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# The role of material resources for rapid technology diffusion in net-zero transitions: Insights from EV lithium-ion battery Technological Innovation System in China

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ABSTRACT

A key challenge to achieving a net-zero transition by mid-century is rapid diffusion of several low-carbon technologies which requires massive upscaling of production capacity including vast use of material resources. However, both diffusion theory and main transition studies frameworks pay insufficient attention to the role of material resources. To better understand the relationships between diffusion, production, and material use in technology diffusion and transitions, we conceptually elaborate the role of material resources in the value chain perspective on Technological Innovation Systems (TIS). We account for how material scarcity appears and how it influences TIS structural and functional dynamics with particular attention to how actors along the value chain respond. Our study of China's Electric Vehicle lithium-ion battery TIS value chain shows that a shortage of critical materials occurred due to structural tensions between sectoral regimes along the value chain which influenced the TIS structural and functional dynamics both within and across sectors. The study contributes new insights on the role of materials in TIS and circular value chains, on how the TIS growth and diffusion phase unfolds, and on how urgency of a net-zero transition and geopolitics influence diffusion.

## 1. Introduction

Climate change mitigation implies that the world needs to reduce greenhouse gas (GHG) emissions at unprecedented speed and scale. In response a rapidly growing number of companies and governments pledge to achieve a net-zero transition by mid-century (Höhne et al., 2021; IEA, 2021a). However, there are only few coherent and concrete plans for how to achieve net-zero and the concept of net-zero itself needs a social science framework around it to make it actionable (Fankhauser et al., 2022). The notion of a net-zero transition thus introduces several new challenges to transition scholars and policymakers (Andersen et al., 2023a, 2023b; Markard and Rosenbloom, 2022).

One new challenge is about rapid diffusion of low-carbon technologies such as solar PV, wind, and electric vehicles (EVs). Due to the mid-century deadline, these technologies must diffuse in most countries simultaneously (IEA, 2021a). This expected diffusion requires a major expansion in manufacturing capacity. The electrification pathway alone will require a 3–5 fold increase in electricity supply technologies, massive expansion of grids, and tens of millions of new EVs (IEA, 2021a). The net-zero transition thus requires both rapid diffusion *and* major upscaling of low-carbon technology value chains (IEA, 2022). While it is well-known that large technological shifts often impact material resource needs (Diemer et al., 2022; Freeman and Louçã, 2001; Li et al., 2024), the enormous scale and unprecedented speed of the net-zero transition are generating concerns that scarcity of material resources could create bottlenecks for the transition if adequate policy measures are not implemented (Bazilian, 2018; IEA, 2021b).

Conventional diffusion theory focusses on technology adoption by rational agents in markets with consideration for individual traits, context, and feedback effects (Hall, 2004). More recent theorizing on diffusion takes a broader approach and emphasizes societal embedding of innovations, considers both market and non-market mechanisms, and embraces the 'messiness' and multiple routes of generalizing innovations (Meelen et al., 2019; Turnheim et al., 2018; Kanger et al., 2019). More fundamentally, while early theory viewed innovation and diffusion processes as largely separate, more recent work considers these

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as parallel and interacting such that innovation remains an ongoing process characterized by reoccurring bottlenecks, re-embedding, and experiments (Garud et al., 2013). The central theoretical frameworks in transitions research such as the Technological Innovation System (TIS) approach and the Multi-level Perspective are largely aligned with latter approach by considering diffusion as a multi-dimensional and non-linear process involving the building of a new system around a focal innovation which is characterized by structural changes and embedding (e.g. new actors, networks, and formal and informal institutions) as well as key processes/functions (e.g. knowledge development, resource mobilization, and legitimation) (Bergek et al., 2008; Geels and Johnson, 2018; Köhler et al., 2019). Transition studies is also attentive to tensions and bottlenecks that may appear during the diffusion process and slow it down (Mäkitie et al., 2022; Löhr and Mattes, 2020; Skjølsvold and Coenen, 2021).

However, common for all these approaches is insufficient attention to the importance of upscaling of technology value chains to support rapid diffusion (Andersen et al., 2020; Köhler et al., 2019), and in particular the role of material resources in that process (Andersen et al., 2023a, 2023b; Marín and Goya, 2021).

Against this background, the research objective of this paper is to propose a new way of endogenizing and understanding the role of material resources in technology diffusion and value chain upscaling in the context of net-zero transitions. In doing so we focus on the TIS approach as a diffusion framework because (a) it distinguishes a formative phase from a diffusion phase (Markard, 2020), (b) because recent development of a multi-sector value chain approach to TIS is promising for understanding value chain upscaling in diffusion (Andersen and Markard, 2020; Stephan et al., 2017), and (c) because the value chain approach facilitates more explicit conceptualization of the role of material resources in diffusion (Rosenberg, 1976; David and Wright, 1997). By providing a novel integration of these strands of literature we advance the TIS framework's account of diffusion dynamics. Our main research questions are:

> RQ1: Why do inter-sectoral imbalances related to material resource flows occur during technology diffusion?
>
> RQ2: How do such imbalances influence TIS value chain dynamics, and actor strategies?

We pursue these research questions by applying and exploring the merits of our proposed framework in a unique case study of the EV lithium-ion battery (EVLB) TIS in China where material scarcities influenced technology diffusion. We analyse the causes of material inter-sectoral imbalances in the TIS value chain and how actors perceive and respond to such imbalances. We focus on the strategies of firms along the focal technology value chain, as well as policymakers.

The paper makes three contributions: *First*, it extends the TIS framework by introducing an explicit conceptualization of material resources and by further integrating TIS phases with the value chain approach to ultimately advance a better understanding of diffusion. We show how innovative responses to material scarcity by actors reopen the era of ferment during diffusion and spread the locus of innovation across the value chain. We also show that actors build new structural couplings across sectors to mitigate structural tensions along the value chain. *Second*, we contribute to more general diffusion theory by showing how material resources can influence diffusion highlighting the relevance of a value chain perspective. *Third*, we present a first empirical case study to explain the emergence and mitigation of material constraints in the growth and diffusion phase of the Chinese EVLB TIS. The case study also shows how the urgency of a net-zero transition and emerging concerns related energy security and geopolitics influence value chain dynamics.

## 2. Theoretical background

In this section we introduce the TIS approach, elaborate a multisectoral value chain perspective on TIS, introduce TIS phases, and the role of material resources in innovation. After that, we integrate these building blocks to articulate a framework for analysing inter-sectoral imbalances related to material resources in TIS value chains.

### 2.1. Technological Innovation Systems as multisectoral value chains

A TIS is defined as a set of actors, networks, and institutions—the system elements—that jointly interact in a specific technological field and contribute to the generation, diffusion, and utilization of a focal technology under influence of an external context (Bergek et al., 2015).

TIS progress can be understood and evaluated in terms of a set of resource formation processes or functions (see Appendix 1) which lead to the creation and accumulation of complementary resources such as knowledge, legitimacy, demand, and specialized labour (Musiolik et al., 2012; Musiolik and Markard, 2011). If system elements are misaligned internally and/or with context elements, it will manifest as weak functions (Markard and Truffer, 2008). To strengthen functions, actors engage in system building activities that involve 'deliberate creation or modification of broader institutional or organizational structures' such as enrolling new actors, and creating new networks or institutions (Musiolik et al., 2012, p. 1035).

This mainstream definition implies a distinction between a material technological system (or focal technology) and a socio-institutional support system comprised of actors, networks, and institutions, i.e. the TIS (De Liso and Metcalfe, 1996). Change in the material system is guided by the TIS. The material system is thus the system 'that is innovated' and the TIS is the system 'that innovates'. These systems therefore 'mirror' each other's configurations and co-develop over time (Andersen et al., 2023a, 2023b; Colfer and Baldwin, 2016; Markard, 2020). The performance of a TIS is indicated by the formation and diffusion of the material technological system.

The technological system of interest is typically the starting point for demarcating the boundaries of the TIS (Bergek et al., 2008). Technology can be seen as a complex and nested system (e.g., electric vehicle) that can be divided into subsystems (e.g., battery pack, motor, controls), which in turn may be divided into lower order subsystems (e.g., battery cells or compounds), and so on. Consequently, a TIS can be meaningfully delineated both as a single or a set of linked subsystems. Due to the recursive nature of technological systems, they typically involve several subsystems and therefore require specialized knowledge from various sectors. As a consequence, most TISs cross and connect multiple sectors (Stephan et al., 2017; Sandén and Hillman, 2011).

A sector is composed of three types of elements including a set of actors producing a specific set of products (e.g. chemicals, cars, steel, or electronics) or services (e.g. electricity supply or finance) through use of technologies and knowledge under sector-specific formal and informal institutions (Malerba, 2002; Geels, 2004). Operation and change in sectors are guided by a dominant sociotechnical configuration of actors, technology, and institutions—which we refer to as a sectoral regime—that outline the positions, roles, and relationships of actors, as well as problem framings, business culture, and mode of innovation.[1] Sectors

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[1] Note that while sociotechnical regimes cover both production and consumption (Geels, 2004), sectoral regimes mainly cover the production domain. In a value chain perspective, production and consumption however happens in different sectors. To explicate how sociotechnical configurations in several sectors not only differ but also how they interact, we use the sectoral regime concept.

may also contain niche sociotechnical configurations that complement or compete with the regime (Malerba, 2005; Geels, 2004; Wirth et al., 2013). A main reason for using a value chain approach to TIS is that the sectoral regimes involved in a TIS differ in multiple dimensions. Such differences can result in inter-sectoral structural tensions[2] impeding the TIS. TIS subsystems are thus embedded in and function under influence from different sectoral regimes (Bergek et al., 2015).

The interactions between TIS value chain sectors are therefore important for TIS performance. Scholars understand sector interactions as functional couplings (exchanges of resources that create functional (inter)dependencies) and as structural couplings (i.e. technological, institutional, or organizational connections between sectors) (Konrad et al., 2008). Structural couplings often enable cross-sector resource flows e.g. by being institutionally connected via markets or technologically coupled via wires or pipes (Andersen and Geels, 2023; Binz and Truffer, 2017).

To better understand and characterize the influence of various involved sectors on TIS dynamics, researchers have recently started to use concepts as TIS value chain or 'sectoral configuration' of TIS (Malhotra et al., 2019; Stephan et al., 2017; Andersen and Markard, 2020). However, this emerging work stream did so far not explicitly consider particularities of diffusion or the role of material resources therein.

### 2.2. Technology diffusion and the TIS growth phase

According to TIS life cycle theory, diffusion of a focal technology in a particular sector requires that the TIS shifts from a formative phase to a growth phase (Markard, 2020). The formative phase is characterized by low sales and sales growth, high uncertainty and technical variation (i.e. competing designs), product innovations, and extensive experimentation by pioneering actors (Anderson and Tushman, 1990). The growth phase, in contrast, is characterized by decreasing technological variety, emergence of a dominant design and initial low sales followed by rapid growth. The locus of innovation moves from competing designs to improving subsystems and components within one design. The dominant design is typically associated with vertical disintegration and specialization of firms in a particular value chain configuration based on actors' resources (Markard, 2020; Tushman and Rosenkopf, 1992). The phase is characterized by upscaling of production capacity along value chain and increasing institutional alignment internally and externally (Agarwal and Tripsas, 2008; Bergek et al., 2008).

The TIS growth phase has received limited attention (Bergek, 2019; Markard et al., 2015) and although we know that cross-sectoral bottlenecks often hamper diffusion (Kanger et al., 2019; Mäkitie et al., 2022), a value chain perspective on the growth phase is so far absent.

### 2.3. Material resources and innovation

Although innovation and transition studies has largely neglected material resources as well as interactions between technological and ecological systems (Ahlborg et al., 2019; Andersen et al., 2018), it is widely acknowledged that the relative availability and price of such resources influence and even shape frontier technological dynamics of the contemporary society (Diemer et al., 2022; Li et al., 2024; Mokyr, 1992). The underlying perspective is that technological systems are immersed in a biophysical environment wherefrom materials are extracted, services obtained, and to which waste materials are returned (Clark and Harley, 2020; Andersen and Wicken, 2021).

Historically, there have been two main innovation responses in face of material scarcity (Rosenberg, 1976). First, innovations that extend the efficiency of existing resources, including (a) increases in production output per unit of resource input (e.g. manufacturing process innovations), (b) productivity increases in resource extraction processes (e.g. mining), (c) improved exploration and discovery (e.g. geological methods), and (d) new technologies to recycle and reuse waste. Second, innovations that create substitutes for scarce resources, including (e) creating new materials while leaving the end product unchanged and (f) innovations in end products that reduce need for scarce resources maintaining similar functionality (Rosenberg, 1976).

Although foundational TIS papers have not explicitly included material resources (Bergek et al., 2008), some subsequent papers have incorporated them under the resource mobilization function which otherwise focuses on human, financial, and infrastructure resources (Hojckova et al., 2020; Nurdiawati and Urban, 2022). A few TIS studies identify material scarcity as a blocking mechanism for TIS formation (Wirth and Markard, 2011; Giurca and Späth, 2017). Even so, material resources tend to be seen as a given, external factor, leading to limited attention to how material scarcity appears or how actors respond to it.

### 2.4. Analytical framework: material resources and TIS value chain dynamics

We combine the reviewed literatures to propose a novel analytical approach that explicate the role of material resources in TIS evolution in three steps (see Fig. 1).

*First*, we distinguish between technological system (focal technology) and TIS to explicitly include the material resource dimension in TIS analysis. The focal technology is an accumulation of material resources operating in a wider biophysical environment from which materials are obtained. Growth of the focal technology depends on the strength of the associated TIS. Accordingly, we suggest that material scarcities often arise from structural tensions in the TIS value chain rather than from the biophysical environment itself.
*Second*, we differentiate three major segments of a TIS value chain: the upstream input sectors (e.g. raw material provision), midstream sectors (e.g. material resource transformation into technological artefacts and the use of them), and downstream recycling and reuse sectors dealing with the second life of the material resources. Our TIS value chain is delineated by flows of material resources. Material scarcity in one subsystem (e.g. in the midstream) may arise from weaker performance in another (e.g. in the upstream or downstream). Underlying inter-sectoral imbalances in material flows are structural tensions between value chain sectoral regimes that manifest as weak functions at the level of individual subsystems/sectors in the value chain (van Welie et al., 2019). We expect that actors when confronted with structural tensions respond with system building activities that address TIS deficiency both within and across sectors.
*Third*, we expect that material resource imbalances are more likely to be important for TIS dynamics in the growth and diffusion phase where it can influence how value chain sectors produce and use materials as well as how they interact with each other.[3]

## 3. Research design and methodology

### 3.1. Case selection and description

This paper aims at theory development through an in-depth case study, which is an appropriate method for developing theoretical

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[2] We agree with Hojckova et al. (2020) that sectors can be viewed as technological systems (e.g. the electricity supply sector/system or lithium mining subsector/subsystem). Still, in this paper we retain the use of the term 'sector' to emphasize socio-institutional specificities of each sector, which is orthogonal to a cross-sector socio-institutional configuration associated with a TIS value chain (Markard and Truffer, 2008).

[3] For discussion on other resource constraints in the growth phase, such as capital and competencies/skilled labour, see Karltorp (2016) and Jacobsson and Karltorp (2012).

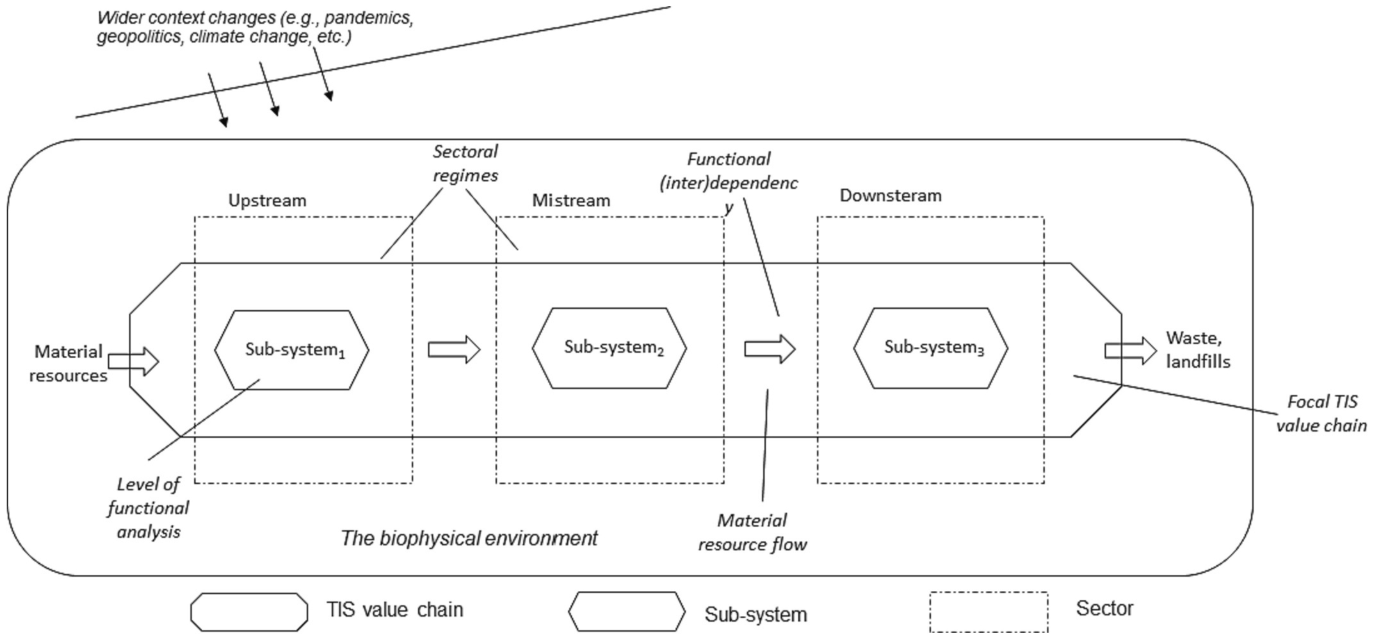

**Fig. 1.** Conceptual framework.

explanations for phenomena that is not well understood (Yin, 2009). Informed by theoretical sampling (Yin, 2009), we chose to study China's lithium-ion battery TIS for four reasons. *First*, EVs is a central technology for the ongoing net-zero transition and whose diffusion is being influenced by material resource concerns (IEA, 2021b). Second, China has a full EV value chain and is a global leader in both battery production and use of EVs that have grown faster than anywhere else in recent years (see Fig. 2). In the last years, the EVLB TIS in China has entered a growth and diffusion phase, which is yet to happen in most other countries. Third, in that growth phase inter-sectoral imbalances related to material resource flows have occurred with major impacts on the TIS. Fourth, actors in the TIS have pursued a variety of interesting and different system building strategies to mitigate material imbalances.

Our temporal scope of analysis is from mid-1990, when the EVLB TIS started forming, until 2022. Spatially, we focus on China. However, as raw material provision is a global market and because China is a major exporter of EV batteries, we refer to events taking place outside China when relevant for what happens within China.

Based on the insights from our interviews, as well as the growth in EV battery production volume shown in Fig. 2, we categorized 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 experimentation with battery technologies and initial market development with generous financial subsidies from the government for private and public EV purchases. The *second phase* (2015–2019) was characterized by a focus on lithium-ion battery technology and strong growth in the *domestic* EV market, triggered by strong subsidy programmes and the introduction of domestic market protection measures by the central government. The *third phase* (2020–) further accelerated sales growth due to a strong increase in demand for EV batteries in both the domestic and global markets during the COVID-19 pandemic, and the projected arrival of the 'TWh period' 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. We thus split the TIS growth and diffusion phase in an early (phase 2 of EVLB value chain) and a late (phase 3) period to get a more granular understanding of its dynamics, cf. Fig. 2.

### 3.2. *Data collection and analysis*

The sectoral configuration of our focal TIS value chain is depicted in Fig. 3. We analysed the impact of material resources on TIS dynamics in terms of TIS functions (Appendix 1) and changes in system components *within* each value chain segment (i.e. *intra-sectoral dynamics*), as well as *inter-sectoral dynamics* (functional and structural couplings). Our TIS analysis is partial because we only analyse TIS dynamics related to material resources. 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.

The paper draws upon three main data sources. First, we used 35 in-depth individual and group interviews with top two or three companies in each segment along the value chain, policymakers, industry associations, third-party think tanks, and scholars in China between October 2020 and March 2021, and in January 2023 (for details, see Appendix 2). On average, each interview lasted around 1 h with some lasted more than 2 h. All interviews were recorded and the recordings were transcribed. Second, we used secondary data compiled from various sources including yearly reports of companies, internal materials of intermediary organizations/think tanks, media reports, professional magazines, industry reports, public speeches by key policymakers, experts, and important organizations. Third, the first author participated in three policy discussion events in Beijing and in three national conferences held between December 2020 and January 2021. Through observations in those events, we had a good opportunity to understand concerns about raw materials and related policy discussions in the value chain. These sources of data enabled us to identify cross-sector imbalances and to gain a better understanding of why and how such imbalances had emerged (RQ1) as well as how the TIS and its main actors respond to them (RQ2).

For data analysis, we combined interpretation-focused coding with presumption-focused coding (Adu, 2019). The purpose of the former is to describe what interviewees said and interpret why they did so, whereas the purpose of the latter coding strategy is to develop a theory or model to explain the phenomenon in which researchers are interested. Based on our coding we grouped together relevant themes into three phases of development. For each phase, we assessed whether and why inter-sectoral imbalances related to material resources appeared in the value chain (RQ1), and analysed how these influenced each value

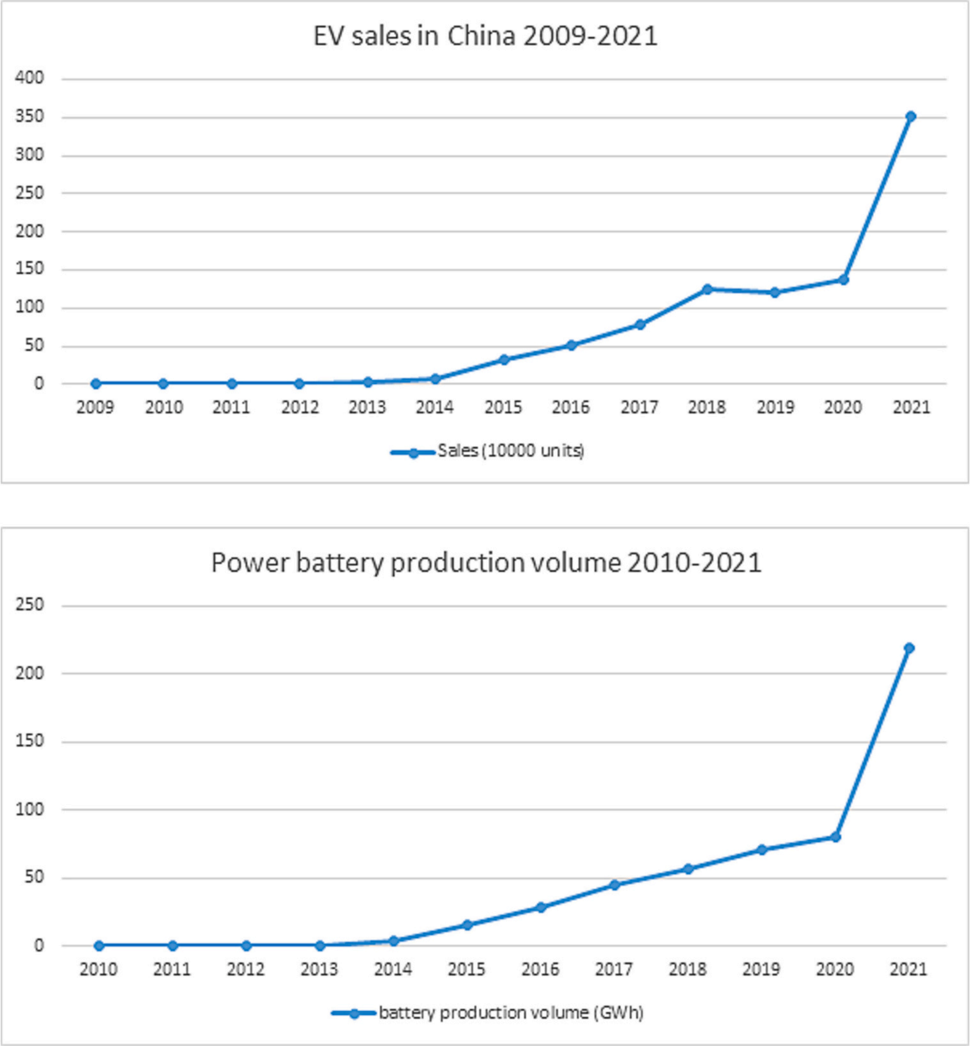

**Fig. 2.** EV and related battery markets in China.
(Source: based on data from China Association of Automobile Manufacturers)

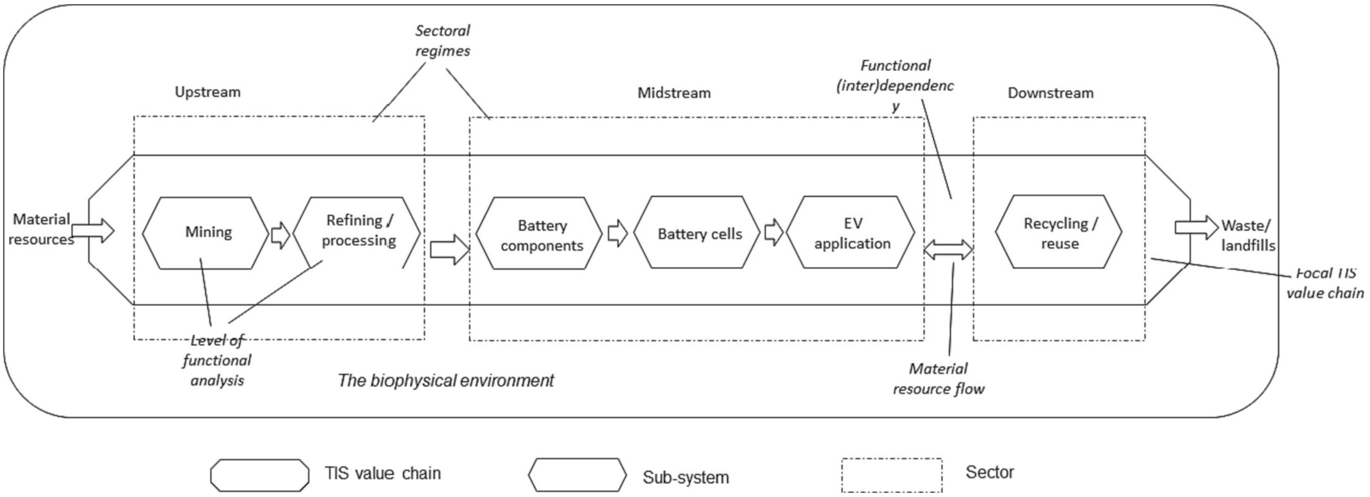

**Fig. 3.** The EVLB TIS value chain.

chain segment in terms of functional and structural dynamics as well as interactions between value chain segments (RQ2). Based on the various sources of data, we try to empirically tease out the different dimensions of the sectoral regimes along the battery value chain (Section 5.1). For our data coding schemes, we first conducted an open coding by labelling and highlighting activities, actors, and events related to the upstream, midstream, and downstream sectors. The outcome of that 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, which we connected to insights from the literature and our analytical framework.

## 4. Analyses: material resources and EVLB TIS evolution

### *4.1. Formative phase: mid-1990s–2014*

### *4.1.1. Material resources and intersectoral imbalances*

China's interest in battery technology for EVs started in the mid-1990s. In the following decade, substantial public R&D investments enabled domestic firms to catch up with global leaders (Expert 5). The development of EV batteries gained substantial momentum in the early 2010s, following the successful deployment of e-buses during the Beijing Olympics in 2008 and Expo 2010 in *Shanghai.*[4]

The resource supply-demand relationship between different sectors was not a major issue in the formative phase since the EV market was small. Material resources flowed via market-based relationships (Expert 4). However, before the emergence of batteries with high energy density, lithium carbonate was used to produce ceramics, glass, grease, and other products. Due to its broad industrial applications, China had long noticed its importance and focused on securing the supply of lithium for the industrialization of the country (Industry Representative 12). This was confirmed by the China Non-Ferrous Metals Industry Association (GOV.CN, 2005), which reported that since 2002 China had risen to become the world's largest producer and consumer of nonferrous metals (including lithium). The possession of a large volume of raw materials (e.g. nickel, cobalt, lithium, copper) needed for industrialization has also been helpful for the development of the domestic EVLB TIS (Industry representative 9, Expert 4).

### *4.1.2. Material resources, TIS dynamics, and actors' strategies*

While the early development of the EVLB TIS did not lead to strong surge in demand for materials for the manufacture of batteries, actors along the value chain have implemented some material resource strategies.

In the *upstream* segment, several actors were expecting strong growth in the EV market and thus for lithium (Industry representatives 12, 13) *[F2]*. Based on this expectation and combined with the booming battery demand for electronic devices, upstream players tried to increase their productivity in resource extraction processes and to expand their lithium production capacity [*F6*] (Leadleo, 2019a). However, the drive to expand material supplies was constrained by strict regulations in the sector. The mining industry has always been highly regulated in China, due in part to concerns about environmental degradation in mining areas and in part to national security considerations. Rather than focusing primarily on domestic mining, the Chinese government has been promoting global sourcing of cheap and concentrated raw materials to meet the need for its industrial development. Domestic material resources were seen as important for security in the event of war or geopolitical tensions (Industry representative 21). For instance, only five new lithium spodumene mines[5] were approved in Sichuan Province, the main concentration of lithium resource, between 2008 and 2013 (Minmetals, 2021) [*F6*]. However, there has always been technological innovations in lithium mining and exploration, which helped to increase the productivity of the spodumene mines (Industry representative 12) *[F1]*. Despite this, the long lead time[6] of the mining projects means that increases in crude lithium and associated lithium salt production volumes can only be achieved gradually, as one of our interviewees pointed out:

> 'in an ideal situation, bringing new mines online can typically take five to eight years […] If uncertainties arise, it can take up to ten years.'
>
> (Industry representative 22)

Essentially, investments and innovations in the formative period and the delayed realization of production helped to meet demand growth in the second phase, and this will be explained in the next subsection.

With regard to the *downstream* battery recycling and reuse, development in this segment was limited, but environmental concerns about spent batteries led to policies for regulating battery recycling. For instance, in 2012, the *State Councils Energy Conservation and New Energy Vehicle Industry Development Plan (2012−2020)* formulated a regulation for battery recycling and reuse. However, concern about material scarcity was not the main motivation for the regulation (Expert 3).

### *4.2. Domestic growth phase: 2015–2019*

### *4.2.1. Material resources and intersectoral imbalances*

The second phase of the EVLB TIS development was characterized by a boom in the domestic EV market, triggered by strong subsidy programmes and the introduction of domestic market protection measures by the central government (Gong and Hansen, 2023). As a consequence, CATL became the global top 1 EVLB supplier in 2017 (Benchmark Mineral Intelligence, 2020), and several competitive Chinese actors appeared in battery component manufacturing. A TIS value chain, including material processing, component manufacturing, cell and pack production, and EV application, emerged in China (Gong and Hansen, 2023). As a result of such midstream expansion, the influence on upstream materials supplies gradually became visible. Nevertheless, material scarcity was not yet a major concern, primarily because the lithium mining projects initiated between 2008 and 2012 started to produce in the domestic growth phase (Industry representative 21). Lithium was thus still largely traded via market-based relationships (Expert 1).

### *4.2.2. Material resources, TIS dynamics, and actors' strategies*

In the second phase of the EVLB TIS development, growing demand for lithium from EVLB production led to changes along the TIS value chain.

In the *upstream* sector, expectations of EV market growth led to a new wave of investments and market growth in resource exploration, mining, and processing [*F4*, *F6*]. In terms of geological mapping and exploration for lithium deposits, several new Li-bearing pegmatite veins (hard-rock lithium ore) were found in Sichuan Province through the implementation of the China National Key Research and Development Programme during period covered by the 13th Five-Year Plan (2016–2019), and by the China Geological Survey project 'Comprehensive Investigation and Evaluation of Jiajika Large Lithium Mineral Resources Base in Western Sichuan'. In addition, more than 40 pegmatite veins have recently been discovered in Jiangxi Province (Wang et al., 2020) [*F1*]. Mining companies increased lithium production from multiple sources, including the spodumene, lepidolite, and brine sources (Leadleo, 2019a) [*F2*]. Overall, the market for lithium ores in China increased from 79,000 to 167,000 tons between 2015 and 2018

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[4] For a detailed analysis of the TIS dynamics in China's EVLB industry, see Gong and Hansen (2023).

[5] 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.

[6] Lead time is the time between when a project commences and when it is completed.

(Leadleo, 2019a) [*F6*].

Furthermore, lithium processing firms in China achieved technological breakthroughs in lithium extraction and refining technologies from lepidolite sources (pegmatite veins), involving compound salt low temperature roasting, fluorine fixation, and tunnel kiln technology (Sinolink Securities, 2021a) [*F1*]. The previous round of investments (i.e. in the first phase) had by then slowly come into production. This led to four new lepidolite mines coming online in Jiangxi Province in 2018 and 2019 (Guosen Securities, 2022) *[F6]*. Improved productivity in mining and processing led to a drop in the cost of lithium carbonate from 100,000 yuan/ton to 35,000–45,000 yuan/ton (Guosen Securities, 2022).

Although several brine mines were newly approved for production during the period 2015–2019, progress was slow because mining from Chinese salt-lake brine is technologically challenging due to the high $Mg^{2+}/Li^{+}$ ratios (Minmetals Securities, 2021). Moreover, due to the long project lead time, these newly approved mines could not immediately be turned into production. In addition, strict regulations in the mining sector hindered rapid expansion of production (Industry Representative 21). For these reasons, the growth in lithium production remained low despite significant investments.

Globally, Chinese mining enterprises became increasingly active in acquiring promising mines and multinationals during 2015–2019, which strongly increased the material availability for processing in China [*F6*]. The interviewees from the Chinese top 2 lithium miners (Ganfeng Lithium and Tianqi Lithium) confirmed that 2015 to 2018 was an important period for their operation since they expanded their resource stocks by active international mergers and acquisitions (Industrial representative 21, 22). Tapping into the global lithium market was highly important for the Chinese EV market uptake in the next phase of the development of the EVLB TIS (for details, see Section 4.3). Since actors in the midstream sectors expected a demand surge in the EV market, major battery manufacturers reacted swiftly and became more active in investing in the upstream mining and material processing sectors in order to secure raw materials supply (see Table 1) [*F6*]. A typical example is CATL's strategic expansion to the upstream activities during that period. Specifically, CATL has formed various relationships (e.g. strategic partnership, joint venture, mergers and acquisitions, supply agreements) with upstream mining companies to secure its material supply.

In the *downstream* sectors, there was limited activity among firms with the exception of some conventional recyclers that were starting to explore the new business field (e.g. GEM), as they expected future growth (Industry representative 15) [F2]. In terms of market size, the output of battery recycling and reuse only reached 87 million yuan in 2018 (Leadleo, 2019b) [*F4*], with several pilot projects being initiated by visionary midstream actors [*F3*]. For instance, in 2015, three investments in the downstream sector were announced by the top listed companies, and the number increased to six in 2019 (see Table 1). However, reverse resource flow was still largely out of the scope of the midstream actors, as large-scale battery retirement was yet to occur (Industry Representative 13).

During this second phase of development of the EVLB TIS, new policies were introduced in relation to detailed management regulations for the retired batteries, as well as the construction of a closed material loop in the EVLB TIS value chain. In this phase, too, stand-alone battery-specific policies emerged that stipulated the details of the responsible body for battery recycling, the construction of recycling networks, and the standards for battery dismantling, recycling, and gradient use. However, similar to the first period and due to the weak implementation of the national policy, the focus of the industry was not so much on material shortages, but rather on preventing the leakage of hazardous chemicals from batteries (Intermediary organization 5, Expert 3).

### *4.3. International growth phase: 2020–*

#### *4.3.1. Material resources and inter-sectoral imbalances*

As the EVLB TIS entered the third phase of development, demand for EVs and batteries increased very steeply, both domestically and internationally. In 2021 and 2022, global installed capacity of automotive batteries reached 300 GWh and 517.9 GWh, respectively, with more than half of this coming from China (SNE Research, 2022). In this context the global EVLB industry is predicted to enter the 'TWh period' by 2025 (Industry representatives 1, 2). While growth was expected, most stakeholders were unprepared for the explosive demand surge for EVs. In this boom phase of the global market, concerns about material scarcity have increased tremendously. While China is currently benefiting from the gradual release of material production capacity of its previous rounds of upstream investments (between 2008 and 2018), the speed of expansion cannot match midstream demand growth (Industrial representative 22). One of our interviewees said:

> 'We're in a lithium supply deficit […] the speed of demand surge is simply a lot quicker than the potential to bring on new supplies'
>
> (Industrial representative 7)

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 further contributed to rising prices for battery raw materials such as lithium. The global geopolitical uncertainty and resource nationalism surrounding the import of raw materials into China is an additional concern:

> '… many lithium and nickel-rich countries and continents, such as Latin America and Indonesia, 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 in material resource flows, as well as concerns about the security of supply.

The situation is further complicated by the fact that raw lithium and related salt products needed to meet the boom in demand for EVs are also increasingly in demand for energy storage and other industrial applications. Competition between the various application scenarios for lithium products may therefore worsen the supply-demand relationship in the coming decade (Industry Representative 7). The situation was clearly expressed by CATL's CEO, 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 will require the entire value chain to collaborate and cooperate to secure the supply of key components and raw materials.'[7]

Such shortages of materials and the resulting rise in prices are already affecting the further diffusion of EVs. For example, major automobile manufacturers in China (e.g., BYD, Great Wall, BMW, SAIC-VW) have announced price increases in response to cost surges from the upstream sectors.

#### *4.3.2. Material resources, TIS dynamics, and actor strategies*

The surge in demand, the rapid increase in material prices, and geopolitical uncertainty have had a huge impact on the EVLB TIS value chain in China. Actors along the value chain have adopted various strategies to cope with such a challenging situation.

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

**Table 1**
Investments within and across value chain segments.

| Invest. | To upstream | | | To downstream | | | Total |
|---|---|---|---|---|---|---|---|
| Sources | Upstream | Midstream | Downstream | Upstream | Midstream | Downstream | |
| 2013 | 3 | 1 | 0 | 0 | 0 | 1 | **5** |
| 2014 | 4 | 1 | 0 | 0 | 1 | 0 | **5** |
| 2015 | 4 | 3 | 0 | 0 | 3 | 0 | **8** |
| 2016 | 5 | 2 | 0 | 0 | 2 | 2 | **9** |
| 2017 | 6 | 2 | 0 | 0 | 2 | 2 | **11** |
| 2018 | 6 | 7 | 1 | 1 | 4 | 4 | **23** |
| 2019 | 7 | 6 | 0 | 1 | 6 | 4 | **22** |
| 2020 | 10 | 17 | 2 | 2 | 14 | 8 | **51** |
| 2021 | 12 | 20 | 2 | 5 | 13 | 9 | **58** |
| Total | **60** | **58** | **5** | **9** | **45** | **30** | **204** |

Note: Own calculation of total number of mergers and acquisitions, new subsidiaries and plants, joint ventures, equity investments, strategic cooperative agreements from interviewed listed companies' annual reports along the value chain. The columns headed ‘to upstream’ and ‘to downstream’ show investments in upstream/downstream activities by actors located upstream, midstream, or downstream. We list numbers of investments rather than size of investments to indicate level of intersectoral interactions.

In the *upstream* sector, many interesting phenomena have occurred. First and foremost, in terms of resource exploration, there have been big achievements in geological exploration, mapping of deposits, and understanding of their quality and specificities [*F1*].[8] Second, we observed a new round of intensive investments in mining [*F6*]. As shown in Table 1, the announced investments by lead firms to the upstream sector increased strongly in the years 2020 and 2021. The shortage of material resources has in particular led to a surge of interest in domestic lithium extraction from salt lakes and therefore an expansion in the absolute volume of lithium resources from brine sources in China can be expected *[F2]*.

The inward-looking strategy has also led to an increase in the number of domestic firms that are specialized in lithium mining activities. For example, there are currently more than 400 lithium-related mining companies in China, among which 64 were newly registered in 2021 (qichacha.com) [*F3*]. The domestic production of lithium is predicted to reach 368,000 tons by 2023[9] (Leadleo, 2019a) *[F6]*. Furthermore, several mining and processing companies have started paying more attention to by-products that used to be discarded but now can be salvaged and sold (Industrial representative 21) [*F4*]. Given the current serious material shortages, some interviewees expected technological breakthroughs in extraction and refining to be the solution [*F1*].

One example of the technological breakthrough is the ‘High Efficiency Lithium Extraction Technology of Salt Lake Raw Brine’ project led by MinMetals (People.cn, 2021) *[F1]*. Also, the progress made in the membranes technology (Xu et al., 2021) has made lithium extraction from brines an attractive business *[F1]*.

In contrast to the early phases when resource exploration and mining to secure supplies of raw materials for battery productions was strictly regulated by the state (Industrial representative 21), increasing numbers of policy documents related to the mining sector have been issued in recent years to facilitate domestic exploitation and exploration.

For instance, in 2021, due to lobbying by EV and battery companies, the Ministry of Industry and Information Technology announced the “Raw Materials Industry Development Plan” in the 14th Five-Year Plan, highlighting the importance of securing material supplies for domestic and global EV market ramp-ups *[F2]*. More importantly, in June 2021, President Xi Jinping remarked 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 from 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 for the development of brine assets in China (People.cn, 2021) *[F2, F5]*. As a result of such political will at the top-level, the domestic lithium mining approval process has been speeded up tremendously. In April 2022, for example, the Ministry of Material Resources approved the development of two domestic lithium mineral projects: the lithium spodumene mine in Sichuan Province and the lithium salt lake resources in Qinghai Province (Ministry of Natural Resources, 2022) [*F6*].

Despite policy support and expected growth in the EV market, several upstream actors have remained reluctant to make major investments in battery-related mining. One issue is the uncertainty arising from changes in future battery technology [-*F6*], as one interviewee mentioned:

> ‘the threat of substitution is very real. […] Mining and processing companies may invest in a market but, due to long project lead times, battery technologies may evolve or the energy transition can stall or even take a totally different direction.’
>
> (Industrial representative 21)

A second issue relates to the combination of very large size and long lead time of mining projects with significant price volatility, the need to increasingly assess ESG (environmental, social, and governance) factors, and the small market size for lithium (in comparison to other large-scale commodities such as copper or aluminium) (Industrial representative 21). For example, battery-grade lithium carbonate prices have gone through two cycles in the past decade, with the first peak in mid-2018, followed by a decline over the next two years and a second price increase starting at the end of 2020 (Appendix 2). More generally, mining companies have been conservative regarding new investments since the global financial crisis in 2011 led to big losses and low liquidity in the sector (McKinsey, 2022). Additionally, project financing in lithium is typically equity-based rather than debt-based due to the high risks in such projects and because it remains a niche market with non-transparent price formation (Reuters, 2020). Low liquidity thus hampers major investments despite high mineral prices. These factors led some miners to postpone investments (Industrial representative 21) *[—F6]*. Moreover, lithium is dominated by smaller players rather than

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[8] The brine-type lithium resource has expanded from surface brine to both shallow brine and deep brine resources, and the hard-rock lithium resources from single granitic pegmatite type to altered granite type, crypto-explosion breccia tube type and sedimentary type. Also, the metallogenic age has extended from the Meso-Cenozoic era to the Paleozoic era and other eras. Moreover, prospecting methods and exploration techniques have developed from single surface prospecting and mapping to an integration of new techniques and methods, such as remote sensing to determine the prospective area, geological surveying to determine the source type, geochemical prospecting to determine the mineral, geophysical prospecting to determine the location of drilling, and drilling to determine the reserves, as well as biological prospecting and deep penetration of the deep exploration (Wang et al., 2022).

[9] By comparison, the production volume of lithium in 2018 was 167,000 tons.

mining majors that have more capital (McKinsey, 2018). Lastly, the rising importance of ESG is making it more difficult to fund mining projects that typically not score highly on ESG metrics (Battery Materials Review, 2022). Due to these issues, we observed tensions in both resource mobilization and expectations between upstream and midstream actors.

As a consequence of this situation, midstream actors became even more active in establishing strategic partnerships (i.e. building structural couplings) with and investing in *upstream* miners and raw materials processors both at home and abroad. For instance, in contrast to in the second phase of the EVLB TIS development, the number of large-scale inter-sectoral investments by listed companies from midstream upstream increased enormously in the years 2020 and 2021, reaching 17 and 20 respectively (see Table 1) *[F6]*. The investments from midstream actors, in turn, augmented knowledge development efforts in the upstream sectors *[F1]*.

In the *midstream* sector, concerns over raw materials supply also influence actors' strategies. First and foremost, technological innovation in the battery field is increasingly targeting the substitution of scarce and expensive minerals with abundant and inexpensive ones (Industry representative 9) *[F1, F2]*. For instance, CATL made a technical breakthrough and introduced its first-generation sodium-ion battery as an alternative to ease lithium shortages for battery usage in vehicles, especially low-speed, three- or two-wheeled vehicles (Industry representative 1) *[F2]*.

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 NMC batteries, and BYD's launch of the blade LFP batteries (Expert 2) *[F1, F3]*:

> ‘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)

Some interviewees also highlighted the continued importance of global trade and logistics cooperation to guarantee smooth inflows of raw materials from lithium-rich continents and countries (Industrial representatives 1, 4, 9). However, at the start of 2022 the ever-increasing prices of lithium oxidate and carbonate forced several automobile manufacturers to enter the mining sector in the form of joint ventures or acquisitions. For instance, BYD purchased six mines in Africa in 2022. Moreover, Great Wall Motors bought a 3.5 % stake in Pilbara Minerals, and Nio was reported to have invested in a mining company headquartered in Australia.

The most interesting policy reaction to the surging demand for critical raw materials in the midstream sector was to encourage the development of hybrid cars (petroleum-electric) *[—F4, —F5]*. The *Energy Conservation and New Energy Vehicle Industry Development Plan (2021–2035)* provides incentives to develop hybrid car technologies as a complementary approach to the development of BEV technologies *[-F5]*:

> ‘China's determination to develop pure battery electric cars has never wavered. However, against the backdrop of battery material shortage, the development of hybrid car technologies is a complementary approach to reducing $CO_2$ emissions in the automotive industry.’
>
> (Official 3)

In the *downstream* sector, due to the COVID-19 pandemic and geopolitical tensions, battery recycling and reuse are increasingly seen as an important complementary source of materials. The number of battery recycling enterprises in China rose from 1019 in 2019 to 3091 enterprises in 2021, and the output value from this segment is expected to reach 5.25 billion yuan in 2023[10] (Leadleo, 2019b) *[F2, F3, F5]*.

In order to recycle and reuse materials from retired batteries, midstream actors are investing more and more in the downstream segment and establishing structural couplings. In 2020 and 2021, the number of investments made by the listed midstream actors to the downstream sector reached 14 and 13, respectively (cf. Table 1)*[F6]*. For instance, Brunp, a subsidiary of CATL, established the 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 promote jointly the recycling and reuse of EV power batteries. Recently, various actors along the value chain, such as Guoxuan, Farasis, and EVE (battery producers), BASFT China (chemical industry), Huayou (mining and material supplies) have all announced their battery recycling and reuse plans and strategies (Industry representatives 4, 8, Official 1).

Downstream actors are working on reducing the costs of recycling EV batteries by working jointly with midstream actors on industry standards (institutional couplings) in terms of battery cell and pack design *[F1]*. This is driven partly by government incentives and partly by expectations of both future material scarcity and massive battery retirements (Expert 1). Indeed, novel, inter-sectoral business models involving electric vehicle manufacturers, battery manufacturers, and third-party recycling and processing enterprises are currently being explored *[F3]*. However, since the first wave of EVLB retirement occurred only very recently, a well-functioning battery recycling network is still under development. Moreover, the project lead time for battery recycling and reuse is taking slightly longer than growth in the midstream sector, as it is taking approximately 3–5 years to bring production online (Industry representative 22). 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) *[F1]*.

With regard to policy, in contrast to the first two phases of the EVLB TIS development, focus in the third phase has been on establishing comprehensive recycling networks to reuse or recycle batteries more efficiently, as well as establishing several pilot programmes *[F3]*. Various policy measures[11] aim to promote the development of the downstream sectors have been announced (Expert 3) *[F2]*.

## 5. Discussion and conclusion

### *5.1. Case insights: sectoral regimes, material flow imbalances, and coping strategies*

Our analysis revealed many nuances of how inter-sectoral imbalances related to material resources were increasingly important for TIS dynamics as the TIS entered a growth phase. In this subsection, we discuss main insights relevant for our research questions.

In terms of why inter-sectoral imbalances related to material resource flows occur during technology diffusion we found that structural tensions between sectoral regimes along the TIS value chain are one of the main reasons (RQ1). In our analysis we identified six dimensions in which upstream, midstream, and downstream sectors differed substantially, see Table 2.

In terms of *price volatility* and *sensitivity to metal price changes*, the

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

[11] 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

**Table 2**
Sectoral regime differences along the value chain.

| Sectoral regime dimension | Upstream | Midstream | Downstream |
|---|---|---|---|
| Price volatility | High | Medium | Medium |
| Sensitivity to metal price change | Low | Medium | High |
| Regulatory & policy environment | Strongly regulated; Exploration and permitting takes time; Growing support to resource exploration, R&D, etc. | Strong government support in the form of strategic R&D projects and demand-side subsidies for 10 years; Market mechanisms increasingly take lead | Regulations were not strictly implemented in the early stages; Recently government has implemented series of favorable policy to facilitating experimentation and pilot projects in recycling |
| Project lead time | Mining: 5–8 years;<br>Processing: 2–3 years | 2–3 years | 3–5 years |
| Investment characteristics and risk-taking attitude | Combination of long verification time, large investment size, high risk, niche metal, conservatism, small actors, and stringent ESG requirements creates investment challenges | Strong investment interests from various investors;<br>Strong confidence from the financial market due to clear market development trend | Seen as a complementary approach to primary resource extraction by investors;<br>Increasingly gaining attention by investors although mostly as pilot projects |
| Future expectations | Even though demand is predicted to surge, uncertainty remains high for the industry. | Positive, actors in the midstream are fully committed to expected future growth by strong expansion of investments in production capacity, product R&D, etc. | Positive, increased interest from midstream. t Many technological, business, institutional obstacles still exist in closing the material loop |

mining sector has traditionally been characterized by high price volatility and high price sensitivity resulting in booms and busts. We found for lithium that although price volatility is high, price sensitivity is rather low because of demand and technology uncertainties as well as challenges with financing. As a consequence, mining companies do not respond quickly to EV demand growth. By contrast, the midstream sectors are characterized by a medium degree of sensitivity to lithium price cycles and fluctuations. Even though midstream actors complained about the surge in material prices, most continued to expand production based on expected growth in the EV market. For the downstream sectors, volatility is medium but sensitivity to global metal prices is high as it was the increased metal prices that drove development of downstream sectors.

As far as the *regulatory environment* of the different sectors is concerned, mining is strongly regulated due to concerns about environmental damage and national security considerations. By contrast, the midstream and downstream sectors are less constrained by regulations.

The sectors also differ in terms of their *investment characteristics* and *project lead times*. Projects in the upstream sector require both extensive mineral exploration and long verification times, e.g. based on feasibility studies (due to regulation). Subsequently, projects in the upstream sector also require long lead times (5–8 years construction). These projects are very large and risky. In addition, reliance on equity funding, investment conservatism, lithium's niche metal status, and relatively small actors create particular investment challenges. By contrast, the midstream sector is characterized by strong interests on the part of investors, partly due to the extensive support from the state. For midstream investors, the uncertainty and risks that they have to bear are rather low, as market development trends are fairly clear and the project lead time is rather short (2–3 years). Lastly, the downstream sector is seen as a complementary approach to primary resource extraction, and therefore it is increasingly gaining the interest and attention of investors, although investments are mostly in an initial, pilot project stage. It usually takes 3–5 years to bring a recycling plant into operation.

Lastly, our results also show strong differences in *future expectations* which lead to diverging actor strategies. For upstream actors, even though demand is predicted to surge, uncertainty remains high, cf. above. Midstream actors are positive about growth in their segment, and therefore they are fully committed to the expected future growth by, for example, strongly expanding investments in their own production capacity and product R&D. Lastly, increased interest in the downstream sector is being shown by actors from the midstream sector. However, many technological, business, and institutional obstacles still exist and therefore it might still take some years before the material loop can be closed. Overall, we show that such cross-sectoral differences can explain the emergence of inter-sectoral imbalances in material resources during diffusion.

In terms of how such imbalances influence TIS value chain dynamics and actor strategies (RQ2), we made several observations.

We saw that actors along the value chain engaged system building activities related to intra-sectoral *resource extending* activities. For example, in the *upstream sectors* we saw expanded geological mapping and mineral exploration, expansions of mining capacity, development of new mining technologies and new types of mines. In the *midstream sectors*, actors invested in improving the efficiency of production processes to optimize material usage. In the *downstream sectors*, we saw both expansions in recycling capacity and innovations in recycling technologies. We also found that some actors attempted to find a *substitute* for the scarce material resources by searching for and experimenting 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 chemistries (e.g. Sodium-ion batteries) to substitute for lithium-ion batteries in electric transportation. Furthermore, policymakers even increased support for hybrid vehicles – a competing TIS – to avoid natural resource scarcity slowing down decarbonization of transportation.

These system building strategies show that material resource availability influenced the direction of search in all value chain segments and thus how knowledge development and experimentation was used to mitigate imbalances. Because market expansion and resource mobilization functions are interlinked across the value chain segments, system building strategies also included strategic interventions in other segments. For example, through different inter-organizational arrangements, midstream actors became involved in upstream and downstream segments because they perceived responses to imbalances in upstream and downstream segments as unsatisfactory. Moreover, in the third phase of EVLB TIS development, several actors from the upstream sector also extended their businesses to the midstream and downstream sectors in order to take advantage of their competitive advantages in raw materials possession.

These findings are illustrated in a summarized form in Fig. 4.

### 5.2. *Implications for theory*

#### 5.2.1. *Material resources, circular value chains and TIS*

Our most general contribution is to conceptualize more explicitly the role of material resources in the TIS framework by distinguishing a technological system and a TIS which reveals how TIS dynamics shape the provision and use of material resources. Overall, we found our

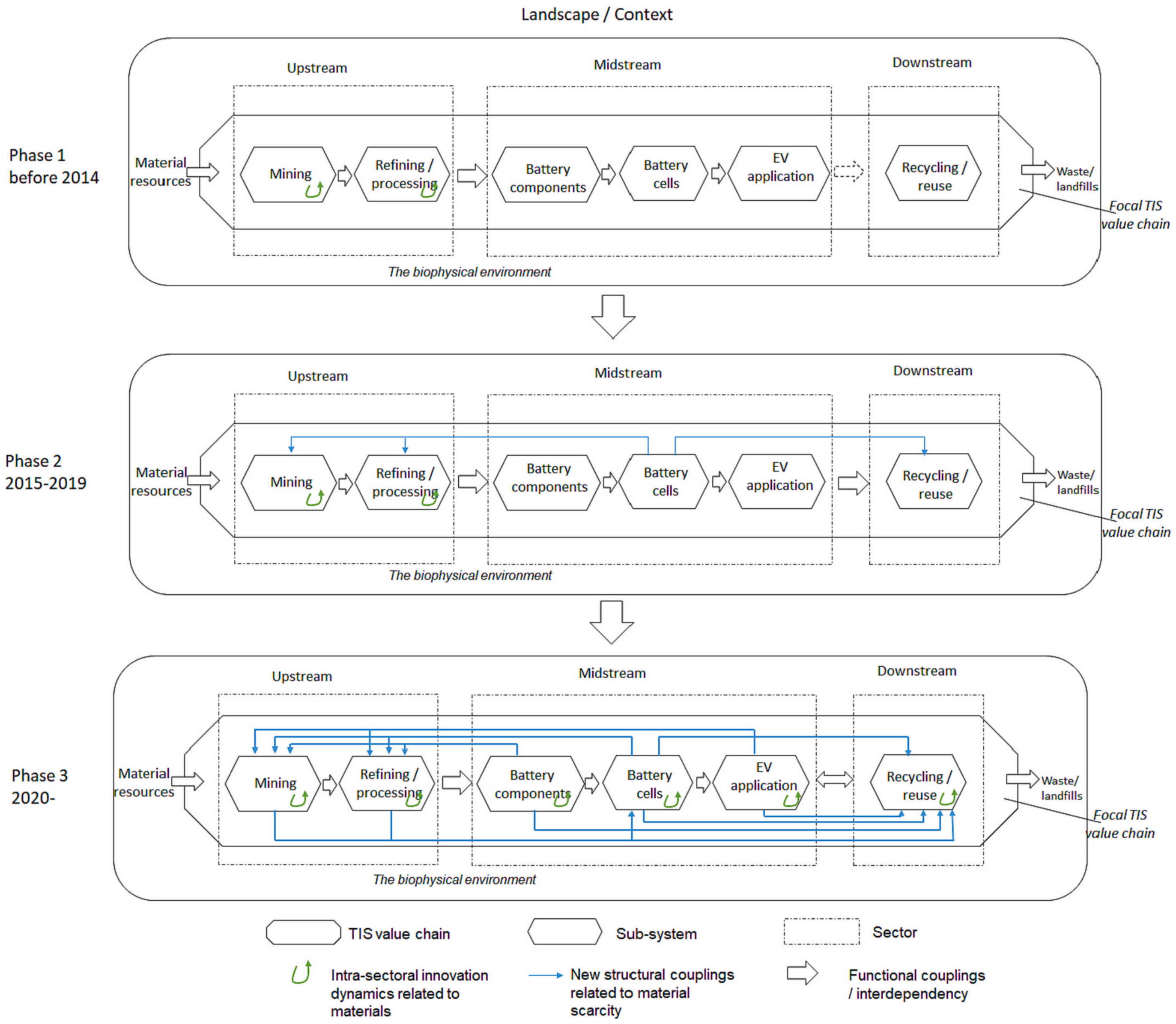


**Fig. 4.** EV lithium-ion battery TIS dynamics in different phases due to cross-sectoral imbalances related to natural resources.

analytical framework useful for understanding how inter-sectoral imbalances related to material resources influence TIS dynamics and vice-versa.

Our approach extends the scope of sectors normally considered part of a TIS by including mining and the 2nd life sectors responsible for reuse and recycling. Our analysis also broadens the resource mobilization function by more clearly emphasizing material resources and how these are obtained from a biophysical environment, and by showing how resource mobilization in different value chain segments are interdependent (i.e., the output of one sector is the input of another in a value chain perspective). These extensions of structural and functional categories in the TIS value chain approach may be useful steppingstones for future research aiming to integrate socio-technical and socio-ecological systems research to better capture how biophysical systems interact with sustainability transitions (Geels et al., 2023; Ahlborg et al., 2019; Andersen and Wicken, 2021).

Moreover, our conceptual approach to TIS also enables analysis of shifts towards circular value chains which involves looking at emergence of and barriers to circular economy inter-sectoral partnerships and business models (Blomsma et al., 2023). As both linear and circular economy logics are considered meta-rules (Kern et al., 2020), our approach can easily be extended to consider the collection of sectoral regimes involved in a TIS as working under a meta-regime shaping the dynamics of the value chain (McMeekin et al., 2019). A circular economy transition in a TIS value chain would thus entail a shift in the value chain (meta) regime. Interestingly, actors only started to pursue circular value chains as material scarcity became significant. In fact, several international midstream actors are recently pursuing similar circular or closed-loop value chain strategies. Our paper thus shows early signals that the speed and scale of decarbonization needed to meet net-zero goals will be a major driver of circular economy transitions revealing how distinct transitions can interact. Studying transitions from linear to circular value chains in this context is a promising topic for further TIS research.

### 5.2.2. *Re-opening the era of ferment and the dynamics of structural couplings*

Our results provide new insights about the TIS growth phase from a value chain perspective. Extant TIS life cycle theory suggests that the growth phase is characterized by emergence of a dominant design and reduced technical variety, institutional strengthening, stabilization of the TIS, and vertical disintegration of firms as well as increased reliance on standardized market transactions for resource exchanges in the value chain (see Section 2.2). However, we observed two interesting deviations from this account.

> First, we saw that material resource scarcity caused increased experimentation with alternative battery technology designs thereby reopening the era of ferment, an increase in institutional support for competing technologies (hybrid vehicles), and actors starting to diversify across the different value chain sectors (i.e. vertical integration). One explanation for this deviation is that extant theorizing implicitly assumes availability of material resources and largely focuses on the midstream sectors. However, to analyse the role of material resources in TIS evolution, a full value chain perspective is needed including material provision and recycling. We have taken a first step in that direction. It is an open question whether scarcity of other types of resources (skills or finance) would result in similar dynamics.
>
> Second, instead of increasing standardized market transactions, we found that, especially in the midstream, actors developed a growing number of new organizational structural couplings in the value chain (e.g., partnerships, vertical integration, subsidiaries, joint ventures) focused on financial capital flows aimed at boosting material resource flows, stimulating knowledge development in other sectors, and to align TIS value chain segments. Our findings suggest that sectoral regime differences create uncertainty for actors. Actors respond by building new structural couplings to achieve coordination when market price signals are insufficient. Indeed, when material scarcity and uncertainty were low (first and second phases), structural couplings between sectors were about material resource exchanges in markets. When imbalances and uncertainty were high, actors responded by creating additional structural couplings (e.g., organizational and institutional couplings) to resolve structural tensions in value chain and secure access to materials. Structural tensions and uncertainty are thus drivers of change to structural couplings. Our analysis gives first insights on how the interfaces between value chain sectors can change over time and how structural couplings are created strategically by actors to improve TIS performance. More systematic knowledge of how functional and structural couplings emerge and how actors create them is needed to further advance the TIS value chain approach (Andersen et al., 2023a, 2023b).

### 5.2.3. *TIS and diffusion theory*

Overall, our findings align with recent theorizing about diffusion of innovation emphasizing that innovation and diffusion are rarely separate processes and that continued experimentation, embedding, tensions, and adjustments are integral to diffusion (Meelen et al., 2019; Turnheim et al., 2018; Kanger et al., 2019). Our findings thus contrast parts of existing TIS literature which sees diffusion as distinct from innovation and as a semi-automatic process driven by self-propelling momentum (Bergek et al., 2008; Bergek, 2019). Instead, diffusion rather resembles ‘development block’ dynamics where a set of diffusing core innovations generate structural tensions across multiple technologies and sectors that actors respond to through entrepreneurial system building (Andersen and Markard, 2020; Musiolik et al., 2020).

Our framework and findings furthermore complement recent diffusion theory by showing the importance of material resources and of taking a value chain perspective. Our analysis also adds insights about how the current era of grand challenges influence diffusion. We saw that urgency of a net-zero transition augmented the tensions between value chain sectors which led to rather radical actor strategies such as unrelated diversification and shifts towards circular economy. Actor and policy responses were also influenced by concerns over energy security and geopolitics related to the role of materials in the intensifying net-zero technology race among China, the US and the EU (Geels et al., 2023). This growing importance of material resources is visible in recent ambitious policy programmes such as the EU's Net Zero Industry Act and the US's Inflation Reduction Act. These properties of the current era seem unique and how they influence innovation and diffusion dynamics merit more conceptual and empirical attention from researchers (also see Finstad and Andersen, 2023).

## 5.3. *Implications for policy*

In general our analysis shows that policy approaches addressing grand challenges (e.g. Rogge and Reichardt, 2016; Schot and Steinmueller, 2018;) should explicitly consider the role of material resources in different transition pathways because material resource availability can effectively influence which pathways are feasible and how fast they can unfold. We briefly emphasize three issues of relevance to policymakers who want to accelerate the diffusion of low-carbon technologies.

> First, policymakers can support material resource *extension* to address possible scarcity such as supporting geological exploration, 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 economy. A key issue is to incentivize actors and ensure coordinated action across the value chain segments to avoid imbalances. As we saw, such developments take time and therefore strategic planning and full value-chain perspective are important.
>
> Second, policymakers can support a *substitution* strategy. In our case this included both supporting alternative battery technologies for EVs and renewed support for hybrid vehicles that require smaller batteries and less materials. This implies a portfolio approach covering multiple different technologies as options to address the same problem. A more radical solution would be to *reduce* the demand for transport or reduce the number of vehicles altogether and instead promote either more public transportation or car-sharing. Countries that pursue a mix of material resource extension, -substitution, and -reduction strategies will arguably have more resilient transition strategies.
>
> 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 (e.g., only extension), it is more likely that imbalances will occur somewhere, ultimately slowing down the global net-zero transition.

## CRediT authorship contribution statement

**Huiwen Gong:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Allan Dahl Andersen:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

# Appendix

## Appendix 1

Functions of Technological Innovation Systems.

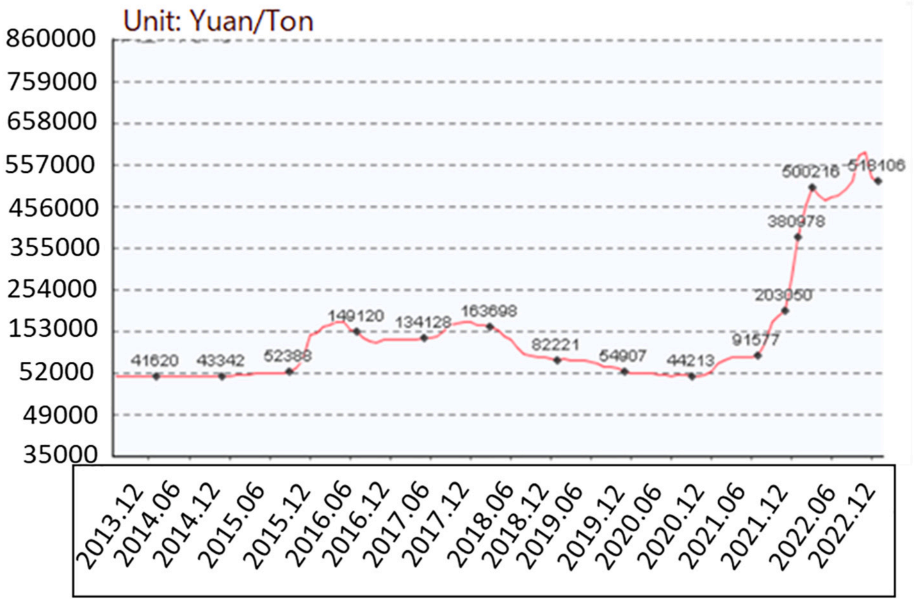
| Function | Description |
|---|---|
| F1: Development of knowledge | The breadth and depth of the formal, research-based knowledge base and how that knowledge is developed, diffused and combined in the system. |
| F2: Influence on the direction of search | The extent to which actors are induced to enter the TIS, or put more subtly, direct their search and investments towards the TIS |
| F3: 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. |
| F4: 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). |
| F5: Legitimation | The socio-political process of legitimacy formation through actions by various organizations and individuals. Central features are the formation of expectations and visions as well as regulative alignment |
| F6: Resource mobilization | The process of accessing resources necessary for TIS growth including human, financial, and material resources (e.g., raw materials, technical components, or subsystem artefacts) |

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

## Appendix 2

Information on interviewees and key firms' position in the value chain.

| Number | Interviewees | Functions and positions |
|---|---|---|
| Industry representatives | | |
| 1 | CATL (battery producer) | RP manager, senior manager |
| 2 | BYD (battery producer) | Engineer |
| 3 | Guoxuan High-Tech (battery producer) | Investment Director |
| 4 | Chiwee (battery producer) | Assistant Director of Industrial Development Department |
| 5 | Tianneng (battery producer) | RP manager, CTO, Engineer (roundtable) |
| 6 | Sunwoda (battery producer) | Investment Director |
| 7 | Eve Energy (battery producer) | Engineer |
| 8 | CALB (battery producer) | Director of Market department |
| 9 | Shenzhen Senior Tech (battery component producer, separator) | Board Secretary, CTO, Investment Director(roundtable) |
| 10 | BTR New Material Group (battery component producer, anode) | Director, vice Director of Strategic Investment Department (roundtable) |
| 11 | Beijing Easpring Material Technology (battery component producer, cathode) | Engineer, market manager |
| 12 | Xiamen Tungsten (Miner, battery component producer, cathode) | RP manager |
| 13 | Zhejiang Huayou Cobalt (miner, processor, recycler) | Investment Director, manager, postdoctoral researcher (roundtable) |
| 14 | GEM (recycler) | Group Vice President, Director of strategy department, Director of international Department, researcher (roundtable) |
| 15 | Brunp (recycler) | Senior Engineer |
| 16 | Guangyhou Tinci Materials (battery component producer, Electrolytes) | Engineer |
| 17 | Shenzhen Capchem battery component producer, (Electrolytes) | Senior Engineer |
| 18 | Volkswagen China (Automaker) | Manager, Investment Department |
| 19 | FAW Group (Automaker) | Vice Director, Investment Department |
| 20 | Geely Auto (Automaker) | Senior Vice President |
| 21 | Tianqi Lithium (Miner) | Senior manager |
| 22 | Ganfeng Lithium (Miner) | Engineer, Strategic Investment Department (roundtable, 3 people) |
| Industry associations and intermediary organizations | | |
| 23 | China EV 100 | Secretary General |
| 24 | China EV 100 | Director of the International Centre |
| 25 | China EV 100 | Head of Research Department |
| 26 | CATARC | Researcher |
| 27 | Battery Industry Association Guangdong | Secretary General |
| Experts, research institutions | | |
| 28 | School of Automotive Vehicles and Transport, Tsinghua University | Professor |
| 29 | Institute of Process Engineering, Chinese Academy of Science | Senior Researcher |
| 30 | Development Research Centre of the State Council | Postdoctoral researcher |
| 31 | School of Mechanical Engineering, Beijing Institute of Technology | Professor |
| 32 | New Energy Vehicle Engineering Centre, Tongji University | Postdoctoral researcher |
| Officials | | |
| 33 | Equipment Centre, Ministry of Industry and Information | Officer |
| 34 | Beijing Bureau of Industry and Information Technology | Head of Industry Section |
| 35 | Department of High and New Technology, Ministry of Science and Technology | Officer |



**Appendix 3.** Battery-grade lithium carbonate price change.
Source: own compilation based on SMM (Shanghai Metal Market) prices.

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