Change programs and provides tax credits for electric vehicle purchases (US Senate 2022).

Such energy transition efforts have driven EV market growth. EVs accounted for 5 percent of new car sales in 2020, 9 percent in 2021, and 14 percent in 2022, and are on track to account for 18 percent in 2023 (IEA 2023). If the EV share of new car sales can maintain up to 6 percent growth per year from 2022, we could see 300 million new EVs on the road, accounting for *60 percent* of new car sales, in 2030 (IEA 2022a).

EV-LIB demand has grown at a similar rate to EV demand (IEA 2022b; IEA 2023). At present, most EVs rely on LIBs for their engines. LIBs are preferred, in part, because LIBs have better performance compared to other batteries and because “there are no commercial alternative battery chemistries available at scale today that meet the performance” of LIBs (IEA 2022c:18). LIBs charge faster, last longer, and have a higher power-to-weight ratio compared to other batteries, meaning that LIB-powered vehicles can travel farther on a single charge. For example, Lucid, a luxury EV manufacturer based in the US, boasts an EPA-estimated range of 516 miles (830 kilometers) for its LIB-powered 2022 Air model (a four-door sedan) on a single charge (Lucid 2023). For comparison, Honda’s (based in Japan) 1997 EV Plus model (a two-door sedan) ran on a nickel-metal-hydride battery and had an EPA-estimated range of about 81 miles (130 kilometers) on a single charge. (Harrison 2021).

Global EV-LIB demand has driven global lithium demand. EV-LIBs accounted for 47 percent of the increase in global lithium demand from 2017 to 2021 (IEA 2022b). In 2022, the EV-LIB share of global lithium demand was 60 percent, compared to only 15 percent five years prior (IEA 2023). As a result, global lithium demand doubled from approximately 40,000 US tons in 2017 to 80,000 in 2021 (IEA 2022b). World mine production jumped from 43,000 US tons to 100,000 in the same period (USGS 2018; USGS 2022). Furthermore, the average annual price per ton of lithium carbonate averaged 13,940 US dollars (USGS 2022) between 2017 and 2021 but jumped to 37,000 US dollars in 2022 (USGS 2023). This growth has been so rapid and attention-grabbing that major news outlets have taken to calling it the "White Gold Rush" (Frankel and Whoriskey 2016; Pressley 2019; Geist 2021; Penn and Lipton 2021; Purper 2021; Holmes 2022; Colias and Patterson 2023).

Few signs indicate that this rush will halt any time soon. By 2040, global lithium demand and world mine production could increase by *4000 percent* respectively (IEA 2022c). And according to Grand View Research, the global lithium market size could grow from 7.49 billion US dollars in 2023 to 16.87 billion in 2030—a compound annual growth rate of 12.3 percent (2023).

EV-LIB SUPPLY CHAIN

LIB-powered EVs rely on a complex supply chain involving (1) raw material mining, (2) raw material processing, (3) cell component production, (4) battery cell/pack production, (5) EV production, and (6) recycling/reuse (IEA 2022b). Though a variety of metals and minerals go into EV-LIBs—including aluminum, cobalt, iron, manganese, and nickel—lithium will be the focus of this section. This section covers each step in the supply chain, from how lithium is extracted and processed to how EV-LIBs and EVs are assembled and recycled. Additionally, this section covers where each step occurs.

Raw Material Mining

Lithium—a low-weight alkali metal—is used in pharmaceuticals, ceramics, glass, and, of course, batteries. Lithium does not exist in a "free state" in nature but can be found in igneous rock, minerals, and underground reservoirs (Kapheim 2020). Global lithium *resources* (confirmed and estimated lithium deposits) are estimated to total 98 million US tons (USGS 2023) and have been discovered in Africa, Asia, Australia, Europe, North America, and South America (BGS 2021). The top five countries are Bolivia (21 million US tons); Argentina (20 million US tons); Chile (11 million US tons); Australia (7.9 million US tons); and China (6.8 million US tons), accounting for 68 percent of global lithium resources (USGS 2023). For some perspective, a typical EV-LIB uses about 17.6 pounds of lithium (EVBox 2023). Twenty-one mining operations are in nine different countries: eight in China; four in Australia; two in Argentina; two in Brazil; one in Argentina, one in Bolivia, one in Portugal, one in the US; and one in Zimbabwe (BGS 2021). Lithium mining companies include Albemarle Corporation (based in the US), Ganfeng Lithium (based in China), Lithium Americas (Based in Canada), Piedmont Lithium (based in the US), Sociedad Química y Minera (SQM) (based in Chile), and Tianqi Lithium (based in China).

Lithium is mined primarily with two techniques: hard-rock mining and lithium brine recovery.[7] Hard-rock mining involves the removal of lithium-containing pegmatites (igneous rocks with an internal crystalline structure), spodumene (gemstone minerals), and other ores from the Earth's surface (Appendix 1). Australia is the leading producer of hard-rock lithium (IEA 2022c), but hard-rock mining also occurs in Brazil, Canada, China, Portugal, and

[7] Other techniques for lithium extraction include clay mining—used in Nevada, US—and co-precipitation extraction from ocean water. That said, these techniques are not commonly used and do not significantly contribute to international lithium supply.

Zimbabwe (BGS 2021), Lithium brine recovery involves the pumping of lithium-rich water from underground reservoirs to evaporation ponds (Appendix 2). Over 12-18 months, the water evaporates via solar radiation and wind, leaving lithium brines (Appendix 3). Chile is the leading producer of lithium brines (IEA 2022c), but lithium brine recovery also occurs in Argentina, Bolivia, and China (BGS 2021).

Raw Material Processing

Processing or refinement involves the removal of unwanted elements from lithium hard-rock and brines. Refinement can produce a variety of lithium compounds, but the two most important for EV-LIBs, are lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH). Both are used in EV-LIBs, and both have pros and cons pertaining to production cost and EV-LIB performance. For example, the costs of refining lithium carbonate and lithium hydroxide from hard rock are similar, but lithium hydroxide is more expensive and energy-intensive to refine from brines (SMM 2022). Regarding performance, lithium hydroxide is preferred because it "decomposes at a lower temperature, allowing the process of producing battery cathodes to be more sustainable and the final product to be long lasting" (Bisley International 2021).

Hard-rock refinement can be done through a variety of methods, but one of the main methods is roasting with limestone (Yelatontsev and Mukhachev 2021). This method involves roasting hard-rock with limestone at 1100-1200°C (2012-2192°F), resulting in a lithium aluminate cake. This cake is acid-leached with calcium hydroxide, resulting in lithium hydroxide. Different chemical solutions can produce lithium carbonate during the acid-leaching process.

Lithium brines are refined during the evaporation process. Like hard-rock refinement, lime is added to evaporation ponds to remove unwanted elements. When the lithium concentration reaches 1-6 percent, the brines are moved to separate facilities at which they receive soda ash treatments to produce battery-grade lithium carbonate (IEA 2022b). Lithium hydroxide can be produced by treating lithium carbonate with additional chemicals.

Some lithium mining companies, like Albermarle Corporation and Ganfeng Lithium, also refine lithium. Mangrove Lithium (based in Canada), and Chengxin Lithium Group (based in China) are companies that primarily work in lithium refinement. China leads lithium refinement, "accounting for close to 60 percent of global lithium chemical production" (IEA 2022b:139).

Cell Component Production

Cell component production involves the production of the active cathode, anode, and electrolyte *materials* (i.e., not the anode, cathode, and electrolyte themselves; these are produced during battery cell/pack production) for EV-LIB cells. Battery-grade lithium carbonate and lithium hydroxide are processed during cell component production to produce materials like lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP), among others. NMC, NCA, and LFP have pros and cons pertaining to production cost and EV-LIB performance. For example, NMC and NCA "offer high energy density" but "[require] more complex and controlled production processes" (IEA 2022b:11). LFP is cheaper to produce, lasts longer, and has a lower risk of catching fire, but has a lower energy density.

Seven companies are responsible for "55 percent of global cathode material production capacity" (IEA 2022b:23). These companies include Sumitomo (based in Japan), Ningbo Shanshan (based in China), Shenzhen Dynanonic (based in China), and Tianjin B&M Science and Technology (based in China).

Battery Cell/Pack Production

Battery cell/pack production is energy- and capital-intensive and requires a multi-step process: electrode manufacturing, cell fabrication, and battery pack assembly. NMC, NCA, or LFP is mixed with solvents and additives, then coated with a foil current connector (IEA 2022b), resulting in the anode and cathode. An anode is a negative electrode that generates ions.[8] A cathode is a positive electrode that receives ions. During cell fabrication, the anode and cathode are rolled, dried, and stacked with a separator (anode/separator/cathode), resulting in a cell. The cell is then filled with an electrolyte and sealed. An electrolyte is a solid or liquid medium for ion transfer between the anode and the cathode. Ion transfer is a chemical reaction that generates electrons.[9] Electrons flow out of the cell to power an EV. As an EV is powered, the energy in the cell for ion transfer depletes. When a cell is recharged, electrons flow into the cell, thereby replenishing the cell's energy. Finally, during EV-LIB assembly, hundreds to thousands of cells are arranged into modules or arrangements of multiple cells. These modules are then assembled into the EV battery pack (Appendix 4).

CATL (based in China), LG Energy Solution (based in South Korea), and Panasonic (based in Japan) lead battery cell/pack production, accounting for 65 percent of global production in 2021 (IEA 2022b:2, 24). Automakers like BYD (based in China) also assemble battery cells and packs. China "is home to 70 [percent] of [global] production capacity for cathodes and 85 [percent] for anodes" (IEA 2022b:2), and produces 75 percent of *all* LIBs (i.e., LIBs used in EVs, computers, cellphones, and other electronic devices) (IEA 2022b).

[8] Ions are atoms or molecules that have a positive or negative electrical charge.

[9] Electrons are subatomic particles with a negative charge of electricity.

EV Production

EV production methods vary but generally involve two main processes: body assembly and power train assembly. Body assembly starts with cutting and shaping metal sheets into the body and exterior panels. The body and exterior panels are then welded and screwed together by machines and workers. The body and panels receive a paint job. After the paint dries, interior paneling and electrical wiring are installed.

Power train assembly can be done simultaneously with body assembly. The power train serves as the frame for the body and is where the LIB and cooling system are located (Appendix 5). Once the body and power train are assembled, the body is installed on top of the power train. The LIB is then connected to "the electric motor, on-board charge module, high voltage distribution box, electric transmission, and thermal systems" (IEA 2022b:25). The EV undergoes finishing touches and quality control checks before being put to market.

EV production cost and time vary. Tesla (based in the US) reported that the average cost per vehicle is 36,000 US dollars in 2021 (HT Auto Desk 2022). Generally, the battery pack accounts for most of an EV's cost. Regarding production time, a new EV can be produced every 30 seconds at Tesla's Gigafactory in Shanghai (The Tesla Space 2022).

BYD, Tesla, and VW Group (based in Germany) lead EV production and accounted for a third of EV production in 2021 (IEA 2022b:25); but every international automaker either has put EVs to market or has plans to, soon (Motavalli 2021). According to the IEA's 2023 EV Outlook Report, the number of EV models available for purchase reached 500 in 2022, "more than double the options available in 2018" (10). China leads EV production and EV sales (Green Car Congress 2021; IEA 2022b).

Recycling/Reuse

EV-LIBs can last five to ten years. Once spent, EV-LIBs can be recycled and reused. Recycling involves recovering critical materials, cathodes, and anodes and reuse involves refurbishing spent batteries for applications other than EVs (e.g., electricity storage) (IEA 2022:19). Techniques for recycling and reuse include pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy involves “smelting the battery in a high-temperature oven, recovering only a fraction of the metals from the cathode” (IEA 2022b:25). Like refining lithium via acid-leaching, hydrometallurgy involves chemical-leaching to pull lithium and other metals from the battery. Both pyrometallurgy and hydrometallurgy break the battery down; direct recycling does not. Direct recycling is used to regenerate the cathode material in a battery (IEA 2022b), which can then be used in other electronic devices. Reuse is seen as a valuable pursuit, in part, because “spent EV batteries still have around 80 [percent] of their usable capacity” (IEA 2022b:25). Recycling and reuse facilities are limited in number and capacity. Li-Cycle (based in Canada) is a company that primarily works in LIB-recycling. That said, some automakers—Kia (based in South Korea) for example—are starting to enter recycling and reuse.

The Concentration of the Supply-Chain

The EV-LIB supply chain is characterized by an abundance of global lithium *resources*. The increased demand for EV-LIBs likely does not risk a lithium resource deficit (Grosjean et al. 2012; Olivetti et al. 2017), and EV-LIBs require a minuscule amount of lithium compared to currently known lithium resources. For example, 6.6 million new EVs were sold in 2021 (IEA 2022b); if all those EVs used 17.6 pounds of lithium—again the amount of lithium used in a typical EV-LIB (EVBox 2023)—the total amount of lithium used would equal 58080 US tons, or

58 percent of the world mine production in 2021 (100,000 US tons) (USGS 2022) and 0.05 percent of currently known lithium resources (98 million US tons) (USGS 2023).

However, lithium resources, particularly continental lithium brines, are geographically concentrated. Most lithium resources (51 percent) are in Argentina, Bolivia, and Chile (sometimes referred to as the "Lithium Triangle" (Appendix 6). Furthermore, lithium is only mined in nine countries (BGS 2021), with two accounting for 77 percent of total world mine production in 2022 (130,000 US tons): Australia (61,000 US tons from hard rock) and Chile (39,000 US tons from brines) (USGS 2023). Chile's lithium mine production in 2022 is more than double China's 14,000 US tons (hard rock and brines) in 2022—the country with the next highest lithium mine production (USGS 2023). That said, lithium processing and EV-LIB production are concentrated in China. China accounts for 60 percent of global lithium processing; 70 percent of the production capacity for cathodes; 85 percent of the production capacity for anodes; 75 percent of *all* LIB production (IEA 2022a; IEA 2022b); 44 percent of EV manufacturing (Green Car Congress 2021); and 50 percent of EV sales (IEA 2022b).

The concentration of resources, mining, processing, and production in specific countries is referred to as *supply-chain concentration*. Though not the focus of this study, supply-chain concentration merits some discussion. First, the concentration of the EV-LIB supply chain indicates countries that are likely important or central in the international trade of EV-LIBs and lithium. Australia, Chile, and China are important countries in EV(-LIB) and lithium production, and, therefore, would likely be important countries in the trade of EV-LIBs and lithium.

Supply-chain concentration is also important because it means that countries *must engage in international trade* to obtain resources and products like lithium, EV-LIBs, and EVs. A country that does not produce lithium but that does have lithium demand (for its automotive industry, its computer and electronics industry, etc.) must import lithium to meet its demand. The necessity of trade implicates the importance of trade *relationships* and the overall pattern of trade relationships.

CHAPTER OVERVIEW

In Chapter 2, I summarize literatures on lithium extraction and green extractivism; supply and demand trends; and EV-LIB and lithium trade networks. I also discuss the concept of ecologically unequal exchange (EUE) and recent EUE research. Finally, I provide an overview of approaches to and concepts of network analysis.

In Chapter 3, I describe my data, sampling, and methods. I describe how I construct the international EV-LIB and lithium compound trade networks. I detail the betweenness, closeness, outdegree, indegree, eigenvector, and core-periphery measurements used in Stage 1. And I explain exponential random graph modeling. In Chapters 4 and 5, I present the results of Stage 1 and Stage 2 respectively. In Chapter 6, I conclude with a discussion of this study’s key findings, this study’s limitations, and directions for further research.

CHAPTER 2: LITERATURE REVIEW & THEORETICAL PERSPECTIVES

In the first section of this chapter, I summarize literatures on lithium and green extractivism; supply and demand trends; and international EV-LIB and lithium trade networks.[10] Taken together, the literature helps us make sense of EV-LIB and lithium trade—its politics; its future direction; its concentration; and its (in)stability. But the analyses in the green extractivism and supply-demand literatures do not address international EV-LIB and lithium trade *networks*; and the analyses in the trade networks literature do not address the *formation* of trade structure and structural inequality. This study contributes to this literature by taking a network approach to analyze the formation of international EV-LIB and lithium compound trade networks' structure and structural inequality.

Following the literature review, I discuss theoretical and methodological perspectives that inform this study. First, I outline the concept of ecologically unequal exchange (EUE). Second, I present recent research that takes a network approach to EUE. Finally, I provide an overview of approaches to and concepts of network analysis. EUE theory and research motivate this study's attention to structural inequality and showcases network-specific methods for analyzing the formation of trade structure.

LITERATURE REVIEW

Lithium & Green Extractivism

"Green extractivism" refers to "intensive resource exploitation [especially for export] framed not only as compatible with climate change, but indeed as *necessary to its mitigation* [emphasis added]" (Voskoboynik and Andreucci 2021:787). Researchers of lithium extraction as

[10] There is also a significant body of literature on the technologies and chemistries for lithium extraction and LIB production and innovation. For a comprehensive book on the subject, see Zhang, Xu, and Henderson (2017).

a form of green extractivism focus on Argentina, Bolivia, and Chile. Argentina, Bolivia, and Chile are where most lithium resources have been found and are where much of the world's lithium mine production takes place. Researchers show that mining corporations and governments in these countries frame lithium extraction as a pathway to economic development and energy security—like the framing of coal, gas, and oil extraction (Dunlap 2021). For example, mining corporations and governments in Argentina promote lithium extraction for its employment opportunities and for its revenues which could contribute to citizens' access to education, electricity, health care, the internet, and other social services (Paz et al. 2023). In Bolivia, some government officials refer to lithium as "white petroleum" and promote lithium extraction as a means of securing and asserting their geo-economic position (Voskoboynik and Andreucci 2021).[11] But mining corporations and government officials also frame lithium as a "clean," "green" commodity,[12] and lithium extraction as a "sustainable" and "climate-friendly" form of mining that will support the production of emission-reducing technologies like EVs (Voskoboynik and Andreucci 2021:799).

Researchers argue that this framing ignores the socio-ecological problems of lithium extraction and legitimizes environmental degradation and social injustice. These problems include water depletion and the threat to Indigenous land and water rights in Argentina, Bolivia, and Chile[13] (Giglio 2021; Jerez et al. 2021; Forget and Bos 2022; Hernandez and Newell 2022;

[11] Officials and market analysts sometimes refer to Bolivia as a "New Saudi Arabia," or the "Saudi Arabia of lithium," (Voskoboynik and Andreucci 2021).

[12]Boer's, Pescatori's, and Steurmer's—and my—use of "energy transition metal" to refer to lithium (2021) (see Chapter 1) would be an example of what Voskoboynik and Andreucci call a discourse of "environmentally benign and climate-friendly extraction" (2021).

[13] I mention in Chapter 1 that Argentina, Bolivia, and Chile are sometimes referred to as the "Lithium Triangle" (Appendix 6). Having discussed green extractivist-framing, it is now appropriate to mention that researchers do critique that moniker, arguing that it "obscures everything [—ecosystems, Indigenous people, peasant farmers,

Mejia-Muñoz and Babidge 2023; Paz et al. 2023); and toxin exposure (Chaves et al. 2021). Recall, lithium brine recovery is a technique for lithium extraction that involves the pumping of lithium-rich groundwater to evaporation ponds. Lithium brine recovery requires large water inputs to produce lithium carbonate. It takes approximately 528,344 gallons (2 million liters) of water to recover one ton of lithium carbonate (Voskoboynik and Andreucci 2021). Furthermore, the rate at which lithium brine recovery operations pump lithium-rich groundwater exceeds watershed recharge rates (Jerez et al. 2021). Lithium brine recovery is so water-intensive that it is sometimes referred to as "water mining."

Recovery operations are often sited in sensitive ecosystems within Indigenous territory. For example, Sociedad Química y Minera and Albemarle have operations in the Salar de Atacama salt (i.e., salars) and watershed. The Salar de Atacama watershed is part of the Chilean Atacama Desert—the driest place on the planet other than the north and south poles—and is part of the Indigenous ancestral territory to the *Atacameño-Lickanantay* people (*Atacameños*). Researchers argue that operations in the Salar de Atacama watershed threaten the ecosystem of the watershed and threaten the *Atacameños* access and rights to land and water.

Government regulations recognize the land and water rights of Indigenous people. For example, the Chilean government ratified the International Labour Organization's Convention No. 169, which recognizes Indigenous peoples' rights to their ancestral lands and grants Indigenous consultation (Giglio 2021; Jerez 2021; Hernandez and Newell 2022). But researchers argue that government officials ignore Indigenous people's land and water rights and right to informed consent; because officials frame places like the Salar de Atacama as "[areas] of impoverished emptiness, in need of being rendered productive through extraction" (Voskoboynik

cultural significance—] but lithium" (Hernandez and Newell 2022:951). In other words, researchers argue that the phrase frames the region *only* in terms of "commodity" and "value."

and Andreucci 2021:798); and because they *legally* classify lithium-rich groundwater as mining property (Jerez et al. 2021).

Though less of a focus in the literature, there is some evidence of lithium extraction operations exposing workers and adjacent communities to pollutants and toxins. Chaves et al. suggest that lithium brine recovery may expose workers to photochemical oxidants[14] which could lead to respiratory inflammation (2021). Additionally, both lithium brine recovery and hard-rock mining—a technique for extracting lithium involving the removal of lithium-rich ores from the Earth's surface—may expose workers and nearby communities to (cancer-causing) pollutants, as both mining techniques produce chemical waste and emit particulate matter that may pollute water and air (Chaves et al. 2021).

These problems have led some to resist lithium extraction and its green-extractivist framing (Jerez et al. 2021; Voskoboynik and Andruecci 2021; Mejia-Muñoz and Babidge 2023). For example, movements of Indigenous people, farmers, workers, and environmentalists have made efforts to limit and prevent lithium extraction in Chile. These efforts include legal challenges to the Chilean government, organized protests, and labor-union blockades of lithium facilities (Mejia-Muñoz and Babidge 2023). These movements deploy counter-discourses that challenge the ecological sustainability of lithium extraction and that "reaffirm the complex social and ecological value" of places like the Salar de Atacama (Voskoboynik and Andreucci 2021:800). Similar movements and politics are emerging elsewhere. For example, Peehee Mu'huh (which roughly translates to "Blood Moon") is a burial site for Paiute and Shoshone communities in northern Nevada, US. The site marks the US Calvary's massacre of 31 Paiute

[14] Photochemical oxidants are secondary air pollutants formed by the action of sunlight on nitrogen oxides, reactive hydrocarbons, and their precursors (Guderian, Tingey, and Rabe 2023). The risk is that lithium brine recovery operations produce these oxidants as the chemically-treated water in the surface ponds evaporates.

and Shoshone people in 1865 (Carlson 2021). Peehee Mu'huh is also the site for the construction of Canada-based, Lithium Americas's Thacker Pass Project—an open-pit mine atop the "largest known lithium resource in the US" (Lithium Americas 2021). Environmentalists and Indigenous activists have drawn on similar protest tactics and counter-discourses to those found in South America (Voskoboynik and Andreucci 2021; Mejia-Muñoz and Babidge 2023) in hopes of preventing the construction of the project.[15]

However, researchers argue that the framing of lithium extraction as not only compatible with but *necessary* for climate action makes opposition to it more untenable than opposition to the extraction of "dirty" commodities (e.g., coal, gas, and oil) (Riofrancos 2022). Speaking to this dilemma, Dorn succinctly writes that the green-extractivist frame means that, "Those who oppose mega-development projects today are not 'only' opposing social plans, but also climate protection" (2022:141).

Overall, this literature provides useful concepts for making sense of the motivations, justifications, and policies for lithium extraction. Additionally, this literature illustrates the stakes, tensions, and contradictions in lithium extraction for economic development, energy security, and climate action; that is, the tension between a "greener status quo and a transformative 'just transition'" (Riofrancos 2022:23). Finally, this literature provides compelling arguments for a more environmentally-just approach to resource and energy-transition governance. That said, the literature does not give analytical attention to international EV-LIB and lithium trade. Information about trade—such as descriptive statistics on EV-LIB and lithium trade from organizations like the IEA—is often used to frame or give background to

[15] The Guardian's coverage of the Thacker Pass Project illustrates the emerging lithium politics that green extractivism scholars speak to; I recommend viewing the referenced video (2021).

a study. But framing, socio-ecological problems, and politics are the subjects of analysis—not trade.

Supply & Demand Trends

The literature on supply and demand trends suggests global lithium demand has grown and will likely continue to grow (Grosjean et al. 2012; Martin et al. 2017; Olivetti et al. 2017; Liu et al. 2019; Greim, Solomon, and Breyer 2020).[16] Indeed, this finding is confirmed by reports from agencies like the US Geological Survey (2013; 2018; 2022; 2023) and the IEA (2022a; 2022b; 2022c). Moreover, the literature shows that EVs are a significant driver of past and projected lithium demand and price increases (Grosjean et al. 2012; Martin et al. 2017; Olivetti et al. 2017; Liu et al. 2019; Greim et al. 2020). Relatedly, though non-battery applications (e.g., ceramics and glass) maintain a significant share of lithium demand, the share of global lithium demand for EV-LIBs has increased in recent years (Martin et al. 2017; Greim et al. 2020).

The literature also shows that though global lithium *resources* are considered abundant, lithium demand increases may outpace the lithium *supply* (i.e., the stock of usable lithium), particularly in the latter half of this century (Grosjean et al. 2012; Olivetti et al. 2017; Liu et al. 2019; Greim et al. 2020). Researchers give the following reasons for potential supply-demand deficits: lithium resources are concentrated in specific countries (Argentina, Australia, Bolivia, Chile), thereby limiting access to those resources; and mining, processing, and production capacities are concentrated in specific countries, thereby risking deficits when an economic shock (e.g., recession), environmental shock (e.g., disaster), geopolitical shock (e.g., war), or

[16] Dips have occurred. For example, the 2007 financial crisis led some countries to restrain their consumption of lithium, thereby reducing global lithium demand (Grosjean et al. 2012) and the COVID-19 pandemic led to reduced industrial demand for lithium (Akcil, Sun, and Panda 2020).

pandemic shock (e.g., COVID-19) occurs. In other words, supply-chain concentrations are shown as potentially constraining factors on countries' ability to meet lithium and EV demand (Martin et al. 2017; Olivetti et al. 2017).

To address potential supply-demand deficits, short-term and long-term, researchers recommend that countries increase supply stocks of lithium (Grosjean et al 2012); increase investment in (domestic) production of lithium (Martin et al. 2017); increase investment in LIB recycling systems (Greim et al. 2020); and increase investment in the innovation of lithium extraction technologies and alternative battery technologies (Olivetti et al. 2017; Liu et al. 2019). Countries already involved in the EV-LIB supply chain and countries entering it are taking such steps, which may, in turn, reduce the concentration of the EV-LIB supply chain. An example from the green extractivism literature: Riofrancos examines the recent phenomenon of lithium onshoring in the Global North (Canada, the US, and countries in the EU)—countries with a history of outsourcing (environmentally) costly industries like resource extraction to other countries in the Global South (countries in South America, Africa, and the Middle East), are now promoting and establishing such industries within their borders, in part, for energy security (2022).

Overall, this literature provides a snapshot of international lithium, EV-LIB, and EV markets and illustrates potential market developments. Unlike those in the green extractivism literature, studies in this literature give analytical attention to international EV-LIB and lithium trade. That said, the studies do not take analyze international EV-LIB and lithium trade as *networks.* The study from Olivetti et al. (2017) is perhaps the closest in that it includes a map of aggregated lithium and cobalt trade flows among countries (234). And some researchers address issues that the trade networks literature addresses; for example, the relationship between supply-chain concentrations, supply-chain shocks, and supply-demand deficits. But the analyses in this literature primarily focus on market features (supply, demand, and price), not network features (e.g., the absence or presence of trade relationships between countries); the latter being more pertinent to this study.

Trade Networks

The finding from the literature on international LIB and lithium trade networks most important to this study, is that not only is the EV-LIB supply chain concentrated in a few developed and emerging countries (Argentina, Australia, Chile, China, Germany, Japan, South Korea) (Sun et al. 2017; Sun et al. 2021; Tian et al. 2021; Hao et al. 2022; Miao et al. 2023); but that *trade relationships* are concentrated among a few developed countries (Liu et al. 2021; Shao et al. 2021; Yang et al. 2021). Countries like China, Germany, and the US tend to have the highest number of trade relationships (exports and imports) with other countries and tend to have the highest value and volume of commodities traded (Chen et al. 2020; Liu et al. 2021; Shao et al. 2021; Tian et al. 2021). For example, Yang et al. mention that: “80 [percent] of the lithium transaction volume is managed by 30 [percent] of exporting countries or regions and consumed by up to 40 [percent] of importing countries or regions” (2021:5). In other words, a Yang et al. find that a small number of countries handle most of the traded lithium volume.

The concentration of exports, imports, and trade relationships in trade networks is referred to as *trade concentration*. “Trade concentration” and “structural inequality” are similar insofar as both describe the extent to which all trade relations in a network involve a single country or a small set of countries. Researchers give three reasons for why trade concentrations are important.

First, trade concentrations mean that countries like China, Germany, and the US *can* make up for their lack of resources or their lack of production capacity through trade.[17] For example, the US is not a leading producer of lithium[18]—now accounting for one percent of world mine production (Riofrancos 2022)—which could hinder sectors like automotive manufacturing and computer and electronics manufacturing.[19] But because of its high import volume *and* because of its large number of LIB and lithium import relationships (Liu et al. 2021), the US can get the lithium and batteries needed to meet manufacturing demand.

Second, trade concentrations mean that countries like China, Germany, and the US are less *dependent* on any one trade relationship *compared* to other countries and can set the terms of trade. Take China. China imports a significant amount of lithium to support its (EV-) LIB manufacturing (Tian et al. 2021) and has a high number of lithium import relationships (Chen et al. 2020; Liu et al. 2021). If trade between China and Bolivia, for example, were threatened—a trade agreement falls outs, a shock disrupts Bolivian lithium mine production—China would still have many other trading partners from which lithium could be imported.

Conversely, South Korea has a robust battery manufacturing sector, but does not have many lithium import relationships and is shown to be especially dependent on Chile for lithium (Liu et al. 2021). If this trade relationship were to cease, South Korea might not have many other

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[17] "Can" is italicized in recognition of the point that a country having a high number of lithium trade relationships does not necessarily mean that said country will obtain lithium needed to meet its demand. For example, a country may have many lithium import relationships, but may get most of its lithium from one partner; were the trade relationship with that partner to fall out, the country would have all those other trading partners but would still take a significant hit to its lithium imports.

[18] According to Miatto et al. the US was "the largest producer and user of lithium worldwide until the 1980s, when foreign production overtook domestic" (2020:8). For comparison, in addition to being the country with the third-highest lithium mine production, China is now the leading importer of lithium, accounting for approximately 24 percent of global lithium imports (Jerez, Garcés, and Torres 2021), largely from Australia and Chile (IEA 2022b).

[19] Automotive manufacturing and computer and electronics manufacturing are the two largest manufacturing sectors in the US, in terms of employment opportunities and contribution to national GDP (NIST 2023).

partners that could meet battery manufacturing's lithium demand. The example of China and South Korea concern import dependence, but similar points apply to export dependence—if Bolivia produces a large amount of lithium but only trades with China, then Bolivia would be entirely dependent on that relationship for lithium exports. And to maintain that trade relationship, Bolivia may be more inclined "to [make] price concessions," to China (Liu et al. 2021:1).

Third, trade concentrations pose risks to the stability of international EV-LIB and lithium trade networks. The relationship between trade concentrations and trade stability—or the "ability of [] other trading countries and trade relations to function normally when certain trading countries or trade relations break down" (Wu et al. 2021:1)—is the primary concern of researchers (Liu et al. 2021; Wu et al. 2021; Yang et al. 2021; Hao et al. 2022; Hu et al. 2023). Regarding risk, researchers focus on the capacity of countries to disrupt trade between other countries (Hu et al. 2023); the capacity of countries to transmit risk through trade flows (Hao et al. 2022); and the risky positions that countries occupy as a function of the overall pattern of trade relationships (Liu et al. 2021). Findings indicate that countries in which the EV-LIB supply chain is concentrated and countries that import and export a large share of total EV-LIB and lithium trade volume, have the greatest capacity to disrupt trade. Specifically, raw material supply restrictions from South American countries like Chile would have a far-reaching effect, impacting most countries participating in lithium trade; and battery supply restrictions from industrialized Asian countries like China, Japan, and South Korea would have a far-reaching effect, impacting most countries participating in LIB trade. That is, supply shocks that originate in countries with a high number of trade relationships could reach (i.e., "avalanche" to [Hu et al. 2023]) many countries.

To prevent disruption to trade stability, researchers make similar recommendations to those made in the supply-demand literature: countries should invest in domestic mining, processing, and production, and should make more trade relationships and/or diversify their trade relationships (Liu et al. 2021; Hao et al. 2022; and Hu et al. 2023). What is more, some researchers show trade relationships that would optimize the stability of EV-LIB and lithium trade. For example, more trade relationships among countries in South America, according to Yang et al., would decrease lithium transportation costs and increase lithium trade efficiency (2021). Additionally, specific trade relationships "from Germany to [South] Korea, from Belgium to [South] Korea, from Argentina to Spain, from Belgium to China, from Chile to England, and from Chile to Canada" would improve the stability of the overall trade system (Wu et al. 2021:9). The formation of more trade relationships (and ideal relationships in particular) is already occurring. Wu et al. (2021) mention that the trade relationship between Germany and South Korea formed in 2019; and more trade relationships are forming between more countries over time (Sun et al. 2017; Tian et al. 2021).

Overall, this literature illustrates international EV-LIB and lithium trade networks—their key countries; their trade concentrations; their (in)stability. Whereas the green extractivism and supply-demand literature do not analyze trade networks, this literature does. Additionally, researchers make a point to provide recommendations for policymakers on how to avoid risk and secure trade. This literature also showcases methods particularly useful for Stage 1; for example, methods for identifying how central a country is in a network.

That said, two points: the first being about a difference between this literature's attention to trade concentrations and this study's attention to structural inequality; the second being about the research gap. (1) Though "trade concentration" and "structural inequality" describe similar patterns of trade relationships, the literature's attention to the former is prompted by its implications for trade stability; whereas this study's attention to structural inequality is motivated by its facilitation of the "transfer of [economic, environmental] 'surplus' from [the] periphery to [the] core" (Bousquet 2012:123). In other words, where this literature sees, and makes convincing arguments about, trade concentration as a pattern of relations that threatens trade stability and, therefore, countries' pursuit of climate action and (sustainable) economic development in accordance with international agreements and national policy; this study sees structural inequality as a pattern of relations that facilitates (ecologically) unequal exchange.

(2) This literature does not give analytical attention to the *formation* of trade structure and structural inequality. Some examine the change in the international EV-LIB and lithium trade over time (Sun et al. 2017; Shao et al. 2021; Tian et al. 2021; Shao et al. 2022). But attention to change in the trade structure is not the same as attention to the determinants of trade structure. Herein lies this study's contribution to the literature on EV-LIBs and lithium trade—it provides an analysis of the formation of trade structure and structural inequality in international EV-LIB and lithium trade networks.

ECOLOGICAL UNEQUAL EXCHANGE

The concept of ecologically unequal exchange builds on dependency theory, world-systems theory, and the concept of unequal exchange. At its most basic level, unequal exchange refers to the "the asymmetric transfer" of a traded commodity or product of value (Hornborg 2011:77). The differences between EUE and unequal exchange are in what commodities or products are studied and in how value is understood. Emmanuel (1972)—an early scholar of dependency theory—understood value and traded products in terms of embodied labor/labor hours invested in a traded product. Specifically, Emmanuel defined unequal exchange as "the idea that on the world market the poor nations are obliged to sell the product of a relatively large number of hours of [labor] in order to obtain in exchange from the rich nations the product of a smaller number of hours of [labor]" (1972:272).[20] Rich or developed countries or regions can subsequently accumulate capital by reinvesting the surplus value derived from the difference in labor hours invested in traded products. Simply put, the labor approach to unequal exchange describes developed countries or regions accruing capital through the labor exploitation of poor or less-developed countries or regions.

World-systems theory posits a similar relationship between "core-states" and "peripheral areas" (Wallerstein 1974). That is, the world-economic division of labor facilitates the transfer of surplus from peripheral countries to core countries. Core countries tend to be developed and are "seen as those governed by state machineries that are strong enough to secure major advantages in the world market for their own citizens, especially through the exploitation of population in peripheral countries" (Babones 2012:329). Peripheral countries tend to be less developed and are seen as "those that do not possess strong enough states to prevent the exploitation of their populations by economic actors…operating with the support of core states" (Babones 2012:329).

EUE describes a similar phenomenon, but in terms of "the value of nature" (Bunker 1984; 1985) or "natural capital" (Jorgenson and Rice 2012). Bunker (1984; 1985)—an early scholar of EUE—critiques Emmanuel's labor approach to unequal exchange, arguing that it assumes "labor is always [taken to be] the primary determinant of value," thereby missing the value extracted from nature (1985:44).[21] Rather, unequal exchange should be understood as the "unbalanced *flows of energy and matter* [transformed by labor into commodities and products]

[20] I generally agree with Hornborg's critique that Emmanuel's definition it is "inaccessible" and that "the phenomenon of unequal exchange is much more general and inclusive" (2011:110).

[21] Bunker levels a similar critique to Amin (1976, 1977) and Bettelheim (1972) as well.

from the extractive *peripheries* to the productive *core* [emphases added]" (Bunker 1984:1018). According to Bunker, the ecological approach to unequal exchange, "provides better measures of unequal exchange in a world economic system than do flows of commodities measured" in labor, prices, and wages (1984:1018); because labor, production, and the "(dis)articulation" or (under)development of societies (1985:34) all require the extraction and consumption of energy and matter.

Similar Bunker, Jorgenson and Rice argue that the asymmetrical transfer of energy and natural resources merits analysis because "all economic production is predicated on ecological additions and withdrawals" (2012:431). Jorgenson and Rice define EUE as "the environmentally damaging withdrawal of energy and other natural resource assets from and the externalization of environmentally damaging production and disposal activities within less-developed countries" (2012:432). Here, developed countries accrue economic, environmental, and social benefits at the expense of less-developed countries not only by energy and natural resource extraction in and export from less-developed countries (i.e., withdrawals), but also by taking advantage of less-developed countries' sink capacity. "Sink capacity" refers to the capacity of a country or region to receive and hold waste (i.e., additions). Attending to both environmental withdrawals and additions, Jorgenson and Rice theorize the "consumption/environmental degradation paradox" (2012:433): Developed countries consume more energy and natural resources than less-developed countries yet host little environmental degradation and less-developed countries under-consume energy and natural resources but host severe environmental degradation.

Contemporary Research on Ecological Unequal Exchange

The throughline in the definitions and assertions of unequal exchange, world-systems, and EUE presented so far, is that the focus is on the *unequal flows of trade.* EUE research often focuses on unequal material flows from and consequent environmental degradation in less developed or peripheral countries or regions. Examples include lumber (Shandra, Leckband, and London 2009); beef (Austin 2010); coffee (Austin 2012); cocoa (Noble 2017); and plastic waste (Bai and Givens 2021). These studies use export and import value or volume, rather than export or import *relationships*, to analyze the unequal quantity of energy and natural resources withdrawn and consumed and the unequal distribution of ecological additions and degradation. That said, EUE is just as much about the overall pattern of relationships between countries (network structure) and asymmetrical power relationships (structural inequality) (Jorgenson and Rice 2012).

More recently, researchers have taken a network approach to analyze the relationships between trade structure, structural inequality, and EUE (Vesia, Mahutga, and Buì 2021; Jorgenson et al. 2022). Using bilateral trade data on exports and imports, Vesia and her colleagues construct an international natural resource (wood, pulp, fertilizers, metals, and fuels) exchange network (2021). They identify the structural position of countries in terms of how central countries in the network are. They then use countries' structural positions—rather than the value or volume of natural resource flows—as independent variables and countries' CO_2 emissions (total, per unit of GDP, and per capita) as dependent variables. This study finds that countries with fewer trade relationships (i.e., less central countries) in the international natural resource exchange tend to be less-developed countries, tend to have more dependent relationships, and tend to be more dependent on their natural resources for their GDP; indicating that "the *structure of the natural resource exchange network* increases the environmental costs of development among less central countries [emphasis added]" (2021:12).

Jorgenson and colleagues use foreign direct investment (FDI) data, rather than bilateral trade data, for the relationships in their networks (2022). This study finds that the amount of FDI a country receives *and* the number of FDI relationships a country has, are positively associated with a country's total carbon emissions and emissions per unit of GDP. In other words, Jorgenson and colleagues argue that the relationships of FDI facilitate "the outsourcing of inefficient and environmentally harmful extraction and production processes, leading to growth in energy consumption and concomitant carbon emissions for receiving nations" (2022:6-7). Simply put, the studies from Jorgenson et al. (2022) and Vesia et al. (2021) show the importance of trade structure and structural inequality for the distribution of economic and environmental "goods" and "bads."

What is more, recent research examines the *formation* of trade structure and structural inequality (Sommer 2020; Theis 2021). That is, like Vesia et al. (2021) and Jorgenson et al. (2022), Sommer (2020) and Theis (2021) take a network approach to EUE in international trade. But the latter two differ in that they use trade relationships as the *dependent* variable in their analyses.

Sommer sets out to "empirically test what factors contribute to [the formation of forestry export relationships], uneven resource exchanges over time, and why some nations form more [relationships] over time" (2020:310). After constructing international forestry trade networks from forestry export data, Sommer uses regression[22] to analyze the effect of GDP, natural resource availability, population size, level of democracy, and environmental treaties on forestry export tie formation. One of the more relevant findings to this study is that the higher a country's

[22] Negative binomial fixed effects regression to be specific.

GDP per capita, the fewer forestry export relationships a country has. Sommer gives two possible reasons for this finding:

> GDP per capita may decrease forestry export [relationships] because more affluent nations may not see advantages in establishing [relationships] that can facilitate environmental degradation…[or] higher levels of GDP may [] contribute to lower forestry export [relationships] due to a more robust environmental awareness and thus less pressure on exports, though these nations may increase imports to meet their resource demands (2021:321).

Sommer's use of regression demonstrates how to analyze the formation of export relationships. Sommer's finding indicates countries with high GDP to export resources to fewer partners but receive resources from more partners.

Finally, Like Sommer (2020), Theis (2021) uses international electronic waste (e-waste) trade relationships as the dependent variable. Theis finds that the international trade of e-waste is, in part, characterized by the unequal exchange of e-waste, whereby e-waste trades are likely to concentrate in semi-peripheral countries like India. However, the main takeaway is that, unlike Sommer, Theis estimates an exponential random graph model (ERGM)—again, a probability model specifically for social networks—to analyze the likelihood of trade tie formation, given countries' income level, regional classification, and structural position. This study estimates ERGMs in Stage 2.

Summary

EUE theory and research motivates this study's attention to structural inequality and its use of a core-periphery model in Stage 1. EUE theory suggests that the importance of structural inequality is not only in its facilitation of and hindrance to countries obtaining EV-LIBs and lithium—as the trade networks literature suggests—but also in its facilitation of (ecologically) unequal exchange between core countries and peripheral countries. From an EUE perspective, we can expect to find a core-periphery pattern of international EV-LIB and lithium trade, by which certain countries occupy the center of EV-LIB and lithium compound trade, and by which certain countries occupy the margins a certain set of countries. Moreover, unlike the trade networks literature, recent EUE research uses network analysis to study the determinants or formation of ecological unequal exchange in international trade networks. From an EUE perspective, we can expect to find differences in GDP between countries to be a determinant in the formation of the EV-LIB and lithium trade networks' overall structure and structural inequality. Inferentially, finding a core-periphery pattern and differences in GDP to be a statistically significant determinant of trade tie formation, would provide some evidence for EUE in international trade of EV-LIBs and lithium.

SOCIAL NETWORK ANALYSIS

The study of international trade structure *is* the study of *networks* or the "*relationships among entities that make up* [a] *system* [emphasis added]" (Borgatti et al. 2022:2). That said, there are many approaches to the study of networks that one can take. Therefore, it is important to clarify the approach this study takes. Using Burt's six models of network analysis or six concepts of network structure (1978; 1980), this section provides an overview of approaches to and concepts for network analysis. The models are defined by "(1) the level of aggregation of actors—individuals versus subgroups within a [network] versus whole [networks], and (2) the approach taken to linkages between actors" (1978:124) I summarize these concepts in Table 1.

Relational Approach to Social Network Analysis

A relational approach to network analysis centers on the *types* and *intensity* of present relationships, or ties, between actors, or nodes. To illustrate, were we to model a group of five friends as a network, a tie could represent "friendship"—the type of tie between friends.

Table 1: Concepts of network structure within each of six modes of network analysis (Burt 1980:80).

Analytical Approaches	Node aggregation in a unit of analysis		
	Node	Multiple nodes as a network subgraph	Multiple nodes/ subgroups as a structured network
Relational	personal network as extensive, dense and/or multiplex	primary group as a network clique; a set of nodes connected by cohesive relations	[network] structure as dense and/or transitive
Positional	occupant of a network position as central and/or prestigious	status/role-set as a network position; a set of structurally equivalent nodes	[network] structure as a stratification of status/role-sets

We could survey members of the friend group, asking "How many hours per week do you spend with each friend?" We could, then, measure the intensity or strength of the friendships and rank-order the friendships in terms of "time spent": stronger friendships are those in which respondents claim to spend more time. Regarding this study, the types of ties are trade ties, specifically export ties. This study does not give analytical attention to the intensity or strength of the export ties, but we could measure in export value or volume, where stronger export ties are those in which the value or volume of exported EV-LIBs and lithium is high.

Relational Approach to a Single Node. A relational approach to a single node, models what is referred to as a "personal network" or "ego network" (the first cell in the first row of Table 1). To be clear, a "single node"—referred to as an ego—can be a single person, a single family, a single business, a single country, and so on. What is then analyzed are the types and intensity of the present ties between a single person, family, business, or country and adjacent persons, families, businesses, or countries—referred to as the ego's alters. A relational approach centers on three aspects of ego networks: range or extensiveness; density; and multiplexity (Burt 1978:90). Range, density, and multiplexity can be examined for any network but, according to Burt (1978), are of particular interest to those who examine ego networks.

The "range" of an ego network can refer to the extent to which an ego has ties with different (i.e., socially heterogeneous) alters (i.e., how diverse the ego's network is); or to the number of alters with which an ego has ties (i.e., how extensive the ego's network is). An example of the former: a high school English teacher having professional ties with many different persons (e.g., students, students' parents or guardians, other teachers in the English department, other teachers outside of the English department, school administration officials, etc.) would have a relatively diverse ego network. An example to the latter: a factory floor manager to whom many workers report, would have a relatively extensive ego network.

An example pertaining to this study: China and Germany have some of the most lithium carbonate trading partners in lithium trade networks (Chen et al. 2020; Tian et al. 2021). Were we to construct ego networks of China and Germany, we could say that China's and Germany's ego networks are relatively extensive compared to other countries in the network. Were we to find that China's and Germany's trading partners vary in terms of regional classification, income classification, and GDP, we could say that China's and Germany's ego networks are relatively diverse.

"Density" refers to "the extent to which all [nodes in a network] are connected by intense" ties (Burt 1978:90). To illustrate, take two network models of office administrators. The ties in the model represent "reports to." The first model is comprised of three administrators, *i*, *j*, and *k*; the second is comprised of three other administrators, *l*, *m*, and *n*. If the first model only has two ties ($j \rightarrow i$; $j \rightarrow k$) out of six possible ties; and if the second has ties back and forth (a total of six ties) between all administrators (*l*→*m*; *m*→*n*; *l*→*m; l*←*m*; *m*←*n*; *l*←*m*) then the second model would have a higher density compared to the first.[23] For an ego network, we would examine the ties between the ego and the alters, and the ties among the alters.

"Multiplexity" for an ego network refers to the extent to which an ego is connected to alters by multiple types of ties. This study only uses export ties for its networks. However, we could model networks using import ties, and foreign direct investment (FDI) (where a tie represents one country receiving FDI from another). If we were to model Argentina's ego network and find that Argentina is tied to its alters through exports, imports, *and* FDI, then we could say that Argentina has high multiplexity.

The Relational Approach to Multiple Actors as a Network Subgraph. The relational approach to multiple nodes as a network subgraph models a subset of ties and nodes within a network "who are connected to one another by strong [or cohesive ties] (Burt 1978:97) (the second cell in the first row of Table 1). According to Burt, the relational approach to network subgraphs is often concerned with cliques (1978:97) or a "maximally complete" subgraph of nodes (Borgatti et al. 2022:326). A "complete" subgraph means that every node in the subgraph has ties with one another. A "maximally complete" subgraph means no other node can be added to the subgraph without breaking the completeness of the subgraph. That is, the addition of a node would form only one or some ties with other nodes, but not ties with all other nodes. The "cohesion" of a group refers to "the extent that clique members prefer intraclique over interclique relations" (Burt 1978:98). If we were to model a network of friendships among students at a school, we might find cliques of students who prefer to spend time with their friends rather than other students.

[23] Though the second group of administrators might have difficulty sorting out a problem if everyone reports to everyone!

Cliques can be identified in international trade. Sun mentions that trade flows among the UK, South Africa, and Egypt in 1938 formed a clique (2002), and that trade cliques can contribute to separate, "autarkic" trade blocs like those of mercantilist European countries in the sixteenth century or Nazi Germany from 1933 to 1945 (Bondarenko 2023). However, the literature on international EV-LIB and lithium trade networks shows that more trade ties are forming between more countries over time (Sun et al. 2017; Tian et al. 2021), which runs counter to what might be expected were the trade characterized by cliques and blocs.

The Relational Approach to Multiple Actors/Subgroups as a Structured Network. The relational approach to the overall network structure models all present ties between all nodes in a network and is concerned with network density and transitivity (the third cell in the first row of Table 1) (Burt 1978:109). Like the density of an ego network, network density captures the extent to which nodes in a network have ties. However, the density of an ego network measures the present ties of an ego to its alters, whereas the network density measures the present ties between all nodes in a network.

"Transitivity" refers to "the tendency for a network to have transitive triples" or "triads" (Borgatti et al. 2022:198). For example, if we were to model a network of coworkers, where the ties in the model represent "likes," we might find a triad wherein coworker *a* likes coworker *b*, coworker *b* likes coworker *c*, and coworker *a* likes coworker *c* ($a \rightarrow b$; $b \rightarrow$c; $a \rightarrow c$). This is an example of a "directed triad." That is, there is a direction to which coworker likes which coworker. In an undirected network, transitivity is referred to as "closure" and can be interpreted as "the likelihood that a pair of [nodes] has [a relationship], given that they have a [node] in common" (Borgatti et al. 2022:198).

The densities of the two EV-LIB trade networks and the four lithium compound trade networks are reported in Chapter 3. As for transitivity, this study does not give analytical attention to it. That said, Borgatti et al. (2022) mention that proximity can be a contributing factor. For example, Tian et al. (2021) find that China, Japan, and South Korea trade EV-LIB materials (e.g., lithium carbonate); which they attribute to regionalized trade agreements and to reduced transportation costs because of the countries' close geographic proximity. Were we to analyze the triads in the trade networks, we could expect China, Japan, and South Korea to form a triad in the EV-LIB and lithium trade network.

Summary. The three relational models of networks aim to model the present ties—their types and their intensity—within a network. Taking a relational approach to international EV-LIB and lithium compound trade networks, we could analyze a wide array of network features—the intensity of trade ties, the multiplexity of the trade networks, and the tendency for certain countries to form trade cliques, triads, or closure. That said, though this study reports network features like density, this study does not take a relational approach to the international trade of EV-LIBs and lithium—rather, this study takes a positional approach.

Positional Approach to Social Network Analysis

A positional approach to network analysis focuses on the "pattern of [ties] defining an [nodes'] position in a system of [nodes]" (Burt 1978:80). Unlike the relational approach, a positional approach considers *all* ties in which a node is involved and is not involved. "Position" can refer to how central a node is, the status of a node's position, the prestige of a node's position, or the role a node serves. This approach especially lends itself to the analysis of differentiation, inequality, integration, and stratification in social networks.

Positional Approach to a Single Node. Like the relational approach, a "single node" can be a single person, a single family, a single business, a single country, and so on. Unlike the relational approach, the positional approach models a single node's position in a network by considering the ties that node has (i.e., that node's ego network) and all other ties in the network (the first cell in the second row of Table 1). A single node's position can be described in terms of centrality.

A node is in a central position in the network to the "extent that all [relationships] in the network involve" that node (Burt 1978:91). For example, the country that has the most lithium export ties would be the most central country in a network of lithium exports. This example is of degree centrality—a node-level measure of how central a node is, based on the number of ties the node has. That said, a single node's centrality can also be described in terms of betweenness, closeness, and eigenvector. This study uses betweenness, closeness, outdegree, indegree, and eigenvector centrality in Stage 1. Chapter 3 elaborates on each.

Positional Approach Multiple Nodes as a Network Subgraph. The positional approach to multiple nodes as a network subgraph models the "jointly occupied network position [of] a set of *structurally equivalent* [nodes] [emphasis added]" (the second cell in the second row of Table 1) (Burt 1978:100). Structural equivalence is the key concept here. "Structural equivalence" refers to a set of nodes "connected by the *same* [ties] to exactly the *same* [nodes] [emphasis added]" (Borgatti and Everett 1992). For example, if South Korea and Japan had the same EV-LIB export ties with the same trading partners, South Korea and Japan would be structurally equivalent. That said, finding two countries with the same trades with the same partners is unlikely (Muñiz 2013). As Borgatti and Everett mention, "The problem is that two nations that occupy the same position (say, 'core') may have similar relations with other positions (say, 'periphery'), but not necessarily the same nations" (1992:22). In practice, structural equivalence partitions a set of nodes into "mutually exclusive classes of equivalent [nodes that] have *similar* relational patterns [emphasis added]" (Borgatti and Everett 1992:3).[24]

Again, the task of this approach is to partition the status positions of structurally equivalent nodes. Nodes occupy status positions via the ties that "occur repeatedly in a system so as to constrain and give unique opportunities to the [nodes] involved in them" (Burt 1978:101). Informed by EUE theory and research, this study partitions countries into "core" and "peripheral" status positions in Stage 1. However, the network approach to core and peripheral status positions is a bit different than the definitions of core and periphery in the previous section. Chapter 3 elaborates.

The "unique opportunities" (Burt 1978:101) core and peripheral countries have, pertain to structural power and structural dependence. According to power-dependence theory, how much power a node has and how dependent a node is on other nodes in a network, are, in part, functions of the pattern of relations in the network and how central the nodes are (Cook et al. 1983; Beckfield 2003). Put simply, power and dependence are not an attribute of a node; "power [and dependence are] the [properties] of social relations" (Emerson 1962:32).

For example, a node with a high degree centrality (i.e., a node with a high number of ties) will have the "power to easily access resources and information from other nodes *because of its central position* [emphasis added]" (Hafner-Burton, Kahler, and Montgomery 2009:570). Additionally, a node with a high degree centrality is less dependent on any one tie. Should the node have 25 ties, and should one tie break, the node still has 24 ties through which it can give and receive what flows through the ties (e.g., disease, disruption, information, resources, etc.).

[24] Sometimes referred to as "regular equivalence" (Vesia et al. 2021:4).

Relatedly, a node that has a high betweenness centrality—that is, a node that falls between many other pairs of nodes—would have the power to "bridge or broker" or control the interactions between other nodes (Hafner-Burton et al. 2009:571).

In sum, the positional approach to multiple nodes as a network subgraph is taken in Stage 1. This approach models countries' positions in the international EV-LIB and lithium trade networks (core and peripheral) as a function of a network's pattern of relations. Countries "jointly occupying" the core position will have more ties compared to countries "jointly occupying" the peripheral position. Core countries will be more central in the network compared to peripheral countries. And core countries will have more power and will be less structurally dependent, compared to peripheral countries.

The Positional Approach to Multiple Actors/Subgroups as a Structured Network. The final approach models "the overall structure of networks" (the third cell of the second row in Table 1) (Burt 1978:116). The previous approach is important for modeling countries' jointly occupied positions. This approach is important for modeling the "centralization" of the network.

"Centralization" refers to the extent to which all ties in a network structure "involve a single [node];" and describes "inequality in the extent to which [nodes] are involved in [ties]" in the overall network (Burt 1978:116-117). This study uses centralization in Stage 1. Doing so, this study can speak to inequality in the overall structure of international EV-LIB and lithium trade networks. Centralizations measure the overall structure of a network in terms of a given centrality (e.g., betweenness, closeness, degree, eigenvector, etc.) (Freeman 1979; Bienenstock and Bonacich 2021; Borgatti et al. 2022). Chapter 3 elaborates.

CHAPTER 3: DATA, SAMPLE, & METHODS

This chapter covers my data, sampling, and method choices. The first section details the network data used in Stage 1 and Stage 2; and the nodal attribute data used in Stage 2. The second section details my sampling criteria and presents the samples for each network. The third section details Stage 1. Stage 1 directly addresses research question 1: What do the structures of international EV-LIB and lithium compound trade networks look like? The final section details Stage 2. Stage 2 directly addresses research question 2: What determines the formation of international EV-LIB and lithium compound trade network structures?

DATA

Network Data

I downloaded bilateral trade data from the United Nations Commodity Trade and Statistics (UN COMTRADE) Database. The UN COMTRADE database is compiled by the UN Statistics Division and contains data from approximately 200 countries on a wide array of commodities (UN COMTRADE n.d.). I downloaded data on the value (in US dollars) of electric lithium-ion accumulator (commodity code: HS 850760) exports from UN COMTRADE to construct two directed Lithium-ion Battery Trade Networks (EV-LIBTNs). I downloaded data on the value (in US dollars) of lithium carbonate (commodity code: HS 283691) and lithium oxide and hydroxide (commodity code: HS 282520) exports from UN COMTRADE to construct four directed Lithium Compound Trade Networks (LCTNs).

Codes and Commodities. I selected Harmonized System (HS) codes because the HS classifies commodities by the materials that make up those commodities. HS classifications, therefore, allow for the specification of EV-LIBs by components and lithium commodities by chemical properties. I selected the HS code for lithium-ion accumulators (i.e., rechargeable lithium-ion batteries)[25] (HS 850760) because the code represents products (e.g., electric vehicle batteries) that have driven global lithium demand over the last decade and that are projected to drive global lithium demand for years to come (IEA 2022a; 2022b; 2022c; 2023). I selected the HS codes for lithium carbonate[26] (HS 283691) and lithium oxide and hydroxide[27] (HS 282520) because the codes represent the most used lithium compounds for EV-LIBs (Weimer, Braun, and vom Hemdt 2019; Shao, Kou, and Zhang 2022). Lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH) are processed precursors to the anode,[28] cathode,[29] and electrolyte[30] materials (e.g., lithium iron phosphate, lithium cobalt oxide) in EV-LIBs. I selected the codes for lithium carbonate and lithium oxide and hydroxide because the codes also represent the lithium that is traded (Shao, Hu, and Zhang 2021). Recall that lithium does not exist in a free or "raw" state in nature. Rather it found in brines and ores that are processed into lithium compounds which are subsequently traded. For example, lithium is carbonated in solar evaporation ponds during lithium brine recovery; the carbonation produces technical-grade lithium carbonate.[31]

Export Value. Consistent with prior research on lithium supply and demand and EV-LIB and lithium trade networks (Olivetti et al. 2017; Liu et al. 2021; Shao et al. 2022) and research

[25] For a full list of what the HS 850760 code for lithium-ion batteries represents, see Taric Support (n.d.c).

[26] For a full list of what the HS 283691 code for lithium carbonate represents, see Taric Support (n.d.a).

[27] For a full list of what the HS 282520 code for lithium hydroxide represents, see Taric Support (n.d.b).

[28] The negative electrode that generates lithium-ions.

[29] The positive electrode that receives lithium-ions.

[30] The solid or liquid medium for lithium-ion transfer between the anode and the cathode. The ion transfer between the anode and electrode through the electrolyte generates the energy that powers lithium-ion devices.

[31] Technical-grade lithium carbonate is lithium carbonate that contains trace amounts of other chemicals. Additional processing is required to produce battery-grade lithium carbonate.

on ecological unequal exchange (Shandra, Leckband, and London 2009; Austin 2010; Austin 2012; Noble 2017; Sommer 2020), I selected export data. However, some researchers use export volume/weight data (Chen et al. 2020; Wu et al. 2021; Yang et al. 2021), while others use export value data (Olivetti et al. 2017; Liu et al. 2021). Similar Liu et al. (2021), I used export value data to account for price fluctuations[32] in lithium carbonate and lithium hydroxide that have occurred over the last decade.[33]

Nodal Attribute Data

I downloaded World Bank data on countries' regional classification, income classification, and GDP for my country (nodal) attribute data.[34] Regional classifications include the following: East Asia and the Pacific; Europe and Central Asia; Latin America and the Caribbean; Middle East and North Africa; North America; South Asia; and Sub-Saharan Africa. Income classifications are defined by gross national income per capita (in US dollars) and are calculated with the World Bank Atlas Method (World Bank n.d.b.). Income classifications include the following: High Income ($13,205 or more in 2021); Upper-Middle Income ($4,256 – $13,205 in 2021); Lower-Middle Income ($1,086 - $4,255 in 2021), and Lower Income ($1,085 or less in 2021). Gross domestic product is in 2015-constant US dollars.

In Stage 2, countries' regional classification, income classification, and GDP serve as parameters. The region attribute serves as a parameter for regional *homophily*: the tendency for countries in the *same* region to trade EV-LIBs and lithium compounds with each other. The

[32] For example, the average annual price per ton of lithium carbonate averaged 13,940 US dollars (USGS 2022) between 2017 and 2021 but jumped to 37,000 US dollars in 2022 (USGS 2023).

[33] Shao et al. (2021) note that trade value can also account for trade volume/trade weight.

[34] I use the Stata module "wbopendata" downloading nodal attribute data from World Bank databases (World Bank n.d.a).

income attribute serves as a parameter for developmental *homophily*: the tendency for countries in the *same* income group to trade EV-LIBs and lithium compounds with each other. The GDP attribute serves as a parameter for developmental *heterophily*: the tendency for countries with *different* GDPs to trade EV-LIBs and lithium compounds with each other. In other words, Stage 2 estimates the likelihood of tie formation between two countries, given countries regional classification, income classification, and GDP.

Additionally, I generated nodal attribute data on each country's core-periphery position in each network by applying a discrete core-periphery model (Borgatti and Everett 1999) to the network data. The model codes each country as core or peripheral by accounting for each country's trades/ties or lack thereof with other countries. Peripheral countries (coded 0) trade EV-LIBs and lithium compounds to core countries but not to other peripheral countries; core countries (coded 1) trade EV-LIBs and lithium compounds to core and peripheral countries. The model also provides a network-level measure of the core-periphery structure of a given network—important for Stage 1. In Stage 2, the core-periphery attribute serves as a parameter for structural *homophily*: the tendency for countries in the *same* structural position to trade EV-LIBs and lithium compounds with each other. In other words, Stage 2 estimates the likelihood of tie formation between two countries, given their core-periphery classification.

SAMPLE

Sampling Criteria

I imposed three sampling criteria to construct the samples for the two directed EV-LIBTNs and four directed LCTNs. First, I included network data from 2012-2020 for the EV-LIBTN samples and I included network data from 2000-2020 for the LCTN samples. Second, I excluded specific reporters and partners from all network samples. Lastly, I excluded trades (ties) valued less than 10,000 US dollars from all network samples.

Periods. I selected the 2000-2020 period for the LCTN samples to observe whether structural changes in the LCTNs (e.g., changes in the number of nodes, changes in the number of ties, etc.) reflect recent increases in global lithium demand and trade. Based on the trade networks literature, we can expect to find the number of participating countries and the number of export ties to increase over time. I divided the 2000-2020 period into four subperiods to maximize cross-national coverage and to minimize annual changes in export value: 2000-2004; 2005-2009; 2010-2014; and 2015-2020. In other words, I created four LCTNs that correspond to four subperiods. I selected the 2012-2020 period for the EV-LIBTNs and divided it into two subperiods for the same reasons as those for the 2000-2020 period: 2012-2014; and 2015-2020. In other words, I create two EV-LIBTNs corresponding to two subperiods. The difference between the 2000-2020 period for the LCTN samples and the 2012 – 2020 period for the EV-LIBTN samples, is due to data availability; trade data on EV-LIBs prior to 2012 was not available from the UN COMTRADE database.

Excluded Reporters and Partners: The UN COMTRADE database includes reporters and partners such as “All,” “World,” “and “Free Zones.” In the database, countries report exports of commodity to “partner” countries. The inclusion of network data for such reporters and partners would skew the networks. For example, “World” would likely be a core node in the networks because nearly every country reports EV-LIB trades and lithium compound with the “World.” The database also includes reporters and partners such as “[Former Democratic Republic] of Germany,” “[Former] USSR,” and “[Former] Yugoslavia.” Given the periods, it is not meaningful to examine, for example, trades between the former USSR (1917/22-1991) and

Afghanistan. Such countries would likely not have reported exports, so the exclusion of them is a redundancy measure to ensure a clean sample. Altogether, I excluded a total of 66 reporters and 102 partners from the EV-LIBTN and LCTN samples.

Excluded Trades: Finally, some countries report exports of a nonzero amount (in kilograms) of EV-LIBs and lithium compounds, but a zero in trade value for those exports.[35] As such, I excluded export values less than 10,000 US dollars to ensure that only significant trades and many countries are included in the EV-LIBTN and LCTN samples.

EV-LIBTN & LCTN Samples

The final EV-LIBTN and LCTN samples are shown in Table 2. The network data constitute the countries/nodes and trades/ties in each network sample. To illustrate, take the 2000-2004 LCTN sample. If Australia exports lithium compounds (valued at 10,000 or more US dollars) to Canada between 2000 and 2004, then Australia and Canada are included as two separate nodes in the 2000-2004 LCTN sample; and the export from Australia to Canada is included as one (directed) tie in the 2000-2004 LCTN sample.

Generally, the number of nodes N in the EV-LIBTNs and LCTNs increases over time: 11 countries join the EV-LIBTN during the 2012-2020 period; 24 countries join the LCTN during the 2000-2020 period. This confirms findings from the trade networks literature (Sun et al. 2018; Tian et al. 2021) that more countries are forming more trade relationships over time. More countries participate in EV-LIB trade than lithium compounds trade. This may be, in part, because downstream products like EV-LIBs and EVs will be in demand from more countries compared to intermediate products like lithium compounds.

There is no change in N between the 2005-2009 LCTN and the 2010-2014 LCTN.

[35] This discrepancy might be due to reporting errors in the database.

Table 2: Node and Tie Counts for EV-LIBTNs and LCTNs

	Nodes N	Ties e	Possible Ties	Density
EV-LIBTNs				
2012 – 2014 EV-LIBTN	179	2150	31862	0.0675
2015 – 2020 EV-LIBTN	190	3611	35910	0.1006
LCTNs				
2000 – 2004 LCTN	85	397	7140	0.0556
2005 – 2009 LCTN	100	464	9900	0.0469
2010 – 2014 LCTN	100	458	9900	0.0462
2015 – 2020 LCTN	109	678	11722	0.0578

Note: Density for directed networks is calculated by e / (possible ties) where possible ties = $n(n - 1)$.

Additionally, e decreases by 6 from the 2005-2009 LCTN to the 2010-2014 LCTN. The decrease in e—however slight—might be due to countries ceasing lithium compound exports during the 2007-2008 financial crisis, which increased exportation costs (Grosjean et al. 2012; Martin et al. 2017).

Otherwise, e in the EV-LIBTNs and LCTNs increases over time: 1,461 ties form in the EV-LIBTN during the 2012-2020 period; 281 ties form in the LCTN during the 2000-2020 period. Additionally, the density (i.e., e expressed as a proportion of the potential ties) of the EV-LIBTNs increases during the 2012-2020 period but remains low. The density of the LCTN remains relatively stable and low during the 2000-2020 period. Low density means that the countries in the networks are sparsely connected.

STAGE 1: DESCRIPTIVE NETWORK ANALYSIS

In Stage 1, I generate network graphs of each EV-LIBTN and LCTN. I then centralize countries' centrality scores to calculate network-level measures for each EV-LIBTN and LCTN. Finally, I use the discrete core-periphery model to measure each EV-LIBTN and LCTN. My goal is to measure, describe, and illustrate structural dependencies in the EV-LIBTNs and LCTNs. In other words, Stage 1 directly addresses RQ1: What do the structures of and the structural inequality in international EV-LIB and lithium compound trade networks look like?

EV-LIBTN and LCTN Graphs

I generate two network graphs corresponding to the two EV-LIBTNs, and four network graphs corresponding to the four LCTNs. I use the graphs to visualize the direction of exports (indicated by the arrows on the ties), and the core-periphery structure of each network. I also use the graphs to point out examples of core and peripheral countries in the EV-LIBTNs and LCTNs.

Centralization

Centralizations measure the overall structure of a network in terms of centrality (Freeman 1979; Bienenstock and Bonacich. 2021; Borgatti et al. 2022). Centralization indexes node-level centrality to measure the extent to which all ties in the network involve a single country, or the extent to which an observed network "resembles a star" (Borgatti et al. 2022: 205) (Figure 1).

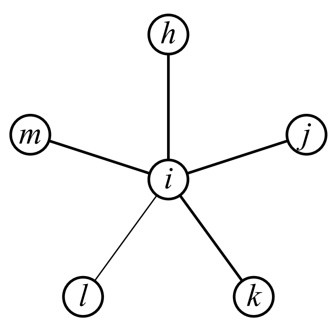

Figure 1: Ideal Star Network ($N = 6$; $e = 5$)

The general equation for centralization is (Freeman 1979):

$$C_{\mathrm{x}} = \frac{\sum_{i=1}^{g} C_{\mathrm{x}}(\mathrm{n}^{*}) - C_{\mathrm{x}}(\mathrm{n}_i)}{\max \sum_{i=1}^{N}\big(C(\mathrm{n}_{*})\big) - (C(\mathrm{n}_i)} \tag{1}$$

or:

$$C_{\mathrm{x}} = \frac{\sum_{i=1}^{g} C_{\mathrm{x}}(\mathrm{n}^{*}) - C_{\mathrm{x}}(\mathrm{n}_{i})}{[(N-1)(N-2)]} \tag{2}$$

where $C_{\mathrm{x}}(\mathrm{n}_i)$ is the centrality for one node; and $C_{\mathrm{x}}(\mathrm{n}^*)$ is the largest value of $C_{\mathrm{x}}(\mathrm{n}_i)$ for any node in the network. That is, centralization divides the sum of the differences between each node's centrality and the centrality of the most central node in an observed network (the numerator), from the maximum *possible* sum of the differences (the denominator). The larger the ratio, the more similar the observed network is to an ideal star network of the same size N, *in terms of a given centrality* (betweenness, closeness, degree, eigenvector, etc.).

To illustrate, take the following Y-shaped network:

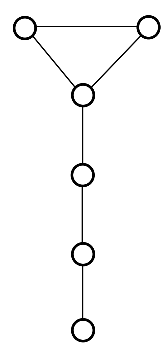

Figure 2: Y-shaped Network ($N = 6$; $e = 6$)

We can calculate the *degree* centralization for this network by starting with the degree centrality (i.e., a node-level measure of the number of ties a node has) of the most central node, which is equal to three. Then, we sum the differences: (3 – 3) + (3 – 2) + (3 – 2) + (3 – 1) + (3 – 1) + (3 – 1) = 8. Next, we calculate the maximum: (6 – 1) (6 – 2) = 20. Finally, we divide the sum of the differences from the maximum: 8 / 20 = 0.4. *In terms of degree*, 0.4 suggests that the most central node in the Y-shaped network has a moderately similar number of ties to what would be observed in an ideal star network of the same size *N* (in this case, size of six) (Figure 1). In other words, the Y-shaped network is moderately like an ideal star network in terms of degree.

Centralization requires a—and in principle can be done for any—measure of centrality (e.g., betweenness, closeness, degree, eigenvector, etc.). In this study, I use betweenness, closeness, degree, and eigenvector centrality. A description of each centrality follows.

Betweenness. Betweenness centrality is a node-level measure of the number of times a given node falls along the shortest path between two other nodes (Freeman 1979; Borgatti et al. 2022). The following equation (Borgatti et al. 2022) for node *i* can be used to calculate a betweenness centrality score:

$$b_i = \sum_{h=i=j} \frac{g_{hij}}{g_{hj}}, \tag{3}$$

where g_{hij} is the number of paths node *i* falls between node *h* and node *j*, and g_{hj} is the total number of paths connecting node *h* and node *j*. Betweenness centrality scores can be interpreted in terms of flow control; that is, how much control a given node has over the flows between other pairs.

In this study, a country's betweenness centrality score measures the number of trades between two other countries that a given country falls along. To illustrate, if an LCTN were to have an ideal star structure (Figure 1),[36] and if country *i* was in the center of the network, then country *i* would fall along every lithium compound trade between every other pair of countries. We could, therefore, interpret country *i* to have the potential to control lithium compound trades between all other countries *h*, *j*, *k*, *l*, and *m*.

[36] To be clear, ideal stars are unlikely to be empirically observed.

Closeness. Closeness centrality is a node-level measure of the sum of the geodesic distances for a given node (Freeman 1979; Borgatti et al. 2022). "Geodesic distance" refers to the length of the shortest path between one node to another node. A "path" is a series of adjacent nodes and ties that do not loop. For example, a tie between node *i* and node *j*; and a tie between node *j* and node *k*; form the path *i*—*j*—*k* (Borgatti et al. 2022). The sum of the geodesic distances for each node is normalized by dividing $N - 1$ from the sum, providing a closeness centrality score. Larger scores indicate that other nodes in the network are relatively close to the given node. Closeness centrality scores can be interpreted in terms of the minimum amount of time and distance it takes for something from a given node to reach another.

In this study, closeness centrality scores indicate the sum of the lengths of trade from one country to others. To illustrate, if country *i* in an LCTN has a high closeness centrality score, then country *i* is a relatively short *geodesic distance*[37] to other countries in the network and could, therefore, receive lithium compounds more quickly. Compared to a country with a low score, country *i* would be in a more advantageous[38] position in the LCTN.

Degree. Degree centrality is a node-level measure of the number of ties a given node has (Freeman 1979; Borgatti et al. 2022). For directed networks, degree centrality should be split into outdegree and indegree. Outdegree centrality is a node-level measure of the number of outgoing ties a given node has. Indegree centrality is a node-level measure of the number of incoming ties a given node has. The reason outdegree and indegree centrality should be used for directed networks, is because there may be asymmetry between the number of the outgoing ties

[37] Not to be confused with geographic distance.

[38]To be clear, high closeness centrality scores do not always translate to "advantage." Advantage depends, in part, on what is flowing through a network. For example, if we were studying actors' disease-exposure risks, we might conclude that an actor with a high closeness centrality score would not be in an advantageous position compared to an actor with a low closeness centrality score.

and the number of incoming ties a given node has (Borgatti et al. 2022). In other words, degree centrality measures the total number of ties and, therefore, might bias conclusions about a given node's structural position within a directed network.

In this study, a country's outdegree centrality score and indegree centrality score measures the number of exports from and the number exports to that country, respectively. To illustrate, if country *i* in an LCTN has an outdegree centrality score of one, then country *i* would only have one trade with one other country *j*. In this scenario, the outdegree centrality score for country *i* indicates that it is structurally dependent on country *j*; country *i* only has one partner to which it can export lithium compounds. If country *i* has a score of three, then country *i* would have three trades with three other countries *j, k*, and *l*. In this scenario, the outdegree centrality score for country *i* indicates that it is less structurally dependent on country *j*; country *i* has two other partners to which it can export lithium compounds.

Eigenvector. Eigenvector centrality is a node-level measure of the number of nodes adjacent to a given node (similar degree). However, the adjacent nodes are weighted by their centrality. The following equation (Borgatti et al. 2022) for node *i* can be used to calculate an eigenvector centrality score:

$$e_i = \frac{1}{\lambda}\sum_{j} x_{ij} e_j \tag{4}$$

where *e* is the eigenvector centrality score and λ (lambda) is the eigenvalue (i.e., a proportionality constant). According to Borgatti et al., "the equation basically says that each node's centrality (e_i) is proportional to the sum of centralities (the e_j) of the nodes it is adjacent to (i.e., where x_{ij} = 1)—in effect [,] a node is only as central as its alters" (2022:173). In terms of flow, eigenvector centrality scores can be interpreted as a measure of how much *potential* a node has for its flows (e.g., disease, disruption, information, resources, etc.) to reach other nodes in the network.[39] In terms of connection, a node with a high eigenvector centrality score is connected to many other well-connected nodes.

In this study, a given country's eigenvector centrality score measures how well-connected it is to other well-connected countries. To illustrate, if country *i* and country *k* in an LCTN have a degree centrality score of one, then both countries only have one partner with which they can trade lithium compounds: partner *j* for country *i*; partner *l* for country *k.* However, if *j* has a degree centrality of three, and if *l* has a degree centrality of zero, then *i* would have a higher eigenvector centrality score than *k*. In this scenario, country *i* has a greater potential to export and import lithium compounds to other countries in the LCTN and is connected to a better-connected country.

The Most Central Node in an Ideal Star Network. Again, centralization divides the sum of differences between each node's centrality and the most central node's centrality in an observed network, by the maximum possible sum of differences. In other words, the centrality of the most central node in an observed network is compared to the centrality of the most central node in an ideal star network of the same size *N*. As such, we can measure the extent to which he extent to which all ties in a network structure "involve a single [node];" and describes "inequality in the extent to which [nodes] are involved in [ties]" in the overall network (Burt 1978:116-117). Table 3 provides a description of the most central node in an ideal star network in terms of each centrality measure.

[39] To be clear, my use of eigenvector is not to trace the flow of lithium compounds and EV-LIBs; it is only to measure the structure of the networks in terms of the potential for lithium compounds and EV-LIBs from one country to reach any number of others. That is, though there are methods to trace material flows (e.g., material flow analysis), doing so is not an aim of this study.

Table 3: Description of Most Central Node in an Ideal Star Network by Centrality

Centrality Measure	Description
Betweenness	The most central node would fall along *every* path between *all* other pairs.
Closeness	The most central node would be *equally* close to *all* other nodes.
Outdegree	The most central node in an ideal *out-star* network (i.e., an ideal star network in which all ties are outgoing from the most central node) would have outgoing ties to *all* other nodes.
Indegree	The most central node in an ideal *in-star* network (i.e., an ideal star network in which all ties are incoming to the most central node) would have incoming ties from *all* other nodes.
Eigenvector[40]	The most central node in an ideal *out-star* network would have the highest *potential* for its flows to reach other nodes.

Core-Periphery Model

The discrete core-periphery model creates the core-periphery attribute data. It also produces an unnormalized, core-periphery, Pearson correlation coefficient as a network-level measure of how similar an observed network is to an ideal star network (i.e., an ideal core-periphery network) (Figure 1). The model relies on the following equations for coding the countries and for calculating the correlation coefficient (Borgatti and Everett 1999):

$$\rho = \sum_{i,j} \alpha_{ij}\delta_{ij} \tag{5}$$

[40] Eigenvector centralization can be tricky. In an ideal (undirected) star, the most central node may not have the highest eigenvector score, because, again, eigenvector measures a given node's centrality as a function of its alters' centrality. If node *i* is the center of the star and node *j* is an alter to *i*, then *j* might actually have a higher eigenvector centrality score because it is directly connected to a *well-connected* node through which flows from *j* could *potentially* reach other nodes in the star (Ruhnau 2000; Butts n.d.). Using an out-star for the theoretical maximum of the sum of differences ameliorates this problem because node *j* now only has an incoming tie from node *i*. There is no potential for a flow from node *j* to reach any other node in the network; whereas node *i* has the highest potential for its flows to reach all other nodes.

$$\delta_{ij} = \begin{pmatrix} 1 \text{ if } c_i = \text{CORE or } c_j = \text{CORE} \\ 0 \text{ otherwise} \end{pmatrix} \tag{6}$$

where α_{ij} is the presence or absence of a tie in the observed network; δ_{ij} is the presence or absence of a tie in the ideal star network; and c_i is the code to which node i is assigned. The coefficient ρ indicates how similar the observed network is to the ideal star network (i.e., an ideal core-periphery structure) of the same size N. The closer the coefficient is to one, the more similar the observed network is to an ideal star network.

STAGE 2: EXPONENTIAL RANDOM GRAPH MODELS

In Stage 2, I estimate exponential random graph models (ERGMs) of the observed EV-LIBTNs and LCTNs to test the extent to which regional classification, income classification, GDP, and core-periphery position determine the formation of ties in the LCTNs and EV-LIBTNs. In other words, Stage 2 directly addresses RQ2: What determines the formation of international EV-LIB and lithium compound trade network structures and structural inequality?

What are ERGMs?

An ERGM is a probability model for social networks. ERGMs belong to the $p*$ class of probability models for social networks.[41] The $p*$ class "[expresses] each relational tie as a stochastic [or random] function of actor or network structural properties" (Wasserman and Pattison 1996: 403). Specifically, ERG modeling uses maximum likelihood estimation to generate a probability distribution of random networks from a starting set of parameters (i.e., nodal or network properties). The random networks are then compared to the observed network, allowing one to determine whether the presence of a tie between two nodes in the observed

[41] For descriptions of the $p*$ class of probability models, see Anderson, Wasserman, and Crouch (1999) and Wasserman and Pattison (1996).

network—the dependent variable in an ERGM—occurs more or less than what would be expected by statistical chance (Robins et al. 2007; Broekel et al. 2014; Block, Stadtfeld, and Snijders 2019; Borgatti et al. 2022). The results of an ERGM indicate the highest possible likelihood that a given set of parameters generates an observed network structure. A more technical description of ERGMs follows.

The General Form of ERGMs

The general form of an ERGM is (Robins et al. 2007:178):

$$\Pr(Y = y) = \left(\frac{1}{k}\right) \exp\left\{\sum_{A} \eta_A g_A(y)\right\} \tag{7}$$

where (*i*) the summation is over all possible configurations *A*; (*ii*) η_A is the parameter for the corresponding configuration *A*; (*iii*) $g_A(y)$ is the network statistic for the corresponding configuration *A* of the observed network graph *y* and is defined as (Robins et al. 2007: 179):

$$gA(y) = \prod\nolimits_{yij \in A} y_{ij} \tag{8}$$

If the network statistic equals 1, configuration *A* is observed in network *y*; if the network statistic equals 0, configuration *A* is not observed in the network *y*; (*iv*) *k* is a normalizing constant and is defined as (Broekel et al. 2014:434):

$$k = \sum_{y} exp\left\{\sum_{A} \eta_A g_A(y)\right\} \tag{9}$$

k is necessary because it ensures that (7) is a probability distribution. Therefore, $Pr(Y = y)$ represents the probability that the observed network graph *y* is also observed in the probability distribution of the random network graphs Y, as a function of the network statistic $g_A(y)$ and the parameters η_A for all permitted configurations A.

Why ERGMs? Network-Level Analysis and the Dependence Assumption

I use ERGMs for two reasons: (1) compared to other *p** models such as stochastic actor-oriented models (SOAMs), ERGMs are network-oriented.[42] That is, whereas the results of a SOAM indicate the likelihood that a specific node's or actor's behavior generates a change in an observed network (Broekel et al. 2014); ERGM results indicate the highest possible likelihood that a given set of parameters generates an observed network. The network orientation of ERGMs is important because this study is directed at analyzing the overall structure of trade networks.

(2) ERGMs assume structural dependence. The dependence assumption holds that the presence of a tie between two nodes in an observed network, depends on the presence of other ties *and/or* the attributes of those two nodes. For example, country *i* exporting lithium compounds to country *j* may be "conditionally dependent" (Robins et al. 2007:179) on its exports to other countries, its regional classification, its income classification, its GDP, and its core-periphery position.[43] The dependence assumption is important because it allows the inclusion of network parameters and nodal parameters that can be controlled for when analyzing attribute and edge effects on the formation of ties.

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[42] There are other notable differences and similarities between ERGMs and SOAMs. For descriptions, see Block, Stadtfeld, and Snijders (2019) and Broekel et al. (2014).

[43] In contrast, the independence assumption that characterizes the *p1* class of probability models for social networks, would assume country *i* exports lithium batteries to country *j* independent of its trade relationships with other countries, its regional classification, its income classification, its GDP, and its core-periphery position. For a description of the *p1* class of probability models for social networks, see Holland and Leinhardt (1981).

The dependence assumption is also important for limiting parameters and, thereby, for limiting the number of configurations possible in an ERGM. Configurations are subsets of a network and can refer to a single tie between two nodes, a reciprocal tie between two nodes, two-stars, three-stars, triads, triangles, and more (Robins et al. 2007). Each configuration corresponds to a parameter. For example, a density parameter for a directed network would correspond to the following configuration: country *i* exports lithium compounds to country *j*. Given a set of parameters from the observed network graph, ERG modeling simulates configurations to generate the random networks; given too many parameters, too many configurations are simulated, and an ERGM cannot be estimated from the observed network.

However, under the dependence assumption, parameters have a nonzero value only if the independent variables in a configuration are assumed to be conditionally dependent; conversely, parameters are zero whenever variables in a configuration are conditionally independent. In other words, the dependence assumption ensures that the configurations in the ERGM are "those in which all possible ties [] are mutually contingent on each other" (Robins et al. 2007:179).

CHAPTER 4: DESCRIPTIVE NETWORK ANALYSIS

This chapter presents the results from the first stage of the analysis. I present network graphs of the electric vehicle lithium-ion battery trade networks (EV-LIBTNs) and the lithium compound trade networks (LCTNs). After showing the visualizations of the networks, I estimate and present the betweenness, closeness, degree, and eigenvector centralizations for the LCTNs and LIBTNs. Lastly, I estimate and present the core-periphery correlation coefficients. Overall, the goal is to illustrate and measure the structural inequality in the trade networks. In other words, I address the first research question: What do the structures of international EV-LIB and lithium compound trade networks look like? From an EUE perspective, we can expect to find distinct core-periphery partitions in the trade networks, by which certain countries occupy a dense center of the networks and certain countries occupy a sparse periphery of the networks.

NETWORK GRAPHS

Figures 3-8 are network graphs of the EV-LIBTNs and LCTNs. The arrows on the ties indicate the direction of an export tie (i.e., who exports to whom). Roughly, the nodes within the inner circle are core countries and the nodes between the inner and outer circles are peripheral countries. Peripheral countries have export ties, but only to core countries, placing them in the margins of the graphs. Core countries have export ties with other core and peripheral countries, placing them in the center of the graphs. For full lists of core and peripheral countries, refer to Appendices 7-12.

Overall, the graphs show far more countries with far more ties in the EV-LIBTNs compared to the LCTNs, illustrating the network densities reported in Chapter 3. This may be, in part, because final, downstream products like EV-LIBs and EVs will be in demand from more

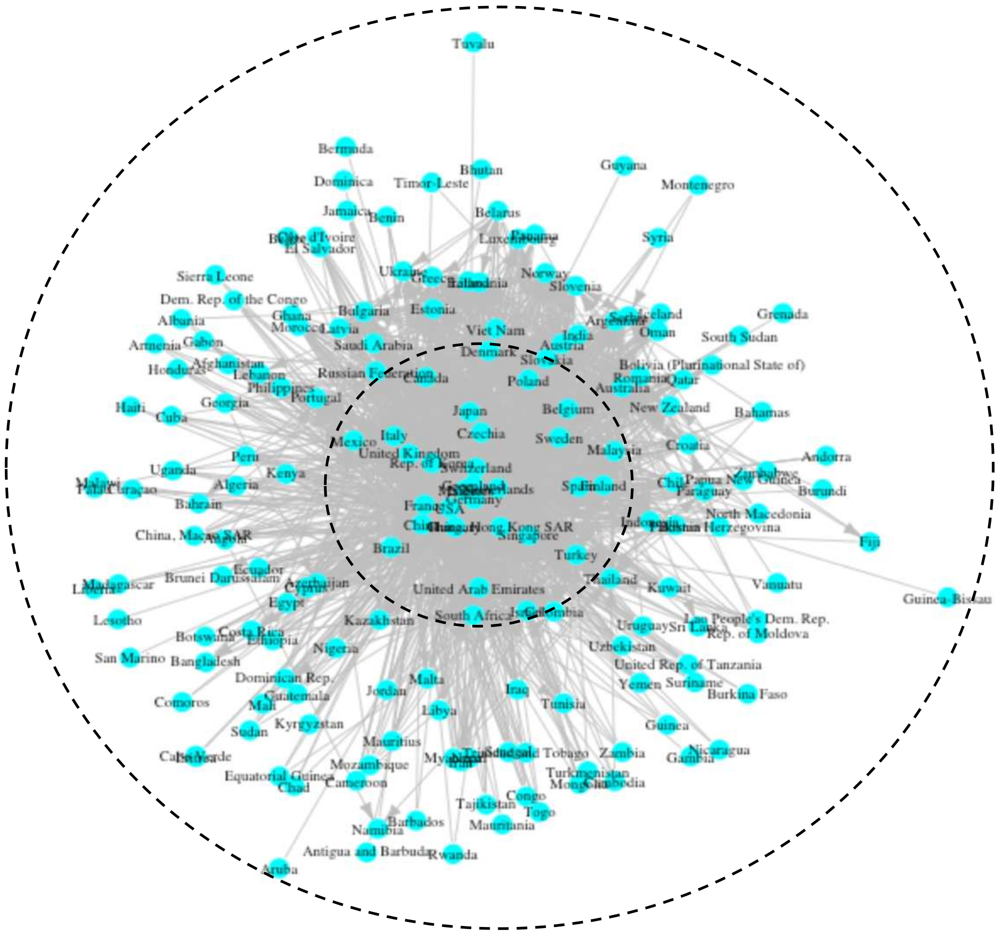

Figure 3: 2012-2014 EV-LIBTN Graph

Notes: Number of Core Countries: 31; Number of Peripheral Countries: 148; Total Number of Countries: 179; Total Number of Trades: 2150

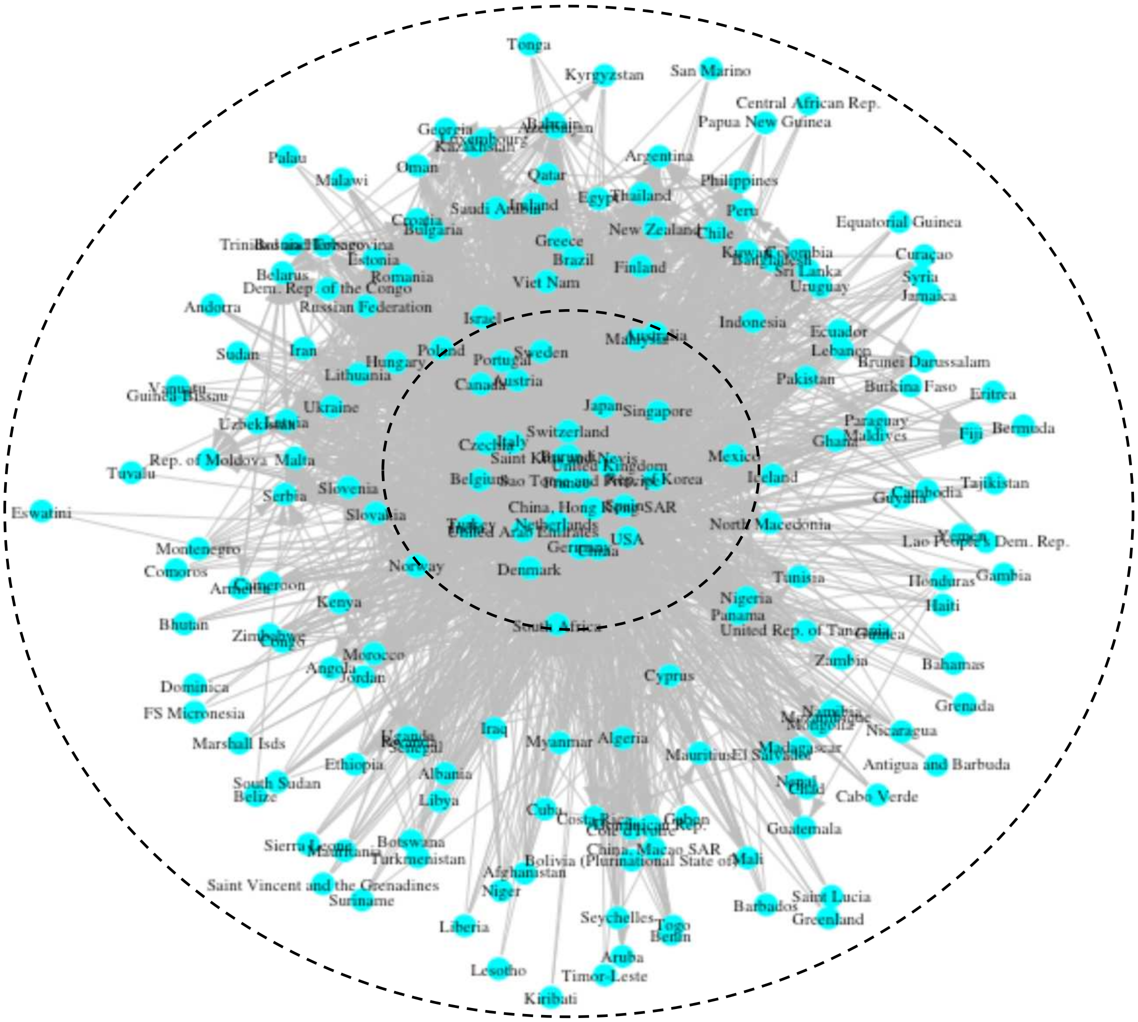

Figure 4: 2015-2020 EV-LIBTN Graph
Notes: Number of Core Countries: 41; Number of Peripheral Countries: 149; Total Number of Countries: 190; Total Number of Trades: 3611

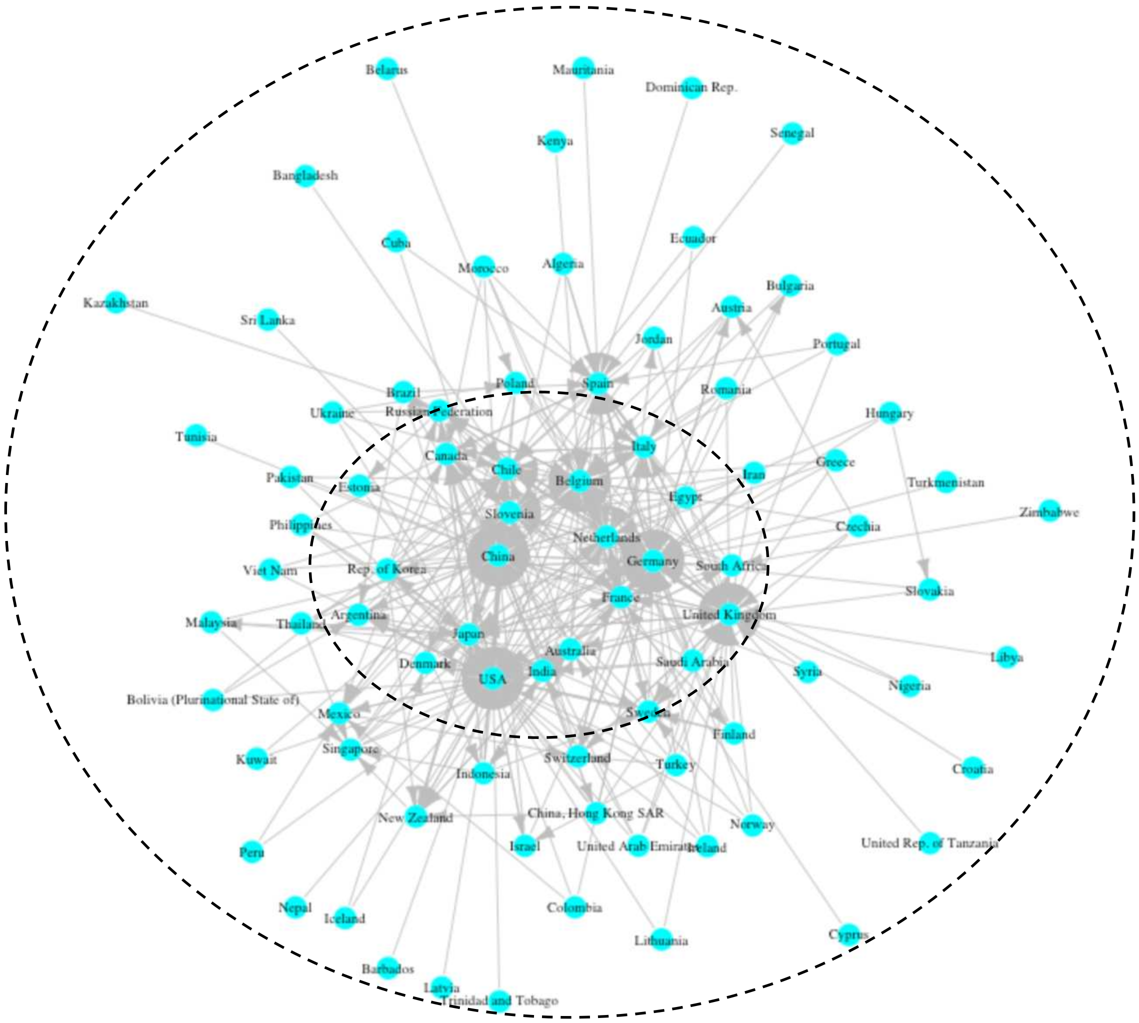

Figure 5: 2000-2004 LCTN Graph
Notes: Number of Core Countries: 12; Number of Peripheral Countries: 73; Total number of Countries 85; Total Number of Trades: 397

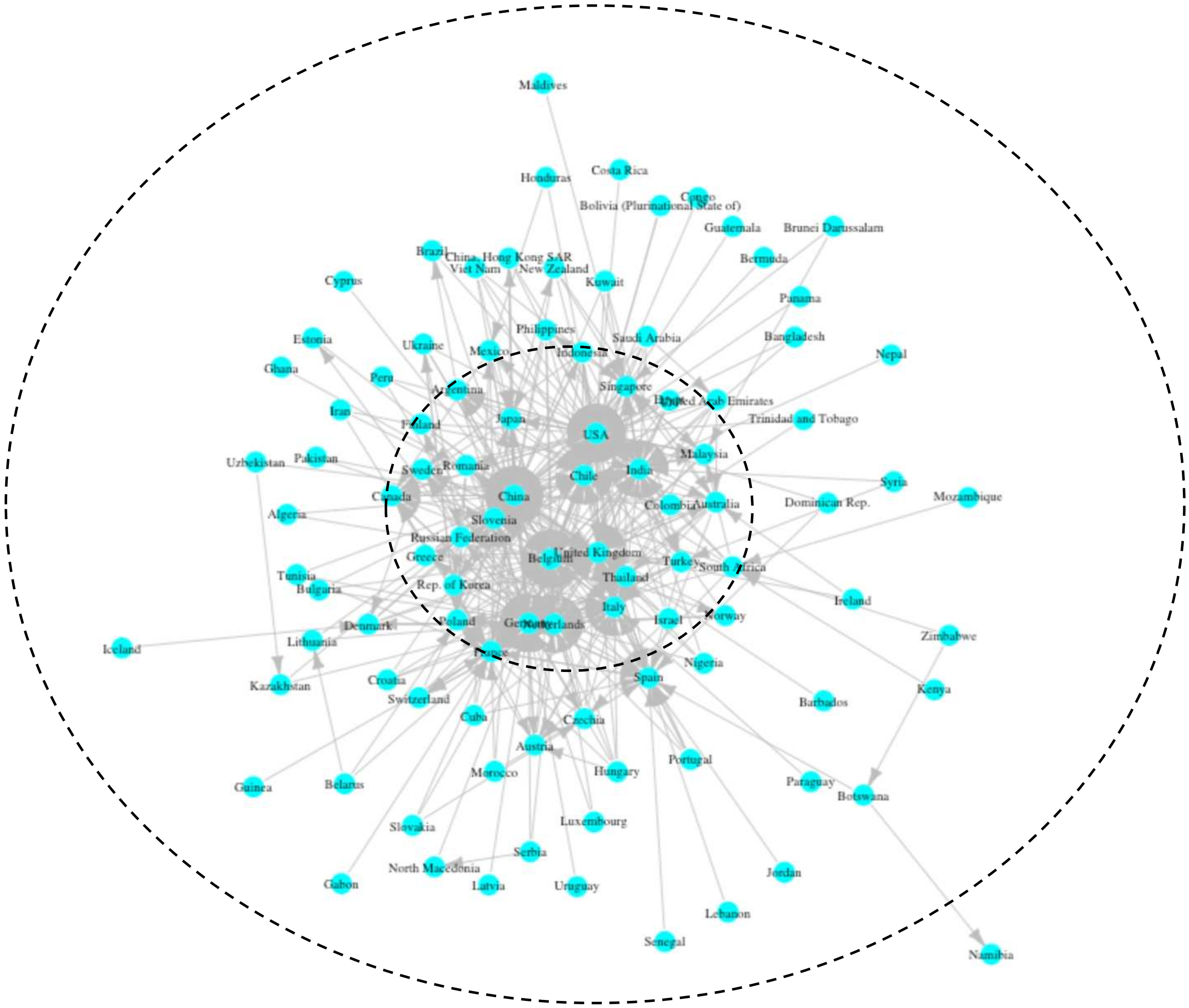

Figure 6: 2005-2009 LCTN Graph
Notes: Number of Core Countries: 15; Number of Peripheral Countries: 85 Total Number of Countries: 100; Total Number of Trades: 464

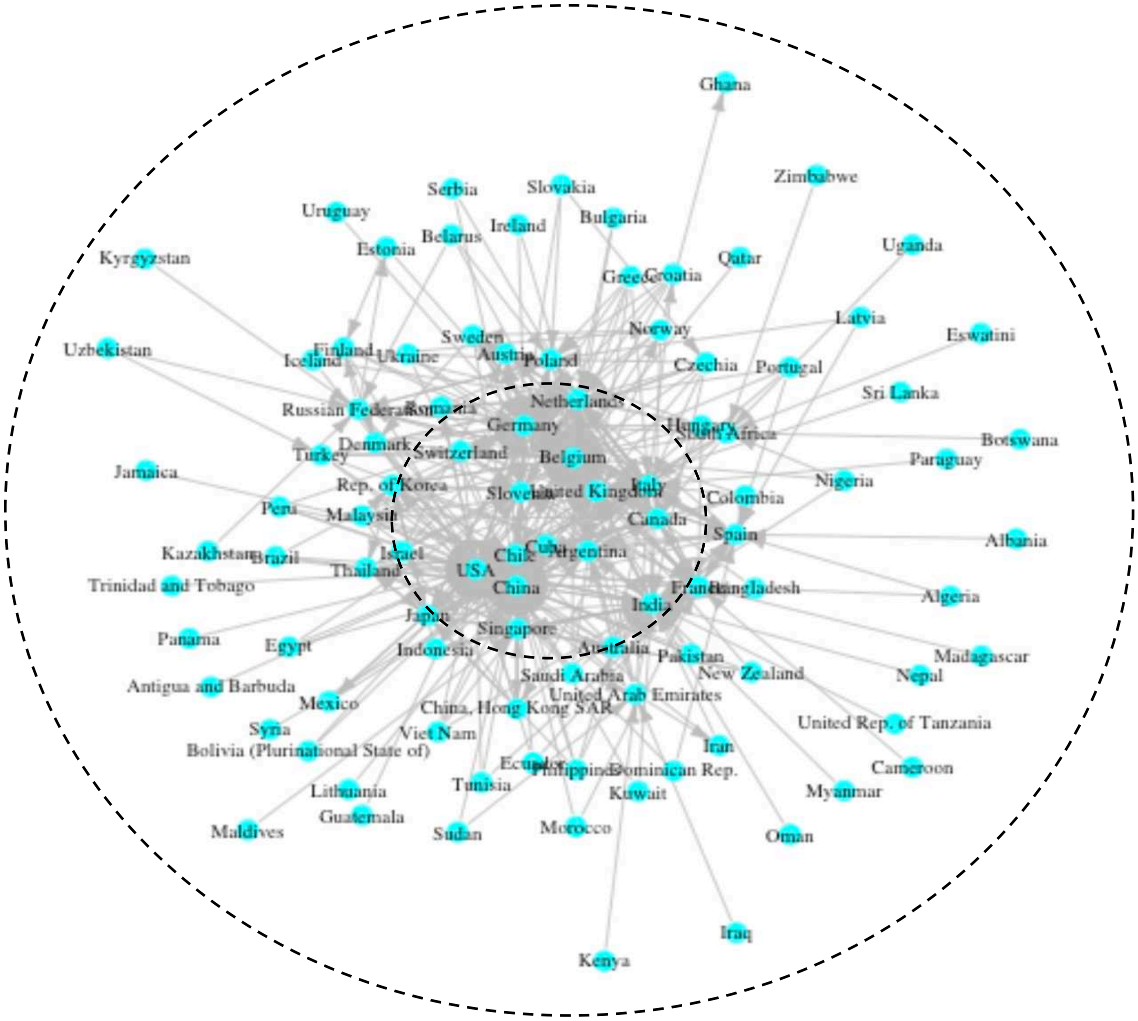

Figure 7: 2010-2014 LCTN Graph
Notes: Number of Core Countries: 16; Number of Peripheral Countries: 84; Total Number of Countries: 100; Total Number of Trades 458

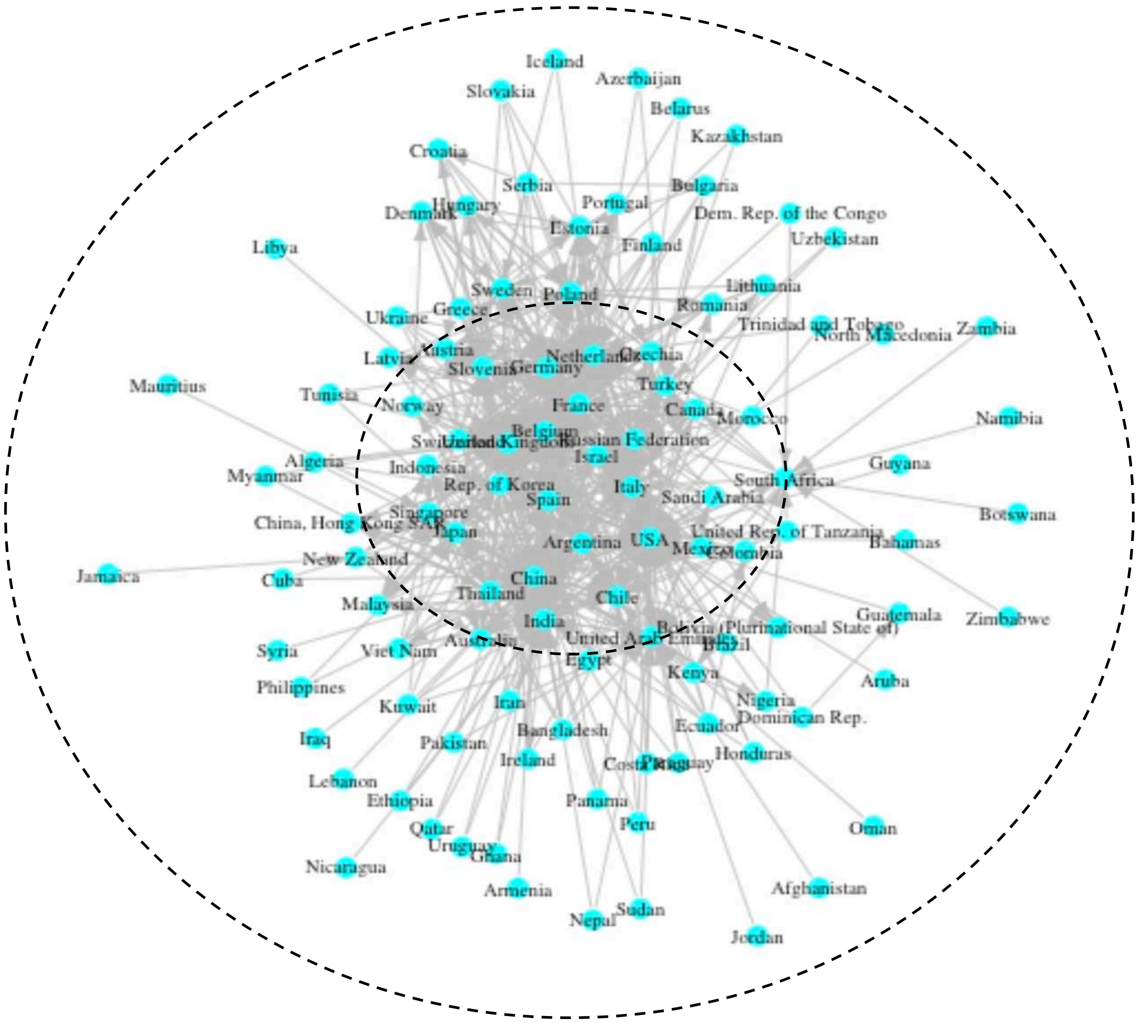

Figure 8: 2015-2020 LCTN Graph
Notes: Number of Core Countries: 18; Number of Peripheral Countries: 91; Total Number of Countries: 109; Total Number of Trades: 678

countries compared to intermediate products like lithium compounds.

Notable core countries in the EV-LIBTN graphs include China, Germany, and the US. These core countries—among few others—maintain their position from the 2012-2014 period to the 2015-2020 period. China, Germany, and the US maintaining their core position is expected. These countries have sizeable EV(-LIB) production capacity and/or EV(-LIB) *demand*; and are shown in the trade networks literature to be central in the EV-LIB and lithium trade networks (Chen et al. 2020; Liu et al. 2021; Shao et al. 2021; Tian et al. 2021). China, Germany, the US, and other core countries have many ties (outdegree and indegree) in the EV-LIBTNs and tend to have more indegree ties than outdegree ties.

Given China's dominance in the EV-LIB supply chain (IEA 2022a; 2022b; 2022c), it would not be unreasonable to expect the country to lead the EV-LIBTNs in the number of outdegree ties—the idea being that because EV-LIB production predominantly occurs in China, a significant number of countries (will have to) import from China. However, though China is a leading exporter, it is not *the* leader. The US has the most outdegree ties of any country in the EV-LIBTNs: 47 in the 2012-2014 period; 69 in the 2015-2020 period. This is unexpected. One possible explanation: China leads the world in EV sales (IEA 2022a). In 2021, EV sales in China were 3.3 million; 1 million more than all of Europe and approximately five times more than the US. As such many of the EV-LIBs that assumingly would be exported to many other countries may, instead, be used in domestic EV production. That said, China does rank in the top five countries in both periods, with 35 outdegree ties in the 2012-2014 period, and 52 in the 2015-2020 period.

Notable peripheral countries in the EV-LIBTN graphs include Argentina, Bolivia, and Chile. These countries—among many others—maintain their peripheral position from the 2012-

2014 period to the 2015-2020 period. Argentina, Bolivia, and Chile maintaining their peripheral position is expected, in part, because these countries have little (to no) EV(-LIB) production capacity and EV(-LIB) *demand*. Peripheral countries have few ties (outdegree and indegree) and tend to have more outdegree ties than indegree ties.

Notable core countries in the LCTN graphs also include China, Germany, and the US. These countries—among few others—maintain their core position from the 2000-2004 period to the 2015-2020 period. China, Germany, and the US maintaining their core position is expected in These countries have significant industrial (automotive; computer and electronics) *demand* for lithium compounds; and are shown in the trade networks literature to be central in the EV-LIB and lithium trade networks (Chen et al. 2020; Liu et al. 2021; Shao et al. 2021; Tian et al. 2021). China, Germany, the US, and other core countries have many ties, and tend to have more indegree ties than outdegree ties.

Additionally, Chile—the country with the third most known lithium resources (confirmed and estimated deposits) in the world (USGS 2023)—maintained a core position from the 2000-2004 period to the 2015-2020 period. And like other core countries, Chile's outdegree ties are fewer than its indegree ties in every LCTN period. This is unexpected. Chile accounts for a significant portion of the total international lithium carbonate trade volume (IEA 2022c). Though much of that volume moves through a small number of export ties or trade relationships, it is reasonable to have expected Chile to still have more outdegree ties than indegree ties. Two possible explanations: Chile may have industrial demand for lithium compounds that it attempts to meet through more lithium compound imports; and/or Chile may handle lithium compounds as they move from country to country. That is, Chile may be an important transit country, through which more countries send lithium compounds to Chile, which are then sent to fewer countries. Regarding the latter explanation, Chile does have relatively middling betweenness centrality scores throughout the periods, meaning that the country falls along a moderate number of trades between countries. For example, in the 2010-2014 LCTN, Chile fell along 42 trades between other countries.

Notable peripheral countries in the LCTN graphs are Bolivia, Brazil, and Portugal—countries in which lithium mine production is located (BGS 2021). These countries—among many others—maintain their peripheral positions from the 2000-2004 period to the 2015-2020 period. Peripheral countries have few ties and tend to have more outdegree ties than indegree ties.

Bolivia is an interesting peripheral country in the LCTNs. Bolivia—the country with the most known lithium resources in the world (USGS 2023)—is in a peripheral position, in part, because the country does not exceed a total of five trade ties (outdegree and indegree)—all of which to core countries—in any of the graphs. That is, the most trade ties Bolivia has in any of the graphs is five (the 2015-2020 graph). In the last period, Bolivia exported lithium to China, the Russian Federation, and the US, with China receiving the most lithium carbonate in terms of value (USD) and volume (kg). This suggests that the export tie between Bolivia and China is Bolivia's strongest/most intense of all its export ties and that Bolivia has a dependence on China for lithium exports. The partnership between Bolivia and China will likely become stronger. In late January of 2023, the Bolivian government signed a one-billion-dollar deal with Chinese lithium-mining and LIB-producing companies, with lithium exports expected to start in 2025 (Bouchard 2023).[44]

[44] That said whether most of the lithium produced by these companies will actually go to China is still a question, according to Bouchard (2023).

CENTRALIZATIONS

Recall, centralization measures the extent to which all ties in a network involve a single node and is a measure of structural inequality. The larger the ratio, the more similar the observed network is to a core-periphery structure (i.e., an ideal star network) of the same size *N*, *in terms of a given centrality* (betweenness, closeness, degree, eigenvector, etc.).

Table 4 shows the centralizations for the EV-LIBTNs.

Table 4: Centralized Measures of EV-LIBTNs

EV-LIBTNs	Betweenness	Closeness	Outdegree	Indegree	Eigenvector
2012 – 2014 EV-LIBTN	0.0865	0.2403	0.1977	0.8248	0.7848
2015 – 2020 EV-LIBTN	0.0895	0.2453	0.2659	0.8670	0.7406

The betweenness closeness, and outdegree centralizations are low and relatively stable. In terms of betweenness, there are trades (core to core; peripheral to core) in the EV-LIBTNs between which core countries do not fall, meaning that there are trades that core countries do not have the ability to broker or control. In terms of closeness, there are core and peripheral countries in the EV-LIBTNs to which other core countries are geodesically distant, meaning the connections between all countries in the network are far apart or sparse. And in terms of outdegree, core countries do not have outdegree ties with all or most other core and peripheral countries. However, the outdegree centralization increases between the 2012-2014 period and the 2015-2020 period, suggesting that core countries may be forming more outdegree ties with other core and peripheral countries in the EV-LIBTNs, particularly with peripheral countries given the slight decrease in the eigenvector centralization from the 2012-2014 period to the 2015-2020 period.

Indegree and eigenvector centralizations are high. The results in Table 4 indicate that, in terms of indegree, the most central country in the EV-LIBTNs has an indegree centrality like what would be observed in an ideal in-star network. That is, there are core countries in the EV-LIBTNs that have many indegree ties with other core and peripheral countries. In terms of eigenvector, core countries tend to be connected with other well-connected core countries in the EV-LIBTNs.

Table 5 shows the centralizations for the LCTNs.

Table 5: Centralized Measures of LCTNs

LCTNs	Betweenness	Closeness	Outdegree	Indegree	Eigenvector
2000 – 2004 LCTN	0.0982	0.2001	0.1365	0.5581	0.7941
2005 – 2009 LCTN	0.0957	0	0.1465	0.5036	0.8131
2010 – 2014 LCTN	0.0658	0	0.1165	0.4634	0.8160
2015 – 2020 LCTN	0.1067	0.2070	0.1755	0.5400	0.8032

Like the results in Table 4, the betweenness, closeness, and outdegree centralizations are low and relatively stable. In terms of betweenness, there are trades in the LCTNs between which core countries do not fall, meaning there are trades that core countries do not have the ability to broker or control. In terms of closeness, there are core and peripheral countries in the LCTNs to which other core countries are geodesically distant, meaning the connections between all countries in the network are far apart or sparse. The closeness centralizations were so low for the 2005-2009 and 2010-2014 period, that no ratio was found within four decimal places. That is, the connections among core countries and the connections between core and peripheral countries are extremely sparse during the two periods. In terms of outdegree, core countries do not have outdegree ties with all or most other core and peripheral countries.

Like the results in Table 4, indegree and eigenvector centralizations are high. The results in Table 5 indicate that, in terms of indegree, core countries in the LCTNs have many indegree ties with other core and peripheral countries. However, compared to the indegree centralizations in Table 4, the indegree centralizations in Table 5 are lower, suggesting that core countries in the

LCTNs have fewer partners from which they receive lithium compounds, *compared to* core countries' partners in the EV-LIBTNS. In terms of eigenvector, there are core countries in the LCTNs that are connected to other well-connected core countries. Furthermore, compared to the eigenvector centralizations in Table 4, the eigenvector centralizations in Table 5 are a bit higher, suggesting that there are even more connections between core countries and other well-connected core countries in the LCTNs, *compared to* those connections in the EV-LIBTNs.

CORE-PERIPHERY CORRELATION COEFFICIENTS

Recall, the discrete core-periphery model compares the observed network to an ideal core-periphery structure (i.e., an ideal star network) of the same size *N* to produce unnormalized, core-periphery, Pearson correlation coefficients. The coefficients indicate how similar the observed network is to an ideal star network—the larger the coefficient, the more similar.

Table 6 shows the core-periphery correlation coefficients for the EV-LIBTNs.

Table 6: Core-Periphery Correlation Coefficients for Lithium-ion Battery Trade Networks (EV-LIBTNs)

EV-LIBTNs	Correlations
2012 – 2014 EV-LIBTN	0.8312
2015 – 2020 EV-LIBTN	0.8529

The results in Table 6 indicate that the overall structures of EV-LIBTNs are quite like a core-periphery structure. The correlations are high and relatively stable from the 2012-2014 period to the 2015-2020 period. Furthermore, the change between periods, however slight, indicates the core-periphery structure of international EV-LIB trade became more pronounced. Though the number of trading countries and the number of trades may have increased between 2012-2020, the core-periphery structure persisted.

Table 7 shows the core-periphery correlation coefficients for the LCTNs.

Table 7: Core-Periphery Correlation Coefficients for Lithium Compound Trade Networks (LCTNs)

LCTNs	Correlations
2000 – 2004 LCTN	0.6568
2005 – 2009 LCTN	0.6481
2010 – 2014 LCTN	0.6590
2015 – 2020 LCTN	0.6932

The results in Table 7 indicate that the overall structures of the LCTNs are like a core-periphery structure. The correlations are high and relatively stable through the periods. Furthermore, the change in the correlations from 2000 to 2020, though slight, indicates the core-periphery structure became more pronounced. Though the number of trading countries and the number of trades may have changed between 2000 and 2020, the core-periphery structure persisted. That said, the correlations are lower than those in Table 6.

DISCUSSION

The results in Tables 4-7 indicate that the overall structures of international EV-LIB and lithium compound trade are characterized by a core-periphery pattern. A small number of (developed) countries occupy the center of EV-LIB and lithium compound trade and a large number of (less developed) countries occupy the margins. These structures are reflected in the network graphs and, according to Tables 6 and 7, have persisted over time. There are some signs that the core-periphery structure of international EV-LIB trade may become less pronounced. The outdegree centralization increased and the eigenvector centralization decreased between the two EV-LIBTN periods. This suggests that core countries are exporting EV-LIBs to more peripheral countries. However, the changes are relatively small and took place over eight years. Furthermore, though core countries may be exporting EV-LIBs to more peripheral countries, the overall core-periphery structure of EV-LIB trade became more pronounced over time according to Table 6. The same can be said the LCTNs. The core-periphery pattern of the EV-LIB and lithium compound trade networks is evidence of structural inequality in the international trade of EV-LIBs and lithium compounds.

The structural inequality in both the EV-LIBTNs and LCTNs lies in the closeness, outdegree, indegree, and eigenvector centralizations. The closeness centralizations in Tables 4 and 5 indicate that core and peripheral countries are sparsely connected. Were the networks closer, we would expect to see more trade ties and more core countries in the networks. Taking the closeness and eigenvector centralizations together, the close connections that are in the networks primarily reside among core countries rather than between core and peripheral countries. In other words, the international EV-LIB and lithium compound trade largely occurs among core countries. Peripheral countries might supply EV-LIBs and lithium compounds to core countries, but once those EV-LIBs and lithium compounds reach those core countries, they are either kept by or further traded among core countries.

The outdegree and indegree centralizations in Tables 4 and 5 indicate that core countries tend to import more EV-LIB and lithium compounds rather than export while periphery countries are more likely to export than import. That is, core countries are the primary drivers of global demand for EV-LIB and lithium compounds and peripheral countries are the primary suppliers. Taking the degree centralizations and eigenvector centralizations together, whatever the number of outdegree ties and indegree ties core countries have, most are with other core countries. This is particularly important for the LCTNs. Recall that lithium compounds are often processed during the extraction process before they are exported, and recall that the extraction process has environmental consequences such as water depletion, water pollution, and air pollution. As such, peripheral countries that extract lithium primarily for export like Bolivia, may be engaged in an ecologically unequal exchange with the core countries to which they export. That is, such peripheral countries may be subject to environmental degradation because of extracting lithium for export but may not be receive downstream products like LIBs and EVs.

Core countries also have more trade ties compared to peripheral countries in both the EV-LIB and lithium compound trade networks. Core countries are able export, import, and—given the difference between their exports and imports—keep EV-LIBs and lithium compounds from many other countries participating in EV-LIB and lithium compound trade. Peripheral countries have fewer avenues to export, import, and keep EV-LIBs and lithium compounds. As such, peripheral countries are more structurally dependent on their trade relationships, compared to core countries.

Peripheral countries' structural dependence suggests that core countries can set the terms of trade; not necessarily by controlling the trade relationships between peripheral countries and other core countries, but by taking advantage of the few trade relationships that peripheral countries have. As a result, peripheral countries may be more willing to make price concessions to core countries and may be more willing to take on the socio-ecological detriments of EV-LIB and lithium production and trade, to maintain the few trade relationships they have. Some peripheral countries may be able to take advantage of core countries' flow dependencies—that is, dependence on the value and volume of the EV-LIBs and lithium compounds that move through trade relationships. Bolivia may have few lithium export relationships, but Bolivia moves a significant amount of lithium through those relationships. Were Bolivia to restrict its export volume, countries like China might not be able to meet their lithium demand as they were prior to the export restrictions. However, export restrictions could hurt Bolivia just as much as—if not more than—China, given Bolivia's small number of export relationships and China's large number of import relationships. Additionally, given more countries' recent investments in lithium mining, processing, and production (Riofrancos 2022), core countries' flow dependence on a few countries like Bolivia, may not be as intense in the near future. Flow dependence aside, the concentration of trade among core countries (indicated by the eigenvector centralization), suggests that peripheral countries' taking advantage of core countries' *structural* dependencies—what few they may have—may be difficult at best.

CHAPTER 5: EXPONENTIAL RANDOM GRAPH MODEL ESTIMATION

The results in the previous chapter indicate that the overall structures of the electric vehicle lithium-ion battery trade networks (EV-LIBTNs) and lithium compound trade networks (LCTNs) are characterized by a core-periphery pattern. In this chapter, I aim to explain the formation of those structures. This chapter directly addresses the second research question: What determines the formation of global lithium compound trade networks and the formation of global LIB trade networks? I present the results of the exponential random graph models (ERGMs) for the EV-LIBTNs and LCTNs. Recall, an ERGM is a probability model for social networks that compares an observed network to randomly generated networks of the same size *N*. ERGM results indicate the highest possible likelihood that a given set of parameters (regional classification; income classification; GDP; structural/status position) generates the formation of a tie and, therefore, the formation of an observed network structure.

The ERGM tables include three models. Model 1 estimates the likelihood of tie formation between two random countries in the networks. Given the sparseness of the networks found in Stage 1, we would expect the likelihood of tie formation between two random countries to be low. Were the networks dense, we would expect to observe a higher likelihood of tie formation between two random countries in the network.

Model 2 estimates the effects of country/nodal attributes (regional classification; income classification; GDP) on the homophilic and heterophilic likelihood of tie formation for a group (e.g., South Asia) compared to a reference group (East Asia and the Pacific). The region attribute serves as a parameter for regional *homophily*: the tendency for countries in the *same* region to trade EV-LIBs and lithium compounds with each other. The income attribute serves as a parameter for developmental *homophily*: the tendency for countries in the *same* income group to trade EV-LIBs and lithium compounds with each other. The GDP attribute serves as a parameter for developmental *heterophily*: the tendency for countries with *different* GDPs to trade EV-LIBs and lithium compounds with each other.

Finally, Model 3 adds the parameter for structural homophily: the tendency for countries in the *same* structural/status position to trade EV-LIBs and lithium compounds with each other. Given the eigenvector centralization results in the previous chapter, we would expect to observe regional homophily and developmental homophily. We would also expect to observe high structural homophily among core countries *compared to* the structural homophily among peripheral countries. That said, from an EUE perspective, we would expect to observe high regional homophily among countries in Latin America, the Middle East and North Africa, South Asia, and Sub-Saharan Africa (i.e., countries in the Global South); and low regional homophily among countries in Europe and Central Asia and North America (i.e., countries in the Global North); *compared to* the regional homophily of East Asia and the Pacific. Additionally, we would expect to observe low developmental homophily among low-income and lower-middle-income countries; and roughly the same developmental homophily among upper-middle-income countries; *compared to* the developmental homophily of high-income countries. Finally, we would expect to find relatively high developmental heterophily, or a high likelihood of tie formation between countries with different GDPs.

RESULTS

2012-2014 EV-LIBTN

Table 8 shows the ERGM results for the 2012-2014 EV-LIBTN.

Table 8: Exponential Random Graph Model of 2012-2014 EV-LIBTN

Variables	Model 1	Model 2	Model 3
Ties	0.0732*** (0.0224)	0.5017*** (0.0882)	0.0215*** (0.1358)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		0.9569 (0.0494)	1.0327 (0.0565)
Latin America and Caribbean		0.2214*** (0.0765)	0.4820*** (0.0854)
Middle East and North Africa		0.3563*** (0.0783)	0.7869** (0.0854)
North America		0.1920*** (0.1538)	0.3279*** (0.1452)
South Asia		0.5760*** (0.1333)	0.9338 (0.1408)
Sub-Saharan Africa		0.3260*** (0.0930)	0.6305*** (0.1006)
Developmental Homophily High Income (Reference)			
Low Income		0.0978*** (0.1358)	0.1792*** (0.1402)
Lower Middle Income		0.1915*** (0.0711)	0.3899*** (0.0801)
Upper Middle Income		0.4070*** (0.0469)	0.6773*** (0.0546)
GDP		1.0002*** (0.0000)	1.0002*** (0.0000)
Core-Periphery Homophily Periphery (Reference)			
Core			13.5583*** (0.0693)
Model Fit AIC	15691	10951	8778
BIC	15699	11043	8878

Notes: Node count: 190; Tie count: 5587; Significance: <0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

Model 1 estimates the likelihood of tie formation between two random countries. The coefficient can be converted to a probability—in this instance, 0.0682. That is, the likelihood of tie formation between two random countries in the 2012-2014 is 6.82 percent, confirming the sparseness of the network found in Chapter 4. Were the 2012-2014 EV-EV-LIBTN dense, we would expect to observe a higher likelihood of tie formation between two random countries in the network. The Akaike information criterion (AIC) and the Bayesian information criterion (BIC) near the bottom of the table, measure how well the model fits the data. The lower the AIC and BIC, the better the fit. In Model 1, the AIC is 15691 and the BIC is 15699. If the AIC and BIC decrease from Model 1 to Model 2, and from Model 2 to Model 3, then we are achieving better model fit as we add nodal attributes.

Model 2 adds the regional and developmental attributes. Controlling for ties, developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2012-2014 EV-LIBTN. That said, countries in South Asia are more likely to form within-group ties (37 percent) compared to countries in East Asia and the Pacific. Countries in the Middle East and North Africa are more likely to form within-group ties (26 percent) compared to countries in East Asia and the Pacific. So on, for countries in Sub-Saharan Africa (25 percent); countries in Latin America and the Caribbean (18 percent); and countries in North America (16 percent). According to Model 2, there is no significant difference between the likelihood of tie formation among countries in Europe compared to East Asia and the Pacific; and there is no significant difference between the likelihood of tie formation among countries in Central Asia compared to East Asia and the Pacific.

Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for every income group for the 2012 – 2014 EV-LIBTN. That said, upper-middle-income countries are more likely to form within-group ties (29 percent) compared to high income countries. Lower-middle-income countries are more likely to form with-in group ties (16 percent) compared to high-income countries, and low-income countries are more likely to form within-group ties (9 percent) compared to high-income countries.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. The AIC is 10951 and the BIC is 11043, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (93 percent) compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4. The AIC is 8778 and the BIC is 8878, indicating that Model 3 has a better fit compared to Model 2 and Model 1.

2015-2020 EV-LIBTN

Table 9 shows the ERGM results for the 2015-2020 EV-LIBTN. Model 1 estimates the likelihood of tie formation between two random countries. The likelihood of tie formation between two random countries in the 2015-2020 EV-LIBTN is 10.15 percent, confirming the sparseness of the network found in Chapter 4 *and* the increase in density between the 2012-2014 EV-LIBTN to the 2015-2020 EV-LIBTN (see Table 2). In Model 1, the AIC is 23344 and the BIC is 23352.

Model 2 adds the regional and developmental attributes. Controlling for ties,

Table 9: Exponential Random Graph Model of 2015-2020 EV-LIBTN

Variables	Model 1	Model 2	Model 3
Ties	0.1130*** (0.0176)	0.5423*** (0.0745)	0.0233*** (0.1115)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		1.2995*** (0.0413)	1.0759 (0.0476)
Latin America and Caribbean		0.2997*** (0.0413)	0.5197*** (0.0653)
Middle East and North Africa		0.5932*** (0.0590)	1.0137 (0.0665)
North America		0.2218*** (0.1272)	0.3513*** (0.1238)
South Asia		0.8932 (0.0931)	0.7424** (0.1048)
Sub-Saharan Africa		0.4607*** (0.0645)	0.6182*** (0.0705)
Developmental Homophily High Income (Reference)			
Low Income		0.1430*** (0.0864)	0.3702*** (0.0930)
Lower Middle Income		0.2240*** (0.0518)	0.5571*** (0.0609)
Upper Middle Income		0.3995*** (0.0375)	0.7269*** (0.0451)
GDP		1.0002*** (0.0000)	1.0002*** (0.0000)
Core-Periphery Homophily Periphery (Reference)			
Core			14.2250*** (0.0561)
Model Fit AIC	23344	16845	13434
BIC	23352	16939	13536

Notes: Node count: 190; Tie count: 3611; Significance: <0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

Developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2015-2020 EV-LIBTN. That said countries in Europe and Central Asia are more likely to form within-group ties (57 percent) compared to countries in East Asia and the Pacific. Countries in the Middle East and North Africa are more likely to form within-group ties (37 percent) compared to countries in East Asia and the Pacific. So on for Sub-Saharan Africa (32 percent), Latin America and the Caribbean (23 percent) and North America (18 percent). According to Model 2, there is no significant difference between the likelihood of tie formation among countries in South Asia and the likelihood of tie formation among countries in East Asia and the Pacific.

Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for every income group for the 2015-2020 EV-LIBTN. That said, upper-middle-income countries are more likely to form within-group ties (27 percent) compared to high-income countries. Lower-middle-income countries are more likely to form within-group ties (18 percent) compared to high-income countries. And low-income countries are more likely to form within-group ties (13 percent) compared to high-income countries.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. The AIC is 16845 and the BIC is 16939, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (93 percent) compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4. The AIC is 13434 and the BIC is 13536, indicating that Model 3 has a better fit than Model 2 and Model 1.

2000-2004 LCTN

Table 10 shows the ERGM results for the 2000-2004 LCTN. Model 1 estimates the likelihood of tie formation between two random countries in the 2000-2004 LCTN. The likelihood of tie formation between two random countries in the 2000-2004 LCTN is 5.61 percent, confirming the sparseness of the network found in Chapter 4. Again, were the 2000 – 2004 LCTN dense, we would expect to observe a higher likelihood of tie formation between two random countries in the network. In Model 1, the AIC is 3068 and the BIC is 3075.

Model 2 adds the regional and developmental attributes. Controlling for ties, developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2000-2004 LCTN. That said, countries in Europe and Central Asia are more likely to form within-group ties (42 percent) compared to countries in East Asia and the Pacific. Countries in Latin America and the Caribbean are more likely to form within-group ties (29 percent) compared to countries in East Asia and the Pacific. So on for Sub-Saharan Africa (27 percent), North America (26 percent), and the Middle East in North Africa (26 percent). According to Model 2, there is no significant difference between the likelihood of tie formation among countries in South Asia and the likelihood of tie formation among countries in East Asia and Pacific Islands.

Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for nearly every income group for the 2000-2004 LCTN. That said, upper-middle-income countries are more likely to form within-group ties (41 percent)

Table 10: Exponential Random Graph Model of 2000-2004 LCTN

Variables	Model 1	Model 2	Model 3
Ties	0.0589*** (0.0516)	0.1666*** (-0.1861)	0.0242*** (0.2585)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		0.7146** (0.1056)	0.6607*** (0.1214)
Latin America and Caribbean		0.4083*** (0.1610)	0.4396*** (0.1720)
Middle East and North Africa		0.3492*** (0.1796)	0.5903** (0.1934)
North America		0.3563** 0.3464	0.3716*** (0.2545)
South Asia		0.7775 (0.3032)	0.9837 (0.3153)
Sub-Saharan Africa		0.3747*** (0.2929)	0.4721* (0.3036)
Developmental Homophily High Income (Reference)			
Low Income		0.2941 (0.7422)	0.3819 (0.7500)
Lower Middle Income		0.3076*** (0.2074)	0.5502** (0.2221)
Upper Middle Income		0.6918*** (0.1061)	1.1331 (0.1209)
Developmental Heterophily GDP		1.0003*** (0.0000)	1.0001*** (0.0000)
Structural Homophily Periphery (Reference)			
Core			11.0899*** (0.1250)
Model Fit AIC	3068	2602	2122
BIC	3075	2678	2204

Notes: Node count: 85; Tie count: 397; Significance: < 0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

compared to high-income countries. Lower-middle-income countries are more likely to According to Model 2, there is no significant difference between the likelihood of tie formation between low-income countries and high-income countries.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. In Model 2, the AIC is 2602 and the BIC is 2678, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (92 percent), compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4. In Model 3, the AIC is 2122 and the BIC is 2204, indicating that Model 3 has a better fit compared to Model 2 and Model 1.

2005-2009 LCTN

Table 11 shows the ERGM results for the 2005-2009 LCTN.

Model 1 estimates the likelihood of tie formation between two random countries. The coefficient for the likelihood of tie formation between two random countries in the 2005-2009 LCTN is 4.69 percent, confirming the sparseness of the network found in Chapter 4. In Model 1, the AIC is 3748 and the BIC is 3755. Model 2 adds the regional and developmental attributes. Controlling for ties, developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2005-2009 LCTN. That said countries in Latin America and the Caribbean are more likely to form within-group ties (27 percent) compared to

Table 11: Exponential Random Graph Model of 2005-2009 LCTN

Variables	Model 1	Model 2	Model 3
Ties	0.0492*** (0.0476)	0.0998*** (0.1817)	0.0105*** (0.2478)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		0.9116 (0.0992)	0.9017 (0.1105)
Latin America and Caribbean		0.3668*** (0.1490)	0.4295*** (0.1579)
Middle East and North Africa		0.3437*** (0.1796)	0.5859** (0.1910)
North America		0.0785*** (0.3924)	1.1491 (0.2862)
South Asia		0.9757 (0.2109)	0.5478* (0.2412)
Sub-Saharan Africa		0.2786*** (0.2247)	0.3574*** (0.2305)
Developmental Homophily High Income (Reference)			
Low Income		0.2671* (0.5313)	0.5060 (0.5360)
Lower Middle Income		0.5051*** (0.1494)	1.0387 (0.1724)
Upper Middle Income		0.7223*** (0.0950)	1.6453*** (0.1154)
GDP		1.0003*** (0.0000)	0.0000** (0.0000)
Core Homophily Periphery (Reference)			
Core			12.9877*** (0.1202)
Model Fit AIC	3748	3139	2550
BIC	3755	3218	2636

Notes: Node count: 100; Tie count: 464; Significance: <0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

countries in East Asia and the Pacific. Countries in the Middle East in North Africa are more likely to form within-group ties (26 percent) compared to countries in the East Asia and the Pacific. So on for Sub-Saharan Africa (22 percent) and North America (7 percent). According to Model 2, there is no significant difference between the likelihood of tie formation among countries in South Asia and the likelihood of tie formation among countries in East Asia and the Pacific. And there is no significant difference in the likelihood of tie formation in Europe and Central Asia and the likelihood of tie formation among countries in East Asia and the Pacific.

Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for every income group for the 2005-2009 LCTN. That said, upper-middle-income countries are more likely to form within-group ties (42 percent) compared to high-income countries. Low-income countries are more likely to form within-group ties (37 percent) compared to high-income countries. And lower-middle-income countries are more likely to form within-group ties (24 percent) compared to high-income countries.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. The AIC is 3129 and the BIC is 3218, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (93 percent) compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4. The AIC is 2550 and the BIC is 2636, indicating that Model 3 has a better fit compared to Model 2 and Model 1.

2010-2014 LCTN

Table 12 shows the ERGM results for the 2010-2014 LCTN.

Model 1 estimates the likelihood of tie formation between two random countries. The likelihood of tie formation between two random countries in the 2010-2014 LCTN is 4.63 percent, confirming the sparseness of the network found in Chapter 4. In Model 1, the AIC is 3712 and the BIC is 3719.

Model 2 adds the regional and developmental attributes. Controlling for ties, developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2010-2014 LCTN. That said countries in Sub-Saharan Africa are more likely to form within-group ties (27 percent) compared to countries in East Asia the Pacific. Countries in Latin America and the Caribbean are more likely to form within-group ties (27 percent) compared to countries in East Asia and the Pacific. So on for the Middle East and North Africa (22 percent) and North America (14 percent). According to Model 2, there is no significant difference between the likelihood of tie formation among countries in South Asia and the likelihood of tie formation among countries in East Asia and the Pacific. And there is no significant difference in the likelihood of tie formation in Europe and Central Asia and the likelihood of tie formation among countries in East Asia and the Pacific. Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for every income group for the 2010-2014 LCTN. That said, upper-middle-income countries are more likely to form within-group ties (35 percent), followed by lower-middle-income countries (22 percent), and low-income countries (15 percent).

Table 12: Exponential Random Graph Model of 2010-2014 LCTN

Variables	Model 1	Model 2	Model 3
Ties	0.0485*** (0.0479)	0.1500*** (0.1859)	0.0194*** (0.2392)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		0.8304 (0.1026)	0.7490* (0.1128)
Latin America and Caribbean		0.3768*** (0.1499)	0.3030 *** (0.1632)
Middle East and North Africa		0.8811*** (0.1808)	0.5325*** (0.1904)
North America		0.8350*** (0.3235)	1.5005 (0.2883)
South Asia		1.3960 (0.2029)	0.9085 (0.2280)
Sub-Saharan Africa		0.3783*** (0.2472)	0.4667* (0.2518)
Developmental Homophily High Income (Reference)			
Low Income		0.1764*** (0.4950)	0.3192* (0.4948)
Lower Middle Income		0.2750*** (0.1578)	0.5349*** (0.1783)
Upper Middle Income		0.5371*** (0.0100)	1.2085 (0.1180)
GDP		1.0002*** (0.0000)	0.0000 (0.0000)
Core-Periphery Homophily Periphery (Reference)			
Core			11.6348*** (0.1152)
Model Fit AIC	3712	3060	2487
BIC	3719	3139	2573

Notes: Node count: 100; Tie count: 458; Significance: <0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. The AIC is 3060 and the BIC is 3139, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (92 percent) compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4. The AIC is 2487 and the BIC is 2573, indicating that Model 3 has a better fit compared to Model 2 and Model 1.

2015-2020 LCTN

Finally, Table 13 shows the ERGM results for the 2015– 2020 LCTN.

Model 1 estimates the likelihood of tie formation between two random countries. The likelihood of tie formation between two random countries in the 2015-2020 LCTN is 5.76 percent, confirming the sparseness of the network found in Chapter 4. In Model 1, the AIC is 5189 and the BIC is 5196.

Model 2 adds the regional and developmental attributes. Controlling for ties, developmental homophily, and developmental heterophily, Model 2 results indicate regional homophily for nearly all regions in the 2015-2020 LCTN. That said countries in Sub-Saharan Africa are more likely to form within-group ties (31 percent) compared to countries in East Asia and the Pacific. Countries in South Asia are more likely to for within-group ties (30 percent) compared to East Asia and the Pacific. So on for the Middle East and North Africa (28 percent), Latin America and the Caribbean (24 percent) and North America (17 percent).

Table 13: Exponential Random Graph Model of 2015-2020 LCTN

Variables	Model 1	Model 2	Model 3
Ties	0.0611*** (0.0393)	0.1418*** (0.1689)	0.0171*** (0.2182)
Regional Homophily East Asia and the Pacific (Reference)			
Europe and Central Asia		1.1009 (0.0917)	1.1528 (0.0995)
Latin America and Caribbean		0.3182*** (0.1328)	0.4509*** (0.1399)
Middle East and North Africa		0.3978*** (0.1385)	0.5424*** (0.1478)
North America		0.1995*** (0.2446)	0.8417 (0.2478)
South Asia		2.3263*** (0.1968)	1.4434 (0.2135)
Sub-Saharan Africa		0.4503 *** (0.1774)	0.6666* (0.1875)
Developmental Homophily High Income (Reference)			
Low Income		0.0823*** (0.3875)	0.2017*** (0.3892)
Lower Middle Income		0.3036*** (0.1377)	0.5904*** (0.1021)
Upper Middle Income		0.5648*** (0.0796)	1.1036 (0.0876)
GDP		1.0002*** (0.0000)	0.0000*** (0.0000)
Core-Periphery Homophily Core			9.4877*** (0.0948)
Model Fit AIC	5189	4157	3433
BIC	5196	4238	3522

Notes: Node count: 152; Tie count: 1138; Significance: <0.0001 *** 0.001 ** 0.01 *; The coefficients are in odds ratio.

According to Model 2, there is no significant difference between the likelihood of tie formation among countries in Europe and Central Asia and the likelihood of tie formation among countries in East Asia and the Pacific.

Controlling for ties, regional homophily, and developmental heterophily, Model 2 results indicate developmental homophily for every income group for the 2015-2020 LCTN. That said, upper-middle-income countries are more likely to form within-group ties (36 percent) compared to high-income countries. Lower-middle income countries are more likely to form within-group ties (23 percent) compared to high-income countries. And low-income countries are more likely to form within-group ties (8 percent) compared to high-income countries.

Controlling for ties, regional homophily, and developmental homophily, Model 2 results indicate relatively high developmental heterophily. That is, for a one-billion increase in the difference in GDP (in US dollars) between countries, the likelihood of a tie forming is 50 percent greater. The AIC is 4157 and the BIC is 4238, indicating that Model 2 has a better fit compared to Model 1.

Model 3 adds the structural position attribute. Controlling for ties, regional homophily developmental homophily, and developmental heterophily, Model 3 results indicate high structural homophily; the likelihood of tie formation among core countries is high (90 percent) compared to the likelihood of tie formation among peripheral countries, confirming the eigenvector centralization results in Chapter 4.

DISCUSSION

Region and income group do play a role in predicting the formation of the EV-LIBTN and LCTN trade structures. Countries do show some tendency to trade within the same region and within the same income group. That said, differences in GDP and core-periphery position play a consistently significant and relatively unchanging role in predicting the formation of the trade structures. Differences in GDP significantly predict the formation of trade ties between countries; and so too does the tendency of core countries to trade with other core countries. Developed core countries are likely to form trade relationships, particularly import relationships, with less developed peripheral countries; but are also likely to form export and import relationships with more core countries. Inferentially, the results suggest that core countries accrue EV-LIBs and lithium compounds through the unequal trade relationships they have with peripheral countries, but then exchange (and keep) those commodities amongst themselves.

CHAPTER 6: CONCLUSION

The trade of EV-LIBs and lithium has grown and will likely continue to grow, as (inter)national efforts toward clean energy transition have been made. This study sets out to analyze the structure of this trade—a structure that not only facilitates and constrains countries' acquisition of commodities necessary for clean energy transition; but that shapes the distribution of economic and environmental "goods" and "bads" of those commodities. Results suggest that the international EV-LIBs and lithium trade networks are characterized by a core-periphery pattern, whereby a small set of developed, core countries occupy the center of the trade networks, and a large set of developed and less-developed peripheral countries occupy the margins of the trade. Results also suggest that the networks' core-periphery pattern is, in part, determined by the differences between countries' GDP and by the structural position that core and peripheral countries occupy. The results of this study provide some evidence of (ecologically) unequal exchange in the trade of EV-LIBs and lithium compounds. That is core countries have more trade relationships through which they can accrue EV-LIBs and lithium compounds compared to peripheral countries, and may, therefore, receive more of the economic, environmental, and social benefits of EV-LIBs and lithium compounds. Peripheral countries have fewer avenues by which they can obtain EV-LIBs and lithium compounds; given their more dependent and disadvantageous position in the networks, peripheral countries may be more willing to make price concessions on EV-LIBs and lithium compounds and may be more willing to take on the economic, environmental, and social detriments, to maintain the trade relationships, they have.

In conclusion, this study begins to address the research gap on the formation of EV-LIB and lithium trade—its structure and its structural inequality. This study also sets the stage for examining the ecologically unequal exchange in and socio-ecological consequences of the trade of “clean” and “green” commodities that are framed as *necessary* for energy transition and climate mitigation.

LIMITATIONS

Regarding Stage 1, the discrete core-periphery model does not identify semi-peripheral countries. Given the importance of the semi-periphery to EUE theory and given the role it plays in international trade, it is important to account for the semi-periphery, but this study cannot. Regarding Stage 2, ERGMs do not work if data is missing; as such, certain countries had to be omitted from the network samples altogether, even though they participated in trade. For example, Venezuela reported lithium exports, but the World Bank dataset did not provide GDP data for most of the years between 2000-2020. As such, Venezuela was omitted from all the networks. Additionally, the ERGMs in this study do not include attributes that would likely shape the formation of the trade structures. For example, given that the EV-LIB supply chain is concentrated in a few countries, the size of a country’s automotive industry, battery industry, and/or mining industry would likely determine the formation of trade relationships between certain countries.

FURTHER RESEARCH

Further research could and should address the limitations of the ERGMs by including more parameters such as foreign direct investment, size of mining or tech industries, and so on. Doing so would improve our understanding of how EV-LIB and lithium trade networks form, or of what the primary drivers of network formation are.

Additionally, further research should examine the socio-ecological problems resulting from the unequal exchange of lithium. Again, the lithium trade networks literature is primarily concerned with the stability of lithium trade, and I did not find any research on the ecologically unequal exchange of lithium and related products. The green extractivism literature touches on localized consequences and politics of lithium extraction, but research on the relationship between, for example, countries' lithium mining and a countries' ecological footprint is not only interesting but needed if we are to better understand the tension in the extraction and trade of lithium and other "green" commodities.

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APPENDICES

Appendix 1: Greenbushes Lithium Mine—The World's Largest Hard-Rock Lithium Mine—West Australia (Treadgold 2016).

Appendix 2: Lithium Brine Recovery Evaporation Ponds, Salar de Atacama, Chile (Facada 2017).

Appendix 3: Lithium Brine Piles (Flo Solutions 2021).

Appendix 4: Cells in the Electric Vehicle Battery Pack (Bower 2022).


Appendix 5: Electric Vehicle Power Train (Baldwin 2021)

Appendix 6: The "Lithium Triangle." Lithium brines are underneath the salt flats (i.e., salars) (Pearce 2022)

Core Countries	Peripheral Countries		
Australia	Afghanistan	Estonia	Nepal
Austria	Albania	Ethiopia	New Zealand
Belgium	Algeria	Fiji	Nicaragua
Canada	Andorra	Gabon	Niger
China	Angola	Gambia	Nigeria
China, Hong Kong SAR	Antigua and Barbuda	Georgia	North Macedonia
Czechia	Argentina	Ghana	Norway
Denmark	Armenia	Greece	Oman
Finland	Aruba	Greenland	Pakistan
France	Azerbaijan	Grenada	Palau
Germany	Bahamas	Guatemala	Panama
Hungary	Bahrain	Guinea	Papua New Guinea
Italy	Bangladesh	Guinea-Bissau	Paraguay
Japan	Barbados	Guyana	Peru
Malaysia	Belarus	Haiti	Philippines
Mexico	Belize	Honduras	Portugal
Netherlands	Benin	Iceland	Qatar
Poland	Bermuda	India	Rep. of Moldova
Rep. of Korea	Bhutan	Indonesia	Rwanda
Romania	Bolivia (Plurinational State of)	Iran	San Marino
Russian Federation	Bosnia Herzegovina	Iraq	Saudi Arabia
Singapore	Botswana	Ireland	Senegal
Slovakia	Brazil	Israel	Serbia
Spain	Brunei Darussalam	Jamaica	Sierra Leone
Sweden	Bulgaria	Jordan	Slovenia
Switzerland	Burkina Faso	Kazakhstan	South Africa
Turkey	Burundi	Kenya	South Sudan
United Arab Emirates	Côte d'Ivoire	Kuwait	Sri Lanka
United Kingdom	Cabo Verde	Kyrgyzstan	Sudan
USA	Cambodia	Lao People's Dem. Rep.	Suriname
Vietnam	Cameroon	Latvia	Syria
	Chad	Lebanon	Tajikistan
	Chile	Lesotho	Thailand
	China, Macao SAR	Liberia	Timor-Leste
	Colombia	Libya	Togo
	Comoros	Lithuania	Trinidad and Tobago
	Congo	Luxembourg	Tunisia
	Costa Rica	Madagascar	Turkmenistan
	Croatia	Malawi	Tuvalu
	Cuba	Maldives	Uganda
	Curaçao	Mali	Ukraine
	Cyprus	Malta	United Rep. of Tanzania
	Dem. Rep. of the Congo	Mauritania	Uruguay
	Dominica	Mauritius	Uzbekistan
	Dominican Rep.	Mongolia	Vanuatu
	Ecuador	Montenegro	Yemen
	Egypt	Morocco	Zambia
	El Salvador	Mozambique	Zimbabwe
	Equatorial Guinea	Myanmar	
	Eritrea	Namibia	

Appendix 7: List of Core and Peripheral Countries in 2012-2014 Electric Vehicle Lithium-Ion Battery Trade Network (EV-LIBTN)

Notes: Number of Core Countries: 31; Number of Peripheral Countries: 148; Total: 179

Core Countries	Peripheral Countries		
Australia	Afghanistan	Eswatini	New Zealand
Austria	Albania	Ethiopia	Nicaragua
Belgium	Algeria	Fiji	Niger
Brazil	Andorra	FS Micronesia	Nigeria
Canada	Angola	Gabon	North Macedonia
China	Antigua and Barbuda	Gambia	Oman
China, Hong Kong SAR	Argentina	Georgia	Pakistan
Czechia	Armenia	Ghana	Palau
Denmark	Aruba	Greece	Panama
Estonia	Azerbaijan	Greenland	Papua New Guinea
Finland	Bahamas	Grenada	Paraguay
France	Bahrain	Guatemala	Peru
Germany	Bangladesh	Guinea	Philippines
Hungary	Barbados	Guinea-Bissau	Qatar
India	Belarus	Guyana	Rep. of Moldova
Ireland	Belize	Haiti	Rwanda
Israel	Benin	Honduras	Saint Kitts and Nevis
Italy	Bermuda	Iceland	Saint Lucia
Japan	Bhutan	Indonesia	Saint Vincent and the Grenadines
Lithuania	Bolivia (Plurinational State of)	Iran	San Marino
Malaysia	Bosnia Herzegovina	Iraq	Sao Tome and Principe
Mexico	Botswana	Jamaica	Saudi Arabia
Netherlands	Brunei Darussalam	Jordan	Senegal
Norway	Bulgaria	Kazakhstan	Serbia
Poland	Burkina Faso	Kenya	Seychelles
Portugal	Burundi	Kiribati	Sierra Leone
Rep. of Korea	Côte d'Ivoire	Kuwait	South Sudan
Romania	Cabo Verde	Kyrgyzstan	Sri Lanka
Russian Federation	Cambodia	Lao People's Dem. Rep.	Sudan
Singapore	Cameroon	Latvia	Suriname
Slovakia	Central African Rep.	Lebanon	Syria
Slovenia	Chad	Lesotho	Tajikistan
South Africa	Chile	Liberia	Thailand
Spain	China, Macao SAR	Libya	Timor-Leste
Sweden	Colombia	Luxembourg	Togo
Switzerland	Comoros	Madagascar	Tonga
Turkey	Congo	Malawi	Trinidad and Tobago
United Arab Emirates	Costa Rica	Maldives	Tunisia
United Kingdom	Croatia	Mali	Turkmenistan
USA	Cuba	Malta	Tuvalu
Viet Nam	Curaçao	Marshall Isds	Uganda
	Cyprus	Mauritania	Ukraine
	Dem. Rep. of the Congo	Mauritius	United Rep. of Tanzania
	Dominica	Mongolia	Uruguay
	Dominican Rep.	Montenegro	Uzbekistan
	Ecuador	Morocco	Vanuatu
	Egypt	Mozambique	Yemen
	El Salvador	Myanmar	Zambia
	Equatorial Guinea	Namibia	Zimbabwe
	Eritrea	Nepal	

Appendix 8: List of Core and Peripheral Countries in 2015-2020 Electric Vehicle Lithium-Ion Battery Trade Network (EV-LIBTN)

Notes: Number of Core Countries: 41; Number of Peripheral Countries: 149; Total: 190

Core Countries	Peripheral Countries	
Belgium	Algeria	Portugal
Canada	Argentina	Rep. of Korea
Chile	Australia	Romania
China	Austria	Russian Federation
France	Bangladesh	Saudi Arabia
Germany	Barbados	Senegal
Italy	Belarus	Singapore
Japan	Bolivia (Plurinational State of)	Slovakia
Netherlands	Brazil	South Africa
Slovenia	Bulgaria	Sri Lanka
Spain	China, Hong Kong SAR	Sweden
United Kingdom	Colombia	Switzerland
USA	Croatia	Syria
	Cuba	Thailand
	Cyprus	Trinidad and Tobago
	Czechia	Tunisia
	Denmark	Turkey
	Dominican Rep.	Turkmenistan
	Ecuador	Ukraine
	Egypt	United Arab Emirates
	Estonia	United Rep. of Tanzania
	Finland	Viet Nam
	Greece	Zimbabwe
	Hungary	
	Iceland	
	India	
	Indonesia	
	Iran	
	Ireland	
	Israel	
	Jordan	
	Kazakhstan	
	Kenya	
	Kuwait	
	Latvia	
	Libya	
	Lithuania	
	Malaysia	
	Mauritania	
	Mexico	
	Morocco	
	Nepal	
	New Zealand	
	Nigeria	
	Norway	
	Pakistan	
	Peru	
	Philippines	
	Poland	
	Portugal	

Appendix 9: List of Core and Peripheral Countries in 2000-2004 Lithium Compound Trade Network (LCTN)

Notes: Number of Core Countries:12; Number of Peripheral Countries: 73; Total: 85

Core Countries	Peripheral Countries	
Belgium	Algeria	Morocco
Chile	Argentina	Mozambique
China	Australia	Namibia
France	Austria	Nepal
Germany	Bangladesh	New Zealand
India	Barbados	Nigeria
Italy	Belarus	North Macedonia
Japan	Bermuda	Norway
Netherlands	Bolivia (Plurinational State of)	Pakistan
Poland	Botswana	Panama
Singapore	Brazil	Paraguay
Slovenia	Brunei Darussalam	Peru
Spain	Bulgaria	Philippines
United Kingdom	Canada	Portugal
USA	China, Hong Kong SAR	Rep. of Korea
	Colombia	Romania
	Congo	Russian Federation
	Costa Rica	Saudi Arabia
	Croatia	Senegal
	Cuba	Serbia
	Cyprus	Slovakia
	Czechia	South Africa
	Denmark	Sweden
	Dominican Rep.	Switzerland
	Egypt	Syria
	Estonia	Thailand
	Finland	Trinidad and Tobago
	Gabon	Tunisia
	Ghana	Turkey
	Greece	Ukraine
	Guatemala	United Arab Emirates
	Guinea	Uruguay
	Honduras	Uzbekistan
	Hungary	Viet Nam
	Iceland	Zimbabwe
	Indonesia	
	Iran	
	Ireland	
	Israel	
	Jordan	
	Kazakhstan	
	Kenya	
	Kuwait	
	Latvia	
	Lebanon	
	Lithuania	
	Luxembourg	
	Malaysia	
	Maldives	
	Mexico	

Appendix 10: List of Core and Peripheral Countries in 2005-2009 Lithium Compound Trade Network (LCTN)

Notes: Number of Core Countries: 15; Number of Peripheral Countries: 85 Total: 100

Core Countries	Peripheral Countries	
Argentina	Albania	Nigeria
Belgium	Algeria	Norway
Chile	Antigua and Barbuda	Oman
China	Australia	Pakistan
France	Austria	Panama
Germany	Bangladesh	Paraguay
India	Belarus	Peru
Italy	Bolivia (Plurinational State of)	Philippines
Japan	Botswana	Portugal
Netherlands	Brazil	Qatar
Poland	Bulgaria	Rep. of Korea
Singapore	Cameroon	Romania
Slovenia	Canada	Russian Federation
Spain	China, Hong Kong SAR	Saudi Arabia
United Kingdom	Colombia	Serbia
USA	Croatia	Slovakia
	Cuba	South Africa
	Czechia	Sri Lanka
	Denmark	Sudan
	Dominican Rep.	Sweden
	Ecuador	Switzerland
	Egypt	Syria
	Estonia	Thailand
	Eswatini	Trinidad and Tobago
	Finland	Tunisia
	Ghana	Turkey
	Greece	Uganda
	Guatemala	Ukraine
	Hungary	United Arab Emirates
	Iceland	United Rep. of Tanzania
	Indonesia	Uruguay
	Iran	Uzbekistan
	Iraq	Viet Nam
	Ireland	Zimbabwe
	Israel	
	Jamaica	
	Kazakhstan	
	Kenya	
	Kuwait	
	Kyrgyzstan	
	Latvia	
	Lithuania	
	Madagascar	
	Malaysia	
	Maldives	
	Mexico	
	Morocco	
	Myanmar	
	Nepal	
	New Zealand	

Appendix 11: List of Core and Peripheral Countries in 2010-2014 Lithium Compound Trade Network (LCTN)

Notes: Number of Core Countries: 16; Number of Peripheral Countries: 84; Total: 100

Core Countries	Peripheral Countries	
Belgium	Afghanistan	Latvia
Chile	Algeria	Lebanon
China	Argentina	Libya
France	Armenia	Lithuania
Germany	Aruba	Malaysia
India	Australia	Mauritius
Italy	Austria	Mexico
Japan	Azerbaijan	Morocco
Netherlands	Bahamas	Myanmar
Poland	Bangladesh	Namibia
Rep. of Korea	Belarus	Nepal
Russian Federation	Bolivia (Plurinational State of)	New Zealand
Slovenia	Botswana	Nicaragua
Spain	Brazil	Nigeria
Thailand	Bulgaria	North Macedonia
United Arab Emirates	Canada	Norway
United Kingdom	China, Hong Kong SAR	Oman
USA	Colombia	Pakistan
	Costa Rica	Panama
	Croatia	Paraguay
	Cuba	Peru
	Czechia	Philippines
	Dem. Rep. of the Congo	Portugal
	Denmark	Qatar
	Dominican Rep.	Romania
	Ecuador	Saudi Arabia
	Egypt	Serbia
	Estonia	Singapore
	Ethiopia	Slovakia
	Finland	South Africa
	Ghana	Sudan
	Greece	Sweden
	Guatemala	Switzerland
	Guyana	Syria
	Honduras	Trinidad and Tobago
	Hungary	Tunisia
	Iceland	Turkey
	India	Ukraine
	Indonesia	United Rep. of Tanzania
	Iran	Uruguay
	Iraq	Uzbekistan
	Ireland	Viet Nam
	Israel	Zambia
	Jamaica	Zimbabwe
	Jordan	
	Kazakhstan	
	Kenya	
	Kuwait	

Appendix 12: List of Core and Peripheral Countries in 2015-2020 Lithium Compound Trade Network (LCTN)

Notes: Number of Core Countries: 18; Number of Peripheral Countries: 91; Total: 109