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The role of natural resources in accelerating net-zero transitions: Insights from EV lithium-ion battery Technological Innovation System in China

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Abstract:

As sustainability transitions in some sectors enter an acceleration phase, widespread diffusion of low-carbon technologies seem inevitable. While the availability of critical natural resources will inevitably influence the pace and direction of sustainability transitions, there is as yet little exploration on the role of natural resources in such upscaling and diffusion processes in transition studies. Drawing on the literature on technological innovation systems (TIS), this paper develops an analytical approach to highlight the natural resource dimension in a TIS value chain and link it to TIS dynamics (functional and structural) in the face of inter-sectoral imbalances caused by natural resource scarcity in accelerating transition processes. Empirically we study China's EV battery TIS which shows that a shortage of critical natural resource (especially lithium) has influenced the TIS functional and structural dynamics both within and across sectors and can severely impact transition processes. Overall, we plea for more research on natural resources in transition studies as many low-carbon technologies enter an upscaling and diffusion phase.

Keywords: Sustainability transition; Acceleration; Technological innovation system; Natural resources; EV battery value chain

1 Introduction

Sustainability transition studies traditionally focused on emergence of novel technologies in individual sectors (Andersen et al., 2020; Geels, 2018). However, the growing consensus around the political goal of achieving a net-zero transition by mid-century, calls for more attention to diffusion of technologies in many sectors that transition in parallel. The mid-century deadline for decarbonization implies that diffusion must be very rapid and take place globally in a short period of time (IEA, 2021b). The net-zero transition envisioned by many is thus unprecedented in terms of speed, sectoral scope, and spatial scale. As a consequence, it presents new challenges for transitions research and policy (Markard & Rosenbloom, 2022).

In this context, concerns over natural resource availability to support a net-zero transition have emerged (Bazilian, 2018; IEA, 2021c). Natural resources, especially minerals, are key ingredients in most low-carbon technologies from solar panels and wind turbines to electricity grids and electric vehicles that are crucial for achieving a net-zero transition (IEA, 2021c). Indeed, the IEA describes the transition as a shift from a '*fuel-intensive*' to a '*material-intensive*' energy system (2021b, p. 28). Not only must many new technological artefacts be built but some even have higher material intensity. For instance, a typical electric vehicle (EV) requires six times the mineral inputs of a conventional car. The scope, scale, and pace of ongoing net-zero transition is starting to influence price and availability of natural resources, and could generate bottlenecks for transitions if adequate policy measures are not implemented. The current rise of the EV prices is, for example, ascribed to scarcity of and upsurge in the upstream raw materials prices (IEA, 2021c). The majority of natural resources of critical importance to a net-zero transition are however not scarce geologically. Concerns therefore rather relate to the ability and willingness of producers and users of those natural resources to respond adequately and timely.

Sustainability transition studies has so far paid limited attention to the role of natural resources (Andersen & Wicken, 2020; Marín & Goya, 2021) and the main theoretical frameworks—such as the Technological Innovation System or Multi-Level Perspective—do not explicitly conceptualize the role of natural resources in innovation or transitions. However, a growing need for better understanding rapid diffusion of multiple technologies in many sectors, implies that transition scholarship must engage more explicitly with natural resources.

Against this background, we focus on and extend the technological innovation systems (**TIS**) framework by integrating an explicit natural resource dimension. A TIS is a sociotechnical system comprised of actors and networks, institutions, and technology whose interaction shapes the generation, diffusion, and utilization of a focal technological artefact (Bergek, Jacobsson, Carlsson, et al., 2008; Jacobsson & Bergek, 2011). Recent work has articulated a multi-sector value chain approach to TIS which helps understand the role of cross-sectoral imbalances (Malhotra et al., 2019; Stephan et al., 2017). While the approach draws attention to mining sectors, the role of natural resources in TIS dynamics has received limited attention. Similarly, theorizing about the TIS growth and diffusion phase is so far myopic to the role of natural resources. We therefore draw on literature about how natural resources influence innovation (David & Wright, 1997; Rosenberg, 1976a) to articulate an extended TIS framework which accounts for the role of natural resources in TIS value chain dynamics in the growth phase. Natural resource scarcity manifests as inter-sectoral imbalances in the TIS value chain. Our main research question is: *how do inter-sectoral imbalances related to natural resource flows influence TIS value chain dynamics?*

To answer this question, we apply and validate the framework in a case study of the EV lithium-ion battery (EVLB) TIS in China. In our analysis we study system level dynamics through micro-level analysis of actors perceive and respond to inter-sectoral imbalances. agency and actor strategies (Farla et al., 2012). We focus on firms along the focal technology value chain, as well as policymakers as the key actors that had strongly influence on the battery TIS dynamics in China. Our data consist of 32 in-depth interviews, observation in several key conferences, and various secondary sources.

We find that the influence of inter-sectoral imbalances related to natural resources become more and more important as the growth phase advances. It focuses innovative activity on providing the scarce resources and extends the locus of innovation in the value chain to include up- and down-stream sectors. It also initiates a search for alternative technologies that depend less on the scarce resources. Lastly, it creates new cross-sectoral couplings and business models.

We make three contributions to transition studies in general and the TIS framework in particular. First, based on our results we conceptualize how inter-sectoral imbalances related to natural resources influence TIS value chain dynamics. This includes distilling new insights about actors' response strategies and cross-sectoral couplings. Second, our extension makes the TIS framework useful for conceptualizing and analyzing shift to circular value chains. Lastly, we present a first empirical case study of the role of natural resources in the growth phase of the Chinese EVLB TIS.

2 Natural resources and Technological Innovation Systems

2.1 Technological innovation systems as multi-sectoral value chains

The TIS framework provides a systemic understanding of emergence and diffusion processes of a focal technology. A TIS is made up by four types of elements: actors, networks, institutions (e.g. regulation and policies), and technology (Bergek, Jacobsson, Carlsson, et al., 2008; Jacobsson & Bergek, 2011). The interplay between elements—i.e. embedded agency—generates the performance of the TIS which is often assessed via a set of functions such as market creation, legitimacy, and knowledge production, see appendix 1 (Bergek, 2019; Bergek, Hekkert, et al., 2008). If system elements are misaligned it manifests as weak functions (Markard & Truffer, 2008).

Recently researchers are paying more and more attention to how TIS dynamics are influenced by its context by looking into various forms of TIS-context relationships including other TISs, sectors, geographical factors, and political systems (Bergek et al., 2015). From this work emerged an explicit value chain approach to TIS which explicates the sectoral configuration of a TIS (Malhotra et al., 2019; Stephan et al., 2017). In this approach, technology is seen as a complex system comprised of components and materials that are organized according to a dominant design of the focal technology (Arthur, 2009; Murmann & Frenken, 2006). Components, and materials are typically produced by specialized actors in distinct sectors and the focal technological artefact is used in still other sectors (Sandén & Hillman, 2011; Stephan et al., 2017).

The starting point for this perspective is that sectors are idiosyncratic. They have, for instance, different modes of innovation, knowledge bases, and institutions (Malerba, 2005). Due to these differences, sectors can complement each other via inter-sectoral relationships to deliver complex products and innovations (Pavitt, 1984). Sectoral differences may however result in various types of tension or imbalances as the TIS evolves because change in one sector may require change in another (Andersen & Markard, 2020; Stephan et al., 2017). For example, actors, if uncoordinated, may respond differently, to different things, and at different times. Such misalignments are likely to affect overall TIS performance (Malhotra et al., 2019; Stephan et al., 2017). Interactions across sectors in a TIS value chain have been conceptualized as *linkages* such as market-based, input-output arm's length transactions, and as *structural couplings* (i.e. shared components) (Bergek et al., 2015; Mäkitie et al., 2018). For example, the TIS of offshore wind shares both actors and technologies with the TIS of offshore oil and gas platforms (Andersen & Gulbrandsen, 2020).

Existing TIS value chain studies have mainly focussed on implications of sector differences for flows of knowledge and have so far ignored the role of natural resources (Andersen & Markard, 2020; Malhotra et al., 2019; Stephan et al., 2017). Some general TIS studies discuss the influence of scarce natural resources for TIS formation (Giurca & Späth, 2017; Wirth & Markard, 2011). However, none of these studies explicitly conceptualize the role of natural resources in TIS value chains or in relation to diffusion and the growth phase of TIS.

2.2 Diffusion and the TIS growth phase

A central feature of accelerating transitions is the diffusion of new technologies in the sector undergoing transition (transport in our case) (Markard et al., 2020). Diffusion requires that the TIS enters a growth phase. The TIS life cycle includes formative, growth, mature, and decline phases (Markard, 2020). The formative phase of a TIS has been intensively studied, and is characterized by high uncertainty and technical variation (i.e. competing designs), product innovations, and extensive experimentation (Anderson & Tushman, 1990). In the formative phase, the sectoral configuration is typically not clear and the TIS relies on resources from existing adjacent sectors (Fontes et al., 2021; Sandén & Hillman, 2011).

A growth phase starts with decreasing technological variety and emergence of a dominant design. The locus of innovation moves from competing designs to improving subsystems and components within one design. The dominant design is associated with a particular sectoral configuration based on actors' knowledge specialization and resources (Markard, 2020; Tushman & Rosenkopf, 1992). The phase is characterized by diffusion, and upscaling of production capacity. Moreover, institutional alignment also increases both internally and externally (Bergek, Hekkert, et al., 2008; Bergek, Jacobsson, Carlsson, et al., 2008).

Compared to the formative phase, the TIS growth phase has so far received less attention (Bergek, 2019). This inter alia concerns that although there is amble evidence that diffusion is often characterized by various bottlenecks within and across sectors (Geels & Johnson, 2018; Kanger et al., 2019; Mäkitie et al., 2022), the value chain perspective has not been systematically linked to TIS phases, i.e. whether and how the sectoral configuration changes and changes in interaction types (e.g. linkages versus couplings) as well as how TIS actors respond to inter-sectoral imbalances.[1] For example, the TIS growth phase is so far myopic to the need for more and more natural resource inputs and to how this could influence cross-sectoral imbalances and TIS dynamics. A root cause of this, we argue, is the lacking conceptualization of natural resources and their influence on innovation which we engage with next.

2.3 Natural resources and innovation

Although Innovation Studies as a field generally ignore natural resources (Andersen & Wicken, 2020), it is widely acknowledged that the relative availability and price of natural resources can influence innovation and the direction of technological trajectories (Hayami & Ruttan, 1971; Landes, 1998; Mokyr, 1992; Rosenberg, 1976b).

The underlying perspective is that sociotechnical systems (e.g., a TIS) are embedded in a natural environment (Andersen & Wicken, 2020; Clark & Harley, 2020). Sectors such as mining and waste management are obvious interfaces between TIS value chains and the natural environment. Due to the stability of the natural environment, there are rarely abrupt natural resource shortages but rather gradually growing scarcity that actors can respond to. The societal impact of natural resource changes depends on actors' ability to respond (Andersen, 2012; David & Wright, 1997).

Historically, there have been two main innovation responses to changing material scarcity (Zhou et al., 2022). First, innovations that extend the efficiency of existing resources including innovations that lead to a) raises in production output per unit of resource input (e.g., manufacturing process innovations), b) productivity increase in resource extraction process (e.g. mining), c) productivity increase in process of exploration and resource discovery (e.g. geological methods), and d) development of techniques to recycle and re-use waste products. Second, another response is to develop innovations that create substitutes for scarce resources including innovations to create new materials while leaving the end-product unchanged (e.g. from natural to synthetic rubber for tire production). another response includes innovation in end-product / artefact that makes it independent of scarce resources (from wood to steel hulls in ships) while maintaining similar or even improved

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[1] It has been indicated that the growth phase may entail that a focal TIS will start having more significant or even transformative impact on the sectors in its value rather than simply receiving inputs from them (Markard, 2020).

functionality (Rosenberg, 1976a). We expect to see similar responses by TIS actors in transitions if material scarcity appears.

2.4 Analytical approach: Natural resources and TIS value chain dynamics

Combining the insights from the abovementioned literatures, we propose an analytical approach to explicate the role of inter-sectoral imbalances related to natural resources in TIS evolution which has implications for how we understand sociotechnical transitions to sustainability. We do so in 3 steps.

First, as a starting point we conceptualize the natural resource dimension of a TIS. We explicitly acknowledge that a TIS is embedded in a natural environment from which the TIS receives natural resources and to which it returns some of those materials at the end of the artefact’s lifetime. We suggest that the neglected TIS function of *materialization* is useful for analysing natural resource flows across sectors in a value chain as it describes changes in sector production capacity which can be a major source of inter-sectoral imbalances, cf. Appendix 1 (Bergek, Jacobsson, & Sandén, 2008).

Second, we differentiate three major segments of a TIS value chain. The upstream input sectors (e.g., natural resource provision), midstream user sectors (e.g., material utilization, technology development, and use of focal artefact), and, downstream waste, recycling and re-use sectors. Prior TIS value chain studies focus on the midstream sectors. Focusing on natural resources, we include both production and after-life activities of resources.This sectoral configuration is tied together by flows of resources (knowledge and materials) and associated actors and institutions. We define *inter-sectoral imbalance* related to natural resources as a situation in which the demand for and supply of natural resources across value chain segments are misaligned.

Third, regarding TIS phases, we expect that natural resource flows do not impact TIS dynamics significantly in the **formative phase** as the main innovation focus of TIS actors in this period is to develop an initial sociotechnical configuration (of actors, technologies, and institutions) that works, i.e. a dominant design (Rip & Kemp, 1998). The inter-sectoral relationships (related to natural resources) most likely take the form of market transactions (i.e. linkages) where midstream actors purchase what they need. In the **growth phase**, however, we expect natural resource flows to be more important and possibly create inter-sectoral tensions. A key issue is whether upstream sectors can provide the inputs midstream producers demand in right volume, quality, and time to avoid inter-sectoral imbalances. If such imbalances occur, TIS actors across the value chain sectors need to respond innovatively by extending or substituting the scarce natural resources to enable further growth and diffusion. Such responses can include new innovations in all segments. Moreover, policy makers may also respond to inter-sectoral imbalances and influence system-level functions. In the absence of innovative responses, higher prices and limited access to critical materials can hamper the TIS which manifests in terms of weak(er) functional performance (e.g., sluggish market development).

In the remainder of the paper we seek to explore and verify these initial theory-derived expectations in a study of China’s lithium-ion battery TIS.

3 Research design and methodology

3.1 Case selection and description

This paper aims at theory development via an in-depth case study which is appropriate for developing theoretical explanations for phenomena that is not well understood (Ozcan et al., 2017; Yin, 2018). In Eisenhardt (2021)’s word, case study is an ideal method for exploring a ‘cool’ yet under-studied phenomenon. While the trend of accelerating EV markets seems inevitable in many parts of the world, the questions of how natural resources are relevant to such acceleration processes and what actor strategies can be expected in face of material scarcity remain largely under-researched. Informed by theoretical sampling (Yin, 2018), we chose to study the growth phase of China’s lithium-ion battery TIS associated with the growing diffusion of EVs in China and abroad (EVLB TIS), focusing particularly on the role of natural resource flows within it.

The selected case provides an important, relevant, and suitable empirical setting for analysing our research question for the following reasons. *First*, China is one of the global lead markets in the field of EVs and battery production. The growth of EVs and battery production have been faster than anywhere else in the world in recent years[2]. The EVLB TIS value chain in China has moved from an early formative phase to an increasingly mature growth phase, which is yet to happen in many other countries. *Second*, due to the rapid diffusion of the EVs in China, the concern on critical natural resource supply (especially lithium) has become an increasingly important factor that influences the functional and the structural dynamics of the TIS. For these reasons China constitutes a *unique* case (Yin, 2018).

Moreover, there are significant differences across the battery TIS value chain sectors that give reason to expect imbalances to occur. Mining sectors, for example, typically operate with 15-20 year investment cycles for new projects including discovery and planning. A new mine can take 10 years from investment decision until it is in operation even without civic resistance (IEA, 2021c). The high capital cost of such projects moreover makes mining firms conservative. Therefore mining is traditionally relative unresponsive to short-term changes in demand (Marín & Goya, 2021). However, midstream manufacturing sectors that use the materials from the mining sector, can scale up relatively quickly as they simply need to build a new factory (IEA, 2021c). Such cross-sectoral differences can lead to natural resource demand-supply imbalances.

Figure 1 shows the impressive growth of EV and related battery market in China since 2009 (2010). Although the government encouraged adoption of EVs since 2009, growth prior to 2015 was very modest. It was only after 2015 that EV sales volume surged, marking the beginning of a rapid growth phase. More impressively, China's EV sales volume reached 3.5 million in 2021, signaling the beginning of the acceleration phase of the transition in the

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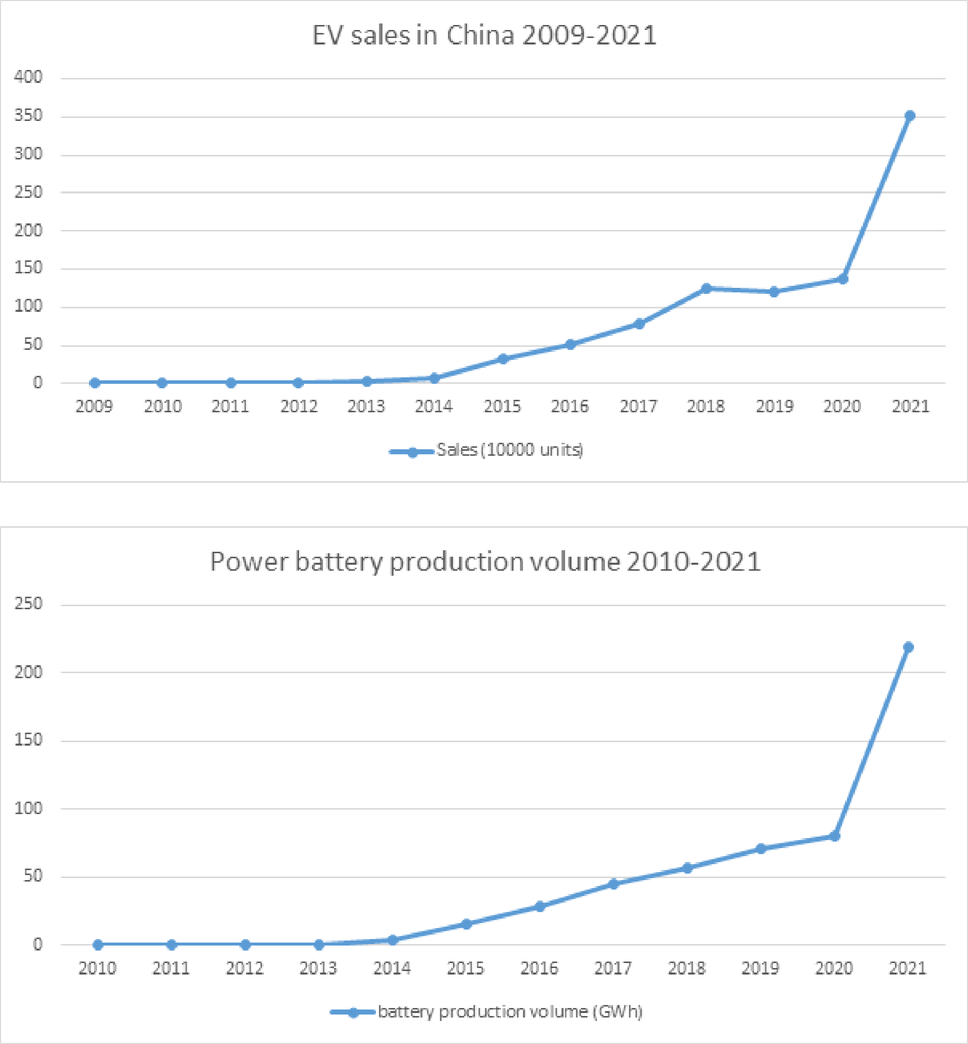
[2] The exception was 2020, when the EU overtook China as the world's largest EV market for that single year

transportation sector internationally. Closely related to the growth of the EV demand, battery production expanded rapidly since 2010 as well, with the industry growing more than 200-fold over the past decade (Figure 1). In particular, since 2015, the market has grown rapidly, exceeding 80 GWh in 2020.

Figure 1: EV and related battery markets in China. Source: China Association of Automobile Manufacturers; GG-LB.com



Based on the insights from our interviews, as well as the growth of EV battery production volume showed in Figure 1, we categorize the development of the EVLB TIS in China into three phases. The *first phase* (before 2014) featured the formation of the EVLB TIS in China with a strong focus on technology development and initial market exploration with generous financial subsidies from the government for private and public EV purchases. The *second phase* (2015-2019) was characterized by a boom in the *domestic* EV market, triggered by strong subsidy programs and the introduction of domestic market protection measures by the central government. The *third phase* (2020-) is characterized by strong increase in demand for EV batteries during the COVID-19 pandemic in the *global* market and the projected arrival of the Twh era in 2025. Due to both the actual and projected increase in

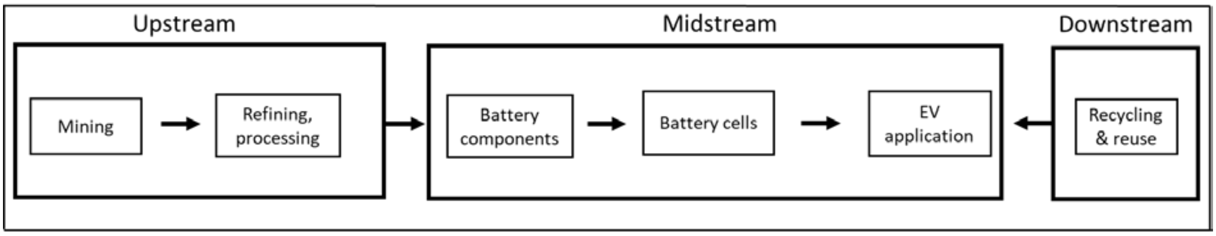
EVLB markets, concerns about the availability of critical raw materials have become the focus of discussion during this phase (Zhou et al., 2022).

As far as key raw materials are concerned, the Benchmark Mineral Intelligence (2020) convincingly showed that China essentially dominates the supply chains for lithium-ion batteries for electric vehicles in terms of raw materials supply: it accounts for 80% of global chemical refining and processing capacity. It also strongly dominates global production of cathodes and anodes (66%) and battery cells (73%). While China undoubtedly plays a dominant role in the global battery minerals processing capacities, the key battery material reserves in the country is rather limited. According to the U.S. Geology Survey (2019), China’s proven nickel, cobalt and lithium reserves account for 3%, 1%, and 6% of the world, respectively. As a result, China's import share of the natural resources (lithium, nickel, and cobalt ores) consumed in China exceeded 70% (Ifeng, 2018).

3.2 Data collection and analysis

The sectoral configuration of our focal TIS value chain is depicted in Figure 2. Based on our analytical approach, we analyse the impact of natural resources on TIS dynamics in terms of TIS functions (Appendix 1) and changes in system components (actors, institutions, and technology) *within* each value chain segment (i.e., *intra-sectoral dynamics*) as well as *cross-sectoral* dynamics (linkages or structural couplings). We include policies concerned with natural resources in the TIS analysis. Note that we perform a partial rather than a comprehensive TIS analysis because we zoom in on TIS dynamics related to natural resources. Therefore we do not discuss all functions for each value chain segment in each phase but only report on functions when there is an impact. For this reason we insert *[labels]* in the analysis with the name of functions when they are relevant rather than structure our text around them. While section 4 presents an empirical account of EVLB TIS evolution across phases and segments, we will in section 5 summarize and discuss theoretical lessons and insights regarding TIS dynamics and natural resources.

Figure 2: The EVLB TIS value chain



The paper draws upon three main data sources. First of all, 32 in-depth interviews and roundtable discussions with industry representatives along the value chain, policymakers, industry associations, third-party think tanks, scholars in China’s major cities and regions from October 2020 to March 2021 (see Appendix 2). On average, each interview lasted around one hour, and all the interviews have been recorded and transcribed. In addition, secondary data was compiled from various sources including yearly reports of companies, internal materials of intermediary organizations/think tanks, media reports, professional magazines, industry reports, public speeches of key policymakers, experts and important organizations. It was collected and compiled chronologically. Finally, the first author participated in three policy discussion events in Beijing and in three national conferences organized during December 2020 to January 2021. Through observations in these events, the authors were provided a good chance to understand the raw materials concerns and related policy discussions in the value chain. For data analysis, we combined interpretation-focused coding with presumption-focused coding (Abu, 2019). The purpose of the first coding strategy is to describe what interviewees said and interpret why they did so, and the second coding strategy is to develop a theory or model to explain the phenomenon that the researchers are interested in. The interview transcripts were coded in which we grouped together relevant themes into three phases of development. For each phase, we first assessed to what extent inter-sectoral imbalances related to natural resources appeared in the value chain. Second, we then analyzed how such inter-sectoral imbalances influenced value chain each segment in terms of functional and structural TIS dynamics. Note that we categorized actor responses in terms of innovation for extending/substituting natural resources. For our data coding schemes, we first conducted an open coding by labelling and highlighting activities, actors and events relate to the upstream, midstream and downstream sectors. The outcome of this first step was the first-order primary codes which were determined by comparing the results from open coding. In the second stage, the primary codes were compared and merged into second- order codes. Finally, we merged the second-order codes into aggregated themes, connecting to the insights from the literature and our analytical framework. In total approximately 500 blocks of the data were coded, and for an illustration of our data structure, see Appendix 3.

4 Results: Natural resources and EVLB TIS evolution

4.1 Formative phase: mid 1990-2014

4.1.1 Natural resources and inter-sectoral (im)balances

China's interest in battery technology for EVs can be traced back to the mid-1990s, when the first Chinese electric bus, *YuanYang*, was jointly developed by Shengli Bus, a state-owned auto company, and the Beijing Institute of Technology (industry representative 3). In the following decade, substantial R&D investments were made by the central government and public funds were allocated to catch up with global leaders in this field (Expert 5). The development of EV batteries began to gain momentum in the early 2010s following the successful deployment of e-buses at the Beijing Olympics in 2008 and the Shanghai Expo in 2010.

The natural resource supply-demand relationship between different sectors was not a major issue in this phase as the market for electric vehicles had not yet taken off. Natural resources flowed via market based relationship (Expert 4). In addition, state leadership had previously focused on securing the supply of raw materials for the industrialization of the country (Industry Representative 12). According to the China Non-Ferrous Metals Industry Association (2005), China has risen to become the world's largest producer and consumer of nonferrous metals since 2002. Possessing a large volume of raw materials (e.g. nickel, cobalt, lithium, copper, etc.) needed for industrialization has also been helpful for the development of the domestic EVLB TIS (Industry Representative 9, Expert 4).

4.1.2 Impact on TIS dynamics

While the early development of the EVLB TIS did not lead to strong demand surge for battery raw materials, actors along the value chain has implemented some resource-specific strategies.

In the **upstream,** although there was no inter-sectoral imbalance related to natural resources, several upstream actors were expecting strong growth in the EV market and thus for lithium in the next decade (industry representatives 12, 13) *[direction of search]*. Based on this expectation, and combined with the booming demand for electronic devices, upstream players tried to increase their productivity in resource extraction process and expanded their lithium production capacity (resource expansion)(Leadleo, 2019a). For instance, five new lithium spodumene mines[3] were approved in Sichuan province between 2008 and 2013 (Minmetals, 2021) *[materialization]*. There were also technological innovation in lithium mining which helped increase productivity of spodumene mines (Industry Representative 12) *[knowledge development]*.

In the **midstream,** actors paid limited attention to natural resources with only a few exceptions, e.g., CATL, a battery producer, that was founded in 2011, acquired Bump, a recycler, in 2013. Battery manufacturers were focused on experimentation and learning in key battery component technologies (anodes, cathodes, separators, electrolytes), and vehicle integration (Expert 2). In terms of R&D, lithium-ion phosphate (LFP) batteries were the main technology used in EVs during this period (Expert 2).

When it comes to the **downstream** battery recycling and reuse, TIS development in this segment was limited in the first phase, but environmental concerns about spent batteries has led to policies regulating battery recycling. For instance, in 2012, the State Council's "Energy Conservation and New Energy Vehicle Industry Development Plan (2012-2020)" formulated regulation for battery recycling and reuse. However, concern about material scarcity was not cited as the reason for the state’s emphasis on battery recycling and reuse (Expert 3).

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[3] Lithium can be extracted from three sources: Spodumene mines, brine mines, and lepidolite mines. In China, most of the lithium has been extracted from spodumene and lepidolite ores, although the country's lithium reserves are mainly found in brines. Due to the high Mg2+/Li+ ratio in Chinese brines, it is technologically extremely difficult to extract lithium from those brine sources at reasonable prices.

4.2 Domestic growth phase: 2015- 2019

4.2.1 Natural resources and inter-sectoral (im)balances

The second phase (2015-2019) was characterized by a boom in the *domestic* EV market, triggered by strong subsidy programs and the introduction of domestic market protection measures by the central government (Industry Representative 4, 6). During this period, CATL became the global top 1 EVLB supplier in 2017 (Benchmark Mineral Intelligence, 2020). Meanwhile in battery subfields such as component manufacturing, Chinese players had achieved some competitive advantages. A TIS value chain including raw materials supply, component manufacturing, cell and pack production, and EV application emerged in China (Industry representative 12). Due to an expected bright future of the EV market, numerous financial and capital resources have been attracted to this emerging industry, and the number of enterprises that entered the midstream battery production reached a peak of 150 in 2016 (Expert 1). As a result of such midstream market boom, the upstream raw materials supply has slowly entered into the public discourse and its influence on the midstream battery technology development and application has become visible.

In this period, several battery-specific policy documents have been announced. Critical policy documents included the “Automotive Power Battery Industry Specification Conditions” (or the “Battery Whitelist”) by Ministry of Industry and Information Technology (MIIT) in 2015; and the annually-adjusted subsidy schemes released jointly by several ministries. The policies stipulated that only EVs that were equipped with batteries that met the conditions specified in the document were eligible to be listed in the "Recommended Model Catalog for the Promotion and Application of New Energy Vehicles" (MIIT, 2015) and thus received subsidies.

Such changes in policy influenced natural resource flows in the TIS. The central government introduced financial incentives to support development and production of higher energy density ternary battery technologies (e-g-. lithium manganese cobalt oxide (NMC) technology rather than LFP battery technology). As a consequence, the installation of NMC batteries in cars increased steadily, and overtook the installed volume of LFP in 2018 (GG-LB, 2021). However, since the production of NMC requires higher input of raw materials such as cobalt and lithium (GG-LB, 2016), this was a structural increase in demand critical natural resources. Even so, material scarcity was still not yet a major concern, and lithium was traded via market-based relationship (Expert 1).

4.2.2 Impact on TIS dynamics

In this phase, growing demand for lithium from EVLB production has led to changes along the TIS value chain. In the **upstream** sector, mining companies have engaged in resource expansion by increasing the lithium production from multiple sources, including the spodumene, lepidolite and brine sources. (Leadleo, 2019a) [materialization]. Overall, the market for lithium ores in China increased from 7,9000 to 16,7000 tons between 2015 and 2018, representing an annual growth rate of 26.2% (Leadleo, 2019a). Lithium firms in China (e.g., Yongxing Materials, Nan's Lithium, Feiyu New Energy, Jiangte Electric) have realized technological breakthroughs in new lithium extraction technologies from lepidolite sources, involving compound salt low temperature roasting, fluorine fixation, and tunnel kiln technology (Sinolink Securities, 2021a, p.1) [knowledge development]. This led to 4 new lepidolite mines being exploited in Jiangxi province in 2018 and 2019 (Guosen Securities Economic Research Institute, 2021) [materialization]. As a consequence, the production cost has dropped from 100,000 yuan/ton to 35-45,000 yuan/ton (Guosen Securities Economic Research Institute, 2021). Although several brine mines were approved for production during this period, production volumes remained rather low because mining from Chinese salt-lake brine mines are technologically very challenging due to high Mg^{2+}/Li^{+} ratio (Minmetals Securities, 2021).

In the **midstream,** since actors along the value chain share the anticipation that a surge of the EV market will be inevitable in the forthcoming years, major battery manufacturers have become more active in investing in the upstream mining and material processing sectors in order to secure raw materials supply (see Table 1). One typical example is CATL's strategic expansion to the upstream activities during this period (see Appendix 4). Specifically, CATL has formed various relationships (e.g., strategic partnership, joint venture, mergers and acquisitions, supply agreements, etc.) with upstream mining companies to secure its lithium, cobalt, nickel supply. Similarly, some visionary midstream companies have begun to expand their investments in the downstream sector to help secure feedstock supplies. For instance, in 2015, 3 investments in the downstream have been announced by the listed companies in the midstream, and this number increased to 6 in 2019 (see Table 1). However reverse resource flow was still largely out of the scope for the midstream actors as large-scale battery retirement was yet to come (Industry Representative 13).

Table 1: Investments within and across value chain segments[4]

Invest.	**To Upstream**			**To Downstream**			**Total**
Sources	upstream	midstream	downstream	upstream	midstream	downstream	
2013	3	1	0	0	0	1	5
2014	4	0	0	0	1	0	5
2015	2	3	0	0	3	0	8
2016	3	2	0	0	2	2	9
2017	5	2	0	0	2	2	11
2018	6	7	1	1	4	4	23
2019	5	6	0	1	6	4	22
2020	8	17	2	2	14	8	51
2021	11	20	2	3	13	9	58
Total	50	58	5	7	45	30	192

Note: The columns "to upstream" and "to downstream" show investments in upstream/downstream activities by actors located in up-, mid-, or down-stream. We list number rather than size of investments to indicate level of cross-sectoral interactions.

In the **downstream**, there was limited activity among firms with the exception of some conventional recyclers moving into this new business field (e.g., GEM), as they expected this downstream segment to take off in 10 years (Industry representative 15) [direction of

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[4] Own alculation of total number of M&As, new subsidiaries and plants, joint venture, equity investments, strategic cooperative agreements from listed companies' annual reports along the value chain. 2013 was the first year that relevant data was available from Sina Finance. http://vip.stock.finance.sina.com.cn/

search]. In terms of market scale, the output of battery recycling and reuse only reached 87 million RMB in 2018 (Leadleo, 2019b). During this phase, new supporting policies were introduced in relation to detailed management regulations of the retired batteries, as well as the construction of a closed- loop in the EVLB TIS value chain. In contrast to the previous period, where battery recycling and reuse policies were incorporated in the broader EV policies, stand-alone battery-specific policies emerged during this phase. These policies stipulated the details of the responsible body for battery recycling, the construction of recycling networks, and the standards and specifications for battery dismantling, recycling and gradient utilization. Similar to the first period, however, the focus was not on material shortages, but on preventing the leakage of hazardous chemicals from batteries (Intermediary organization 5, Expert 3).

4.3 International growth phase: 2020-

4.3.1 Natural resources and inter-sectoral (im)balances

As the industry entered the third phase of development, demand for electric vehicles has skyrocketed both domestically and internationally. Consequently, the installation of automotive batteries reached 300 GWh, representing a year-on-year growth rate of more than 100% in 2021 (SNE Research, 2022). In this context the global EVLB industry is predicted to enter the "Twh era" by 2025 (Industry Representative 1, 2). In this global market booming phase, concerns over material scarcity has increased tremendously. In addition, the outbreak of the Covid 19 pandemic and the blockage of global logistics due to the lockdown of various regions of the world have caused prices for battery raw materials such as lithium to skyrocket (see Appendix 5). In addition, the global geopolitical uncertainty surrounding the import of raw materials into China is an additional concern, as "*many lithium- and nickel-rich countries have tightened regulations on the export of key metals* in recent years…" (Intermediary 2). These material shortages and the accompanying increase in commodity prices have led to inter-sectoral imbalances as well as concerns about the security of material supply (Zhou et al., 2022). This was nicely expressed by CATL's CEO, Dr. Robin Zeng,

> *"…the next three to four years will be the most difficult period for power batteries and upstream and downstream enterprises, especially in the pressure to reduce costs at a time when raw material prices are skyrocketing and demand for those materials are rapidly surging. …upstream and downstream enterprises will face unprecedented challenges, which requires the entire industry chain to collaborate and cooperate to secure the supply of key components and raw materials."*[5]

4.3.2 Impact on TIS dynamics

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[5] Quoted from Robin Zeng's speech at the Gaogong Lithium-ion Battery & Electric Vehicle Annual Meeting 2020, Shenzhen.

Such a surge in demand due to the upturn in the global EV market, as well as the rapid increase in material prices due to the disruption of the COVID pandemic and geopolitical uncertainty, had a huge impact on the NVLB TIS value chain in China. Actors along the value chain have adopted various strategies to either expand the supply of critical raw materials (increase productivity in the domestic mining sector, recycling and reuse key materials), or work on innovative substitutes to reduce the dependence on rare materials (especially in the midstream sector).

In the **upstream,** the shortage of raw materials led to a surge of interest in *domestic* lithium extraction from salt lakes and as a result, an expansion of the absolute volume of lithium resource from brine sources in China *[direction of search]*.

> *".. For a long time, the lithium produced in China came mainly from spodumene and lepidolite ores.... However, these two sources account for only 20% of total lithium reserves in the country. Almost 80% of China's lithium reserves come from brine sources."* (Expert 4).

Theoretically, the extraction of lithium from brines is more economically viable and consumes less energy, but the quality of lithium brines in China is rather poor, featuring low lithium content and high Mg2+/Li+ ratio, and thus has hindered large-scale lithium production from brines (Xu et al., 2021).

> *" …before 2015, China's salt lake exploitation was in the early stages of development, resulting in the high cost of lithium extraction to 60-80,000 yuan / ton, more costly than lithium extraction from spodumene and lepidolite ores, and the production volume was also quite limited. …However, in the last two years, several scientific and technological breakthroughs have been achieved in this field, and the average production cost has now dropped to 30,000 yuan / ton*." (Sinolink Securities 2021b, p.14)

One example of the technological breakthrough is the "High Efficiency Lithium Extraction Technology of Salt Lake Raw Brine" project led by MinMetals (Mining.com, 2021) *[knowledge development]*. Also, the progress made in the membranes technology (Xu et al., 2021) have made lithium extraction from brines an attractive business *[knowledge development]*. Such an inward-looking strategy has also led to the increase of domestic firms that are specialized in lithium-mining activities. For instance, there are more than 400 lithium-related mining companies in China, among which 64 were newly registered in 2021, representing a growth rate of 20.3% compared to the year before (*Expert 5*). The domestic production of lithium is predicted to reach 36, 8000 tons in China by 2023[6] (Leadleo, 2019a) *[materialization]*.

In response to expected material scarcities, midstream actors also became more active in establishing strategic partnerships (or, structural couplings) with and investing in *upstream* miners and raw materials processors both at home and abroad. For instance, in contrast to the second phase, the number of large-scale cross-sectoral investments by listed companies

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[6] In comparison, the production volume of lithium in 2018 was 16,7000 tons.

from midstream to upstream increased enormously in 2020-2021, reaching 17 and 20, respectively (see Table 1) *[resource mobilization]*.

In contrast to the early phases, to secure the supply of raw materials for battery productions, increasing number of policy documents have been issued related to the mining sector in the last few years. In 2021, for the first the first time in history, the Ministry of Industry and Information Technology has announced the "Raw Materials Industry Development Plan" in the 14th Five-Year-Plan, highlighting the importance of securing material supply for domestic and global EV market ramp-ups. More importantly, in June 2021, President Xi Jinping made the remark during his visit to Qinghai that the province should accelerate the construction of a world-class salt lake industrial base in order to meet the increased domestic industrialization demand (especially the EVLB manufacturing). As a consequence, the government released its "Action Plan for Building a World-Class Salt Lake Industrial Base" showing the support of top leadership to the development of brine assets in China (Mining.com, 2021) *[legitimation]*. As a result of such political will at the top-level, domestic lithium mining approval process has been speeded up tremendously. In April 2022, the Ministry of Natural Resources approved the development of two domestic lithium resources mineral development projects: i.e. lithium spodumene mine in Sichuan Province and lithium salt lake resources in Qinghai Province (Ministry of Natural Resource, 2022). All the abovementioned policy documents showed the determination of the Chinese government to accelerate the development of its domestic lithium resources.

In the **midstream**, concerns over raw materials supply also influence actors' strategies. First of all, technological innovation in the battery field is increasingly targeting substituting scarce and expensive raw materials with abundant and inexpensive ones, or simply getting rid of them (Industry representative 9) *[direction of search]*. For instance, to move away from cobalt, the company Svolt has dedicated itself to the exploration of cobalt-free battery technology (i.e. cobalt-free NMx battery pack). In 2021 the first cobalt-free batteries were mass-produced by the company in Changzhou. More impressively, CATL made a breakthrough in the sodium-ion battery technology, and introduced its first generation sodium-ion battery as an alternative to ease lithium shortages for battery usage in vehicles (especially low-speed, two-wheeled vehicles) in the same year (Industry Representative 1) *[knowledge development]*. Furthermore,

> "*…new technologies such as solid-state batteries, hydrogen fuel cells, methanol cells, etc. are all currently being experimented and developed, which will significantly improve the performance of battery chemistries while to some degree reduce the use of critical raw materials* " (Industry representative 7).

Moreover, experimentation with process innovations in manufacturing is taking place to improve the material efficiency of the existing chemistries, such as CATL's breakthrough in Cell-to-Pack technology in the NMC batteries, and BYD's launch of the blade LFP batteries (Expert 2) *[experimentation]*.

> “*…Today, the global battery community is engaging in a technological quest for non-scarce materials, …and Chinese battery producers are making a significant contribution to this effort*.” (Intermediary Organization 4)

The most important policy reaction to the surging demand for critical raw materials in the midstream was to encourage the development of hybrid cars in addition to the support for the development of pure battery electric vehicles (BEVs). In the Energy Conservation and New Energy Vehicle Industry Development Plan (2021-2035) issued by the State Council by the end of 2020, incentives have been provided to develop hybrid car technologies as a complementary approach to the development of BEV technologies *[legitimation]*.

> “*China's determination to develop pure battery electric cars has never wavered. However, against the backdrop of battery material shortages, the development of hybrid car technologies is a complementary approach to reducing CO2 emissions in the automotive industry*.” (Industry Representative 20).

In the **downstream**, battery recycling and after-life management is increasingly gaining attention as well. The number of registered power battery recycling enterprises in China rose from 1,019 in 2019 to 3,091 enterprises in 2021 (China Operation Newspaper, 2022), and the output value from this segment is expected to reach 5.25 billion RMB in 2023[7] (Leadleo, 2019b).

In order to recycle and reuse critical materials from retired batteries, midstream actors are investing more and more in the downstream segment and establishing structural couplings. In 2021, the number of investments made by the listed midstream actors to the downstream reached 14, 13, respectively. cf. Table 1 *[resource mobilization]*. For instance, Brunp, a subsidiary of CATL, established a Battery Material Industrial Park Project in Hubei to specialize in battery recycling and reuse in 2021 (Industry representative 2). Moreover, SAIC, one of the largest EV makers in China, reached a strategic cooperation agreement with CATL to jointly promote the recycling and reuse of EV power batteries. Lately, various actors along the value chain such as Guoxuan, Farasis and EVE (battery producer), BASFT China (chemical industry), Huayou (mining and material supply), etc., have all announced their battery recycling and reuse plans and strategies (Industry Representative 4, 8; Official 1).

Midstream actors are also working on reducing the costs of recycling EV batteries by working jointly on industry standards in terms of battery cell and pack design. This is driven partly by government incentives and partly by expectations of both future material scarcity and massive battery retirements (Expert 1) *[direction of search]*. Indeed, a novel, cross-sectoral business model involving electric vehicle manufacturers, battery manufacturers and third-party recycling and processing enterprises is emerging. Electric vehicle manufacturers are responsible for battery collection, professional recyclers for dismantling and recycling, and other manufacturing sectors (e.g., shipping industry, energy storage) for second life reuse and battery manufacturers for procurement of recycled raw materials (Industry Representative 14, 15) *[experimentation]*. However, since the first wave of EVLB retirement

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[7] In comparison, the output of battery recycling and reuse reached 87 million RMB in 2018 (Leadleo, 2019b)

occurred only very recently, a well-functioning battery recycling network is still in development.

In expectation of market growth, downstream actors are also currently exploring new mechanical and hydrometallurgical technologies that can rapidly extract valuable materials from existing battery packs and change the chemistries to ensure successful recycling and reuse (Industry representative 14) *[knowledge development]*.

Regarding recycling and reuse policy, in contrast to the first two phases, in which the motivation for designing battery recycling and reuse policies was to prevent the leakages of hazardous chemicals, the policy focus has now been placed on establishing comprehensive recycling networks to efficiently reuse batteries or recycle the key minerals. For example, several pilot programs have been implemented for the recycling and reuse of EV batteries *[experimentation]*. As can be seen from the various measures published in this phase (e.g., "New Energy Vehicle Power Battery Gradient Utilization Management Measures" in 2020, "Highlights of Energy Conservation and Comprehensive Utilization Efforts in 2020," "Management Measures for the Gradual Utilization of New Energy Vehicle Power Battery" in 2021), these measures aim to encourage enterprises with competence and technological strength to develop the power battery recycling segment and thus promote the standardized development of the downstream sector(Expert 3) *[direction of search]*.

5 Discussion and conclusion

In this section we distil the main findings from our analysis, and discuss their implications for the TIS framework and for policy.

5.1 The role of natural resources in the growth of EV Lithium-ion battery TIS

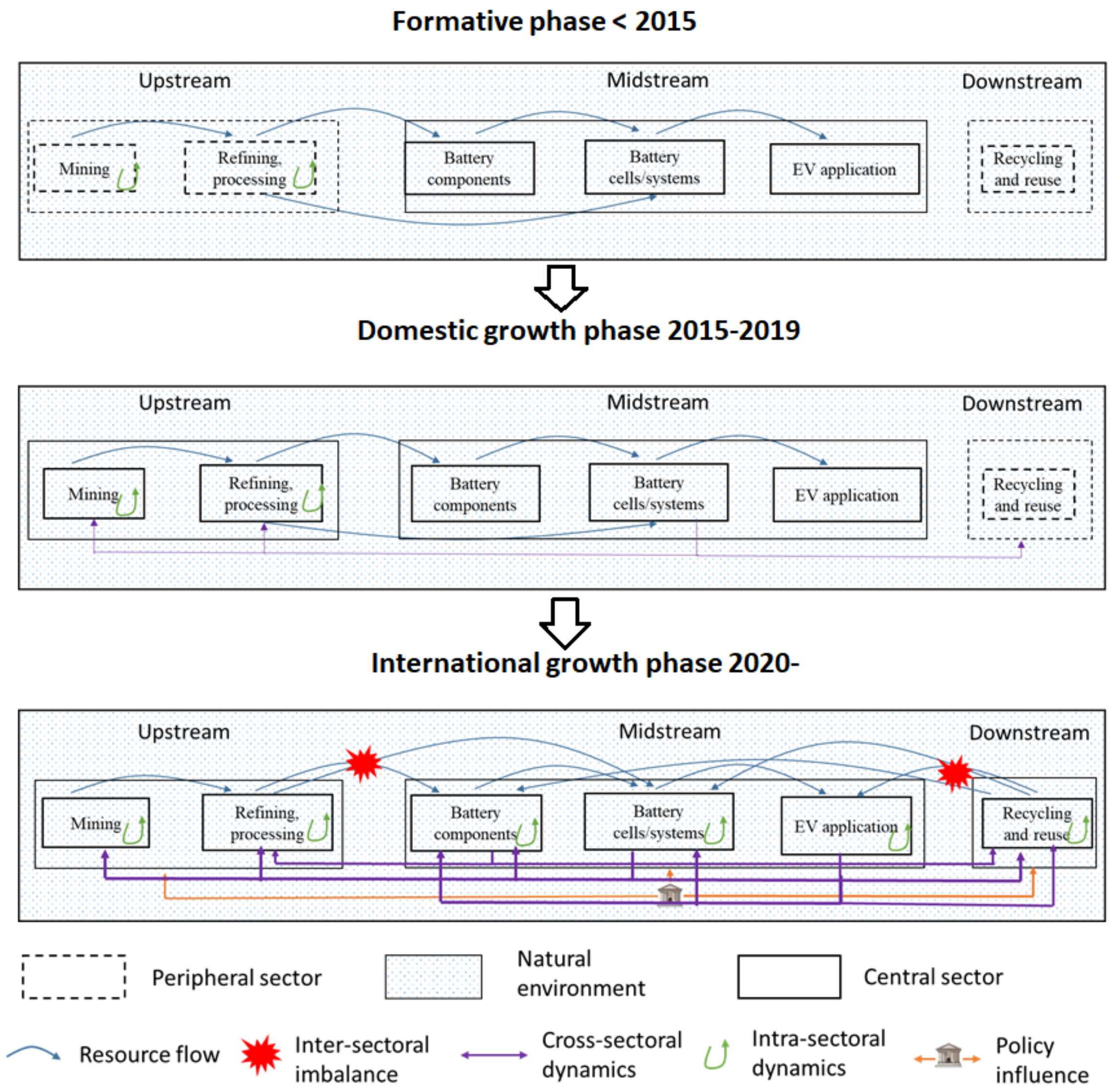
Our analysis showed many nuances of how inter-sectoral imbalances related to natural resources were increasingly important for overall TIS dynamics as the TIS entered a growth phase, see detailed summary of analysis in appendix 6 and 7. Our results are thus consistent with most of our expectations formulated in section 2.4 but also bring additional insights.

In terms of response strategies, in the face of material scarcity, we saw that actors along the value chain engaged in *resource extending* activities in response to cross-sectoral imbalances. For example, in the upstream sectors we saw expansions of mining capacity and development of new mining technologies and new types of mines over time. Moreover, in the midstream, actors invested tremendously in improving the efficiency of production processes to optimize material usage. Finally, in the downstream, we saw both expansions in recycling capacity and innovation in recycling technologies. We also saw that due to expected scarcity, midstream actors attempted to *substitute* the scarce natural resources via search for and experimentation with alternative materials and chemistries (e.g., cobalt-free batteries) within the dominant design category of lithium-ion batteries. Moreover, some actors even started to explore entirely different dominant designs (e.g., solid-state batteries) to substitute for electric transportation. Moreover, policymakers increased support for hybrid vehicles (gasoline-electric)—a competing TIS—to avoid that natural resource scarcity slows down decarbonization of transportation. As expected, we also saw that actors in all value chain segments were involved in response strategies as size and importance of imbalances increased. Indeed, the surge of demand for key resources in the midstream segment started to induce technological changes in up- and down-stream segments.

The analysis of response strategies is closely related to the functions of knowledge development and experimentation to bring forward new innovations to mitigate imbalances. However, our analytical focus on functional dynamics across value chain segments revealed additional nuance to how actors perceive and react to natural resource availability. For example, we saw that natural resource availability influenced the direction of search and expectations of actors in all segments. Actor expectations were moreover central for coordinating agency across value chain segments and legitimacy created through supporting policies was important for shaping those expectations. We also saw that market formation in up- and down-stream segments was driven by market formation in the midstream, i.e. sales of EVs internationally. Interestingly, we found a surge in cross-sectoral interactions (structural couplings) as sectoral imbalances increased. Especially, we saw that midstream actors via different inter-organizational arrangements got involved in up- and down-stream segments. This suggests that midstream actors perceived responses to imbalances in up- and down-stream segments as unsatisfactorily which would be expected based on inter-sectoral differences such as lead times and conservatism in mining.

We also observed important structural dynamics in the TIS such as new entry of actors, new forms of cross-sectoral networks, and new policies to address imbalances. We summarize and illustrate these findings in Figure 3. Next, we discuss conceptual implications of our results.

Figure 3: EV Lithium-ion battery TIS dynamics in different phases due to cross—sectoral imbalances related to natural resource



5.2 Insights for the Technological Innovation Systems framework

Our most general contribution is to conceptualize integrate natural resources in the TIS framework in four ways. First, we explicitly situate a focal TIS (sociotechnical system) in a natural environment from where natural resources are collected and waste returned. Second, we consider the natural resource stock of a TIS as part of the technology component. Third, we approximate natural resource flows in a TIS value chain under the hitherto neglected function of materialization. Lastly, we included both upstream sectors of natural resource provision and downstream sectors of natural resource waste management and recycling. Overall, our analytical framework was useful for understanding how inter-sectoral imbalances related to natural resources influence TIS dynamics, cf. summary in section 5.1. We note that the materialization function is a useful addition to the list of TIS functions, especially for analysing the growth phase where upscaling of the TIS is crucial (Bergek, 2019). Our results hold further new insights for the TIS framework which we will discuss below.

5.2.1 The growth phase of TIS and the dynamics of its sectoral configuration

Our analysis has exposed the limited integration of value chain and life cycle thinking within the TIS framework. Our analysis shows how imbalances in the TIS value chain reverted aspects of the TIS life cycle in the midstream segment. Natural resource scarcity caused increased experimentation with alternative battery technologies thereby partly re-opening the era of ferment. The scarcity also caused an increase in institutional support for hybrid vehicles (a competing solution) illustrated by new policy measures to support such low-carbon vehicle technologies that require less lithium. However, seeing growing technical variety, competing designs, and institutional uncertainty in the growth phase is not what one would expect from theory (Markard, 2020). Indeed, current TIS life cycle theorizing implicitly assumes unproblematic availability of natural resources. To account for the role of natural resources in and present a reasonable account of TIS evolution, TIS life cycle thinking need to look beyond the midstream and adopt a full value chain perspective. Even so, it is not self-evident how the boundaries of a TIS value chain are set. Boundaries were traditionally set by a specific technological field (e.g. battery technology) or/and an application (e.g. EV) (Bergek, Hekkert, et al., 2008). The sectoral configuration of TIS approach suggests that boundaries are set by extent of participating sectors (Stephan et al., 2017). However, from extant research it is not clear what participation implies.

Based on our results, we suggest a new way of managing this issue by distinguishing between peripheral and central sectors in a TIS value chain related to resource flows (see Figure 3). The starting point for delineating the boundaries of a TIS value chain is a focal knowledge field and application sector(s) which constitute the midstream segment.[8] In relation to that, peripheral sectors are those that are important parts of the value chain but deliver inputs via one-way relationships (e.g., in the first phase of development, TIS dynamics in the midstream did not affect peripheral up- and down-stream sectors). Central sectors have two-way relationships with the midstream, i.e. they are affected by and respond innovatively to developments in the midstream (e.g., in the third phase, demand surge for EV batteries have led to responses from the up- and down-stream sectors). Our analysis shows that it changes over time which sectors are peripheral and central, cf. Figure 3. In the formative phase, the midstream was the primary locus of activity in the EVLB TIS. However, in the domestic growth phase, actors in upstream material supply started responding with innovations and investments to changes in midstream. In the current phase, the downstream sectors also become central.

Our findings thus suggest that the sectoral configuration of a TIS and the locus of innovation activity within it can keep changing as the focal artefact diffuses because of cross-sectoral imbalances. Analytically, the latter phenomenon resembles a ‘development block’ which

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[8] Note that we here for simplicity ignore spatial and temporal scopes of delineating a TIS.

describes how a core innovation generates structural imbalances across related technologies and sectors (Carlsson & Stankiewicz, 1991; Dahmén, 1950). Structural imbalances are resolved by entrepreneurs via investments and innovation. Drawing on these insights, we suggest that focusing on cross-sectoral imbalances and responses to them, is a useful approach for integrating TIS value chain and life cycle thinking further, and thus for grasping and analysing the dynamics of TIS value chains across distinct phases of development, cf. Figure 3.

Such dynamic understanding of the sectoral configuration of TIS seems particularly important in the current context of grand challenges that need urgent action. For example, in relation to our case, if there are sufficient natural resources, TIS life cycle theory does not need to think about up- and down-stream segments. But in a context where multiple low-carbon technologies—that typically rely on the same type of natural resources such as nickel, copper, and lithium (Watari et al., 2019; IEA 2012b)—need to scale up and diffuse globally in a short period of time to realize the political goals of net-zero emissions by mid-century (IEA, 2021a), the usefulness and relevance of the TIS framework is arguably much greater if a broader value chain understanding is applied.

5.2.2 Changing nature of cross-sector interactions

Another symptom of limited integration of TIS value chain and life cycle thinking is the absence of theorizing about *how* value chain sectors interact over time. Currently, the literature distinguishes between linkages and couplings, but this is not systematically connected to changes in the TIS.

General life cycle theory suggests that the emergence of a dominant design is associated with vertical disintegration and specialization of firms due to decreasing uncertainty about the direction of technological change, i.e. a shift from couplings (i.e. overlapping actors and networks) to linkages (i.e. arm’s length, market-based relations) in the value chain (Agarwal & Tripsas, 2008; Helfat & Teece, 1987).

However, our analysis shows that opposite development in the TIS growth phase. We observe that due to sectoral imbalances, midstream actors develop a growing number of cross-sectoral relationships leading to structural coupling of sectors. In our case, these relationships manifest in multiple forms—e.g. partnerships, vertical integration, subsidiaries, joint ventures—and are mostly focused on capital flows to boost natural resource flows, i.e. resource mobilization and materialization in up- and down-stream sectors. Some collaborations focusing on recycling materials however concerned knowledge development and integration along the whole value chain.

Our findings suggest that cross-sectoral imbalances create uncertainty for actors and that actors respond to this by creating new structural couplings across the value chain. In this case, couplings thus serve as coordination devices in a situation where price signals do not suffice such as to incentivize mining firms to expand production or for actors to co-develop new knowledge. As we have shown in the empirical part, when sectoral imbalances and uncertainty are low (phase 1 and 2), the cross-sectoral interactions will resemble linkages (i.e. arm's length, market-based relations). However, when imbalances and uncertainty are high, cross-sectoral interactions will more likely resemble structural couplings (i.e. overlapping actors and networks).

Relating these insights to the 'development block' approach to TIS value chain outlined above, we propose that imbalances and uncertainty are important mechanisms driving structural couplings across TIS value chain sectors. Hence, when cross-sectoral interactions are characterized by imbalances, an increase in structural couplings is likely. Without imbalances, cross-sectoral interactions are likely to resemble linkages. Most likely more mechanisms exist (Argyres & Bigelow, 2010; Klepper, 1997), and we suggest that future TIS scholarship should investigate these further to arrive at a better understanding of why, when, and how the sectoral configuration of TIS is dynamic. Understanding such mechanisms is especially important for designing policies to help alleviate cross-sectoral imbalances on the pathway to net-zero.

5.2.3 Circular value chains and Technological Innovation Systems

As a final point, we note that our extension of the TIS approach in this paper enables analysis of moves towards circular value chains. Our approach particularly seems helpful for analysing the emergence of and barriers to cross-sectoral partnerships and business models that attempt to change the way in which value chain sectors interact with each other, i.e. from a linear to circular economy logic (Blomsma et al., 2022).

Our analysis showed that actors only started to pursue circular value chains when cross-sectoral imbalances in natural resources became significant. We observe that in this third phase, several major international EV producers are developing cross-sectoral partnerships with mining and recycling companies outside of China (Bloomberg 2021; The Korea Economy Daily, 2021). This suggests that the speed and scale of decarbonization needed to meet Net-zero goals will be a major driver of circular value chains (Zhou et al 2022). Studying shifts from linear to circular value chains in this context is thus a promising topic for further TIS research.

5.3 Policy implications

Our analysis shows that the policy discourse around grand challenges need to think more about the role of natural resources and upscaling. Our results have implications for policymakers who want to accelerate the diffusion of low-carbon technologies.

First, policymakers can support natural resource extension to address possible scarcity (Zhou et al 2022). As our case showed, this involved supporting expansion of mining and processing as well as management and recycling of material waste. It also includes stimulating innovation along the value chain to improve material efficiency and even pursuing circular chains. A key issue is to incentivize actors and ensure coordinated action across the value chain sectors to avoid imbalances. In this context, industry standards are important to facilitate smooth reversed material flows.

Second, policymakers can also pursue a natural resource substitution strategy. In China, for example, this included both supporting alternative battery technologies for EVs and renewed support for hybrid vehicles that require smaller batteries and less materials. This approach implies a portfolio approach which includes multiple different technologies as option to address the same problem. A more radical solution, which was not observed in China, would be to reduce the number of vehicles altogether and instead promote either more public transit or less transportation. That could present policy strategies for material efficient transition pathways (IEA, 2019). Countries that pursue a mix of natural resource extension and substitution strategies will arguably have most resilient transition strategy.

Third, given the urgency and scale of the net-zero transition, international coordination across governments seems crucial. If countries are uncoordinated and pursue the same strategy (only extension), it is more likely that imbalances will occur somewhere. Finally, forecasting and assessing natural resource needs should become an essential part of net-zero policymaking, as a scenario of sustainability transition that is built on the supply of raw materials can cause many problems in the long run.

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Appendix 1: Functions of technological innovation systems

Development of knowledge	The breadth and depth of the formal, research-based knowledge base and how that knowledge is developed, diffused and combined in the system.
Influence on the direction of search	The extent to which supply-side actors are induced to enter the TIS, or put more subtly, direct their search and investments towards the TIS
Entrepreneurial experimentation	Knowledge development of a more tacit, explorative, applied and varied nature – conducting technical experiments, delving into uncertain applications and markets and discovering/creating opportunities etc.
Market formation	Articulation of demand and more “hard” market development in terms of demonstration projects, “nursing markets” (or niche markets), bridging markets and, eventually, mass markets (large-scale diffusion).
Legitimation	The socio-political process of legitimacy formation through actions by various organisations and individuals. Central features are the formation of expectations and visions as well as regulative alignment, including issues such as market regulations, tax policies or the direction of science and technology policy.
Resource mobilisation	The extent to which the TIS is able to mobilize human capital, financial capital and complementary assets from other sources than suppliers and users and the character of this mobilization.
Materialisation	The development of (and investment in) artefacts such as products, production plants and physical infrastructure.

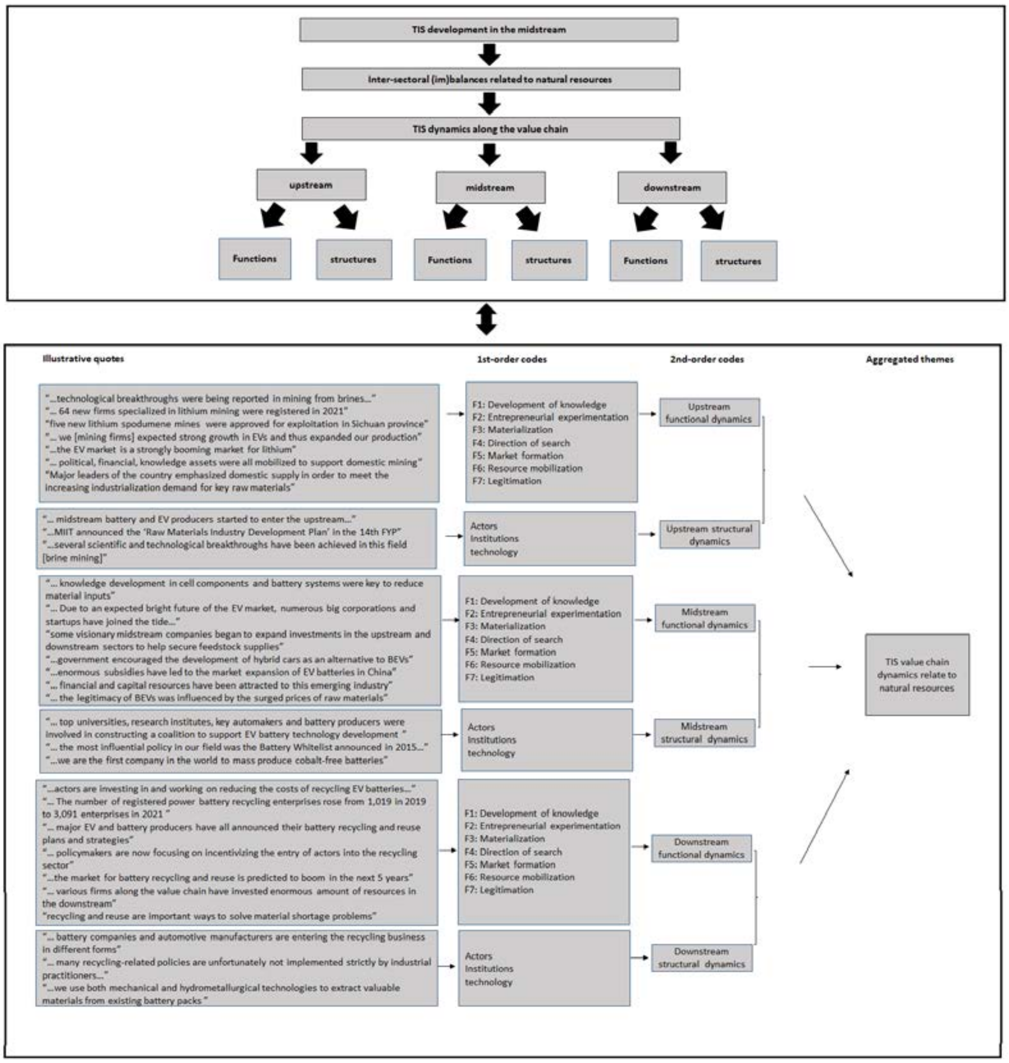
Sources: Bergek (2019), Bergek et al (2008)

Appendix 2 Information on interviewees

Interviewees	**Functions and positions**
Industry representatives	
CATL	RP manager
CATL	Senior engineer
BYD	Engineer
Guoxuan High-Tech	Investment Director
Chiwee	Assistant Director of Industrial Development Department
Tianneng	RP manager, CTO, Engineer (roundtable)
Sunwoda	Investment Director
Eve Energy	Engineer
CALB	Director of Market department
Shenzhen Senior Tech	Board Secretary, CTO, Investment Director(roundtable)
BTR New Material Group	Director, vice Director of Strategic Investment Department (roundtable)
Beijing Easpring Material Technology	Engineer, market manager
Xiamen Tungsten	RP manager
Zhejiang Huayou Cobalt	Investment Director, manager, postdoctoral researcher (roundtable)
GEM	Group Vice President, Director of strategy department, Director of international Department, researcher (roundtable)
Guangyhou Tinci Materials	Engineer
Shenzhen Capchem	Senior Engineer
Volkswagen China	Manager, Investment Department
FAW Group	Vice Director, Investment Department
Geely Auto	Senior Vice President
Industry associations and intermediary organizations	
China EV 100	Secretary General
China EV 100	Director of the International Centre
China EV 100	Head of Research Department
CATARC	Researcher
Battery Industry Association Guangdong	Secretary General
Experts, research institutions	
School of Automotive Vehicles and Transport, Tsinghua University	Professor
Institute of Process Engineering, Chinese Academy of Science	Senior Researcher
Development Research Centre of the State Council	Postdoctoral researcher
School of Mechanical Engineering, Beijing Institute of Technology	Professor

New Energy Vehicle Engineering Centre, Tongji University	Postdoctoral researcher
Officials	
Equipment Centre, Ministry of Industry and Information	Officer
Beijing Bureau of Industry and Information Technology	Head of Industry Section
Department of High and New Technology, Ministry of Science and Technology	Officer

Appendix 3 Data structure



"...technological breakthroughs were being reported in mining from brines..."
"... 64 new firms specialized in lithium mining were registered in 2021"
"five new lithium spodumene mines were approved for exploitation in Sichuan province"
"... we [mining firms] expected strong growth in EVs and thus expanded our production"
"...the EV market is a strongly booming market for lithium"
"... political, financial, knowledge assets were all mobilized to support domestic mining"
"Major leaders of the country emphasized domestic supply in order to meet the increasing industrialization demand for key raw materials"

"... midstream battery and EV producers started to enter the upstream..."
"...MIIT announced the 'Raw Materials Industry Development Plan' in the 14th FYP"
"...several scientific and technological breakthroughs have been achieved in this field [brine mining]"

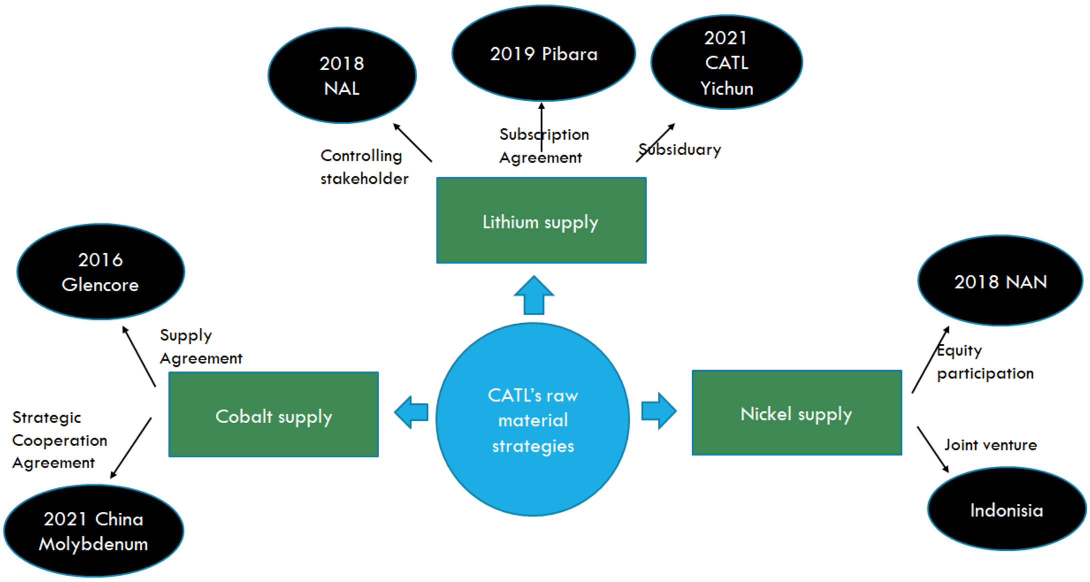
"... knowledge development in cell components and battery systems were key to reduce material inputs"
"... Due to an expected bright future of the EV market, numerous big corporations and startups have joined the tide..."
"some visionary midstream companies began to expand investments in the upstream and downstream sectors to help secure feedstock supplies"
"...government encouraged the development of hybrid cars as an alternative to BEVs"
"...enormous subsidies have led to the market expansion of EV batteries in China"
"... financial and capital resources have been attracted to this emerging industry"
"... the legitimacy of BEVs was influenced by the surged prices of raw materials"

"... top universities, research institutes, key automakers and battery producers were involved in constructing a coalition to support EV battery technology development "
"... the most influential policy in our field was the Battery Whitelist announced in 2015..."
"...we are the first company in the world to mass produce cobalt-free batteries"

"...actors are investing in and working on reducing the costs of recycling EV batteries..."
"... The number of registered power battery recycling enterprises rose from 1,019 in 2019 to 3,091 enterprises in 2021 "
"... major EV and battery producers have all announced their battery recycling and reuse plans and strategies"
"... policymakers are now focusing on incentivizing the entry of actors into the recycling sector"
"...the market for battery recycling and reuse is predicted to boom in the next 5 years"
"... various firms along the value chain have invested enormous amount of resources in the downstream"
"recycling and reuse are important ways to solve material shortage problems"

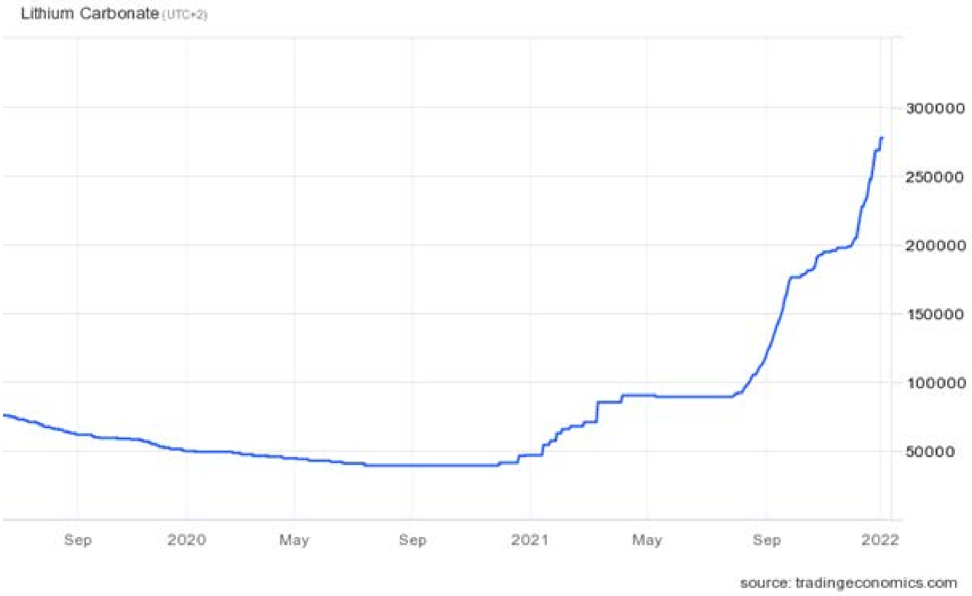
"... battery companies and automotive manufacturers are entering the recycling business in different forms"
"... many recycling-related policies are unfortunately not implemented strictly by industrial practitioners..."
"...we use both mechanical and hydrometallurgical technologies to extract valuable materials from existing battery packs "

Appendix 4: CATL’s (partial) strategic actions in securing critical raw materials supply



Source: own compilation based on CATL’s annual reports

Appendix 5: Lithium carbonate price change



source: tradingeconomics.com

Appendix 6: Summary of TIS functional dynamics related to natural resources

	Phase 1			Phase 2			Phase 3		
Function	Upstream	Midstream	Downstream	Upstream	Midstream	Downstream	Upstream	Midstream	Downstream
Knowledge development and diffusion (F1)	Technological breakthroughs in spodumene mines	Development and knowledge accumulation in LFP battery technology	Limited knowledge development	technological breakthroughs in a new lithium extraction technology (lepidolite)	Development and knowledge accumulation in NMC battery technology (high energy density, but require critical raw material inputs, e.g., cobalt, lithium)	Limited knowledge development	Technological breakthroughs in mining from brines with high Mg2+/Li+ ratio	New battery design research Design battery for recycling	-New R&D investments on battery recycling/reuse - Development of mechanical and hydrometallurgical technologies for recycling
Influence on the direction of search (F2)	Expansion of production in the expectation of strong growth in EV market	-Direction of search was based on technology competence and knowledge accumulation of domestic firms	/	Expansion of production in the expectation of strong growth in EV market	NMC technology surpassed LFP technology in market share due to strong preference of key policy documents	/	-Expecting major growth in midstream and shortages -Policy support for expanding domestic mining	-Expecting major growth in EV and shortage of natural resource -Policy encouraged multiple technological trajectories due to material concerns	-Expecting major growth in EV and shortage of natural resource from upstream -policy incentivized entry
Entrepreneurial experimentation (F3)	/	Commercialisation of LFP and other battery technologies	Limited activities	/	Commercialization and mass-production of MNC and LFP battery technologies	-Visionary actors from midstream invested in pilot projects in downstream -Conventional recyclers moved into this new field	-New projects and solutions	-New battery projects focused on new technology exploration -New manufacturing process	-recycling network pilots - increased number of registered firms specialized on battery recycling and reuse

Appendix 6 continued

	Phase 1			Phase 2			Phase 3		
Function	**Upstream**	**Midstream**	**Downstream**	**Upstream**	**Midstream**	**Downstream**	**Upstream**	**Midstream**	**Downstream**
Market formation (F4)	EV market exploration showed the potential of this emerging market for lithium demand	Early EVLB market exploration	/	Domestic EVLB market boom led to further market formation for raw materials	Domestic EV and battery market boom	Limited market formation, as recycling and reusing the raw materials from retired batteries was still expensive	Pull from midstream	Global EVLB market boom	Pull from midstream
Legitimation (F5)	/	Strong policy incentives to form an initial socio-technical configuration that worked in the midstream	/	/	Strong policy incentives to upscale the socio-technical configuration that proved to work in the midstream	/	-Policy strategy on raw material sufficiency	-Policy support for hybrid vehicles as alternative (-)	-strengthened policy support for recycling
Resource mobilization (F6)	/	Political, financial and human capitals flowed into the emerging battery field for technology catching up	/	Political, financial and human capitals flowed into the midstream to construct a domestic battery value chain	Some investments from visionary actors from midstream	Some investments from visionary actors from midstream	-Investment by midstream actors -Policy support by local and central governments	Political, financial and human capitals being mobilized to form global leaderships in midstream sector	-Investment by mid- and down-stream actors -Government incentives
Materialization (F7)	New spodumene mines being approved for extraction	/	Policy encouraged the construction of battery recycling networks and infrastructure although not being implemented strictly	-Expanded lithium production from spodumene sources -New lepidolite mines being approved for extraction	Policy encouraged the construction of battery recycling networks and infrastructure although not being implemented strictly	/	-Open new mines and increase processing capacity -Policy support for domestic production of key raw materials	-Major expansion of production capacity and EV use	-Expansion of capacity -Construction of battery recycling networks and infrastructure

Appendix 7: Summary of TIS structural dynamics related to natural resources

	Phase 1			Phase 2			Phase 3		
Function	**Upstream**	**Midstream**	**Downstream**	**Upstream**	**Midstream**	**Downstream**	**Upstream**	**Midstream**	**Downstream**
Actors	Limited new entry	New actors and networks focusing on technology catch-up	/	Limited new entry	Major growth in number of actors	Limited number of early entrants	New entrants	Consolidation, number of firms remain stable	Major growth in actors
Institutions	/	Policy support for battery production	/	/	Policy support EVLB market growth	/	New policy	Policy support for hybrids in transport	Battery recycling network pilot projects
Technology	Technological breakthroughs in spodumene mining	Development of LFP technology;	/	Technological breakthroughs in lepidolite mining	Development of NMC technology;	/	Technological breakthroughs in brine mining	New battery designs	Mechanical and hydrometallurgical technologies