Interaction between two technologies analysed with Technological Innovation Systems as a framework: A case study of two electricity storage technologies in the Netherlands

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Interaction between two technologies analysed with Technological Innovation Systems as a framework: A case study of two electricity storage technologies in the Netherlands

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Executive Summary

The progress of Electrical Energy Storage (EES) technologies like Super Capacitors (SC) and Lithium-Ion Batteries (LIB) is important to the development and implementation of renewable energy technologies and the sustainability of electrical grid systems. EES plays a crucial role in the transition towards climate neutrality.

This master thesis analyses the two EES technologies LIB and SC, using a Technological Innovation System framework, focusing on their interaction It does so by applying the framework of Ortt & Kamp (2022) to analyse and describe the Technological Innovation Systems (TISs) of both technologies. The new insights from such analyses are crucial to the development of strategies and policies that aid the transition to cleaner energy systems. Both business actors and policy makers active in the EES sector currently lack such structural TIS approaches to support and improve their decision making.

In addition, interaction between TISs (such as those of LIB and SC) is expected to stretch further than just mere competition and complementation. Yet, there is an absence of specific approaches to analyse these interactions within the TIS frameworks. Understanding and fostering the development of technologies such as the focal EES technologies, requires new approaches to map and describe these interactions. This study provides a conceptualized approach to analyse interaction and attempts to support future studies to such interaction.

The notion of a technological system is first described by Carlsson and Stankiewicz (1991) as "... a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology". The framework as presented by Ortt & Kamp distinguishes itself by taking a company's perspective in reviewing the performance of a technology by analysing its TIS. Their framework proposes a set of seven important Building Blocks (BBs), and seven relevant Influential Conditions (ICs), that together make a specific representation of the focal technology and its relevant contexts. The interaction of both TISs is analysed with the help of a conceptualized approach to study TIS interaction. This conceptualized approach is based on the framework of Ortt & Kamp (2022).

With that, the main research question for the research is formulated as follows:

How are the Technological Innovation Systems of two Electrical Energy Storage technologies – Super Capacitors and Lithium-Ion Batteries – performing, and potentially interacting with each other?

To answer the main research questions, the following three sub-questions were formulated:

1. How can the modes of interaction between Technological Innovation Systems (TISs) be conceptualized in a conceptual framework?
2. How are the Technological Innovation Systems (TISs) for each of the two Electrical Energy Storage (EES) technologies Super Capacitors (SC) and Lithium-Ion Batteries (LIB) currently performing?
3. What TIS interactions exist between the SC and LIB TISs?

The study in this thesis commences with a literature review in chapter 2 on the EES, LIB, SC, the current stance of research to interaction of TISs, and the details of the framework as presented by Ortt & Kamp (2022). The next part of the thesis follows up with the conceptualization of specific interaction modes. These modes simplify the complex set of possibilities, in which one TIS can exert an influence on another TIS. To limit the amount of possibilities, the study concentrates solely on those BBs and ICs of two TISs, that are completely or partly controllable by business actors within the TIS.

This selection leaves all BBs and 2 ICs in the consideration for TIS interaction. The excluded ICs are also deemed generic to TISs, making their interaction with a TIS not originating from another TIS, but rather from a generally applicable context.

The seven BBs and 2 ICs are in chapter 3 subdivided into three categories for simplifications of the amount of modes of interaction between TISs. These three categories are (i) Product Attributes, (ii) Market and Value Chain, and (iii) External Environment. Product Attributes involve the price, quality and performance characteristics of a technology, normally considered in two BBs of a TIS. The Market and Value Chain involve the technology's production system, complementary products and services, customers and network formation and coordination. These aspects are normally considered in four BBs of a TIS. The last category of the External Environment addresses the aspects of technology-specific institutions, and the knowledge and awareness of the technology and its applications. These characteristics are normally described in one BB and two ICs of a TIS. For potential modes of unidirectional interaction, a set of nine interactions follows when combining these categories of two TISs.

Chapter 4 sees SC and LIB analysed in after a brief historical review , using the TIS framework of Ortt & Kamp (2022). The analysis of the SC EES TIS finds that the technology likely has to evolve further, based on lacking customers, and room for improvement regarding the technology's price, knowledge and known applications. The knowledge should increase at the customer side within the chain, which together with high prices leads to a considerable lack of customers. LIB has the ability to diffuse rather well, looking at its TIS for EES. No aspect within its TIS fully block or hamper the performance, although threats present themselves. These threats mainly relate to the risks that come with application of LIB, the harmful raw material components, and the problems of society and institutions with the impacts of both the production as well as the waste of the technology. Chapter 5 applies the conceptualized approach to review the interactions between the two focal EES TISs. Obvious interactions due to competition between both are logically present. In both TISs business actors compete based on price, performance and quality. Applications are searched and selected based on the best fit, and for these applications business actors of especially the SC TIS advocate for their technology's advantages over the characteristics of LIB. Risks, accidents, and challenges with resources and socio-cultural aspects that impact the LIB TIS are leading to new characteristics and insights for LIB, which directly impacts the TIS of SC in various ways and through various aspects. It encourages actors in the SC TIS to promote the strengths of SC where LIB has weaknesses.

Using the framework of Ortt & Kamp (2022), results of this thesis offer the first analysis of the TISs of SC and LIB. This, combined with a conceptualized framework for TIS interaction, can be seen as a relevant starting point for academics and business actors and other actors. It is suggested that detailed assessment of the roles of specific BBs and ICs in the TIS interaction can improve quality and accuracy of analysis. For future research, it is recommended to further sharpen the proposed TIS interaction framework, and refresh the analyses of the TISs of LIB and SC. It is useful to adapt the conceptualized interaction framework on other technologies due to the expected different characteristics and interactions. This thesis contributes to the literature of TISs, TIS interactions and system analyses of EES technologies, being the analysis of both LIB and SC in this case. It offers a foundation for academics, business actors and policy makers to create a better understanding of their focal technology, and enables them in better decision making and better formulation of effective strategies. This in turn potentially contributes to accelerated knowledge creation in the field of renewable energy technologies, fostering innovation and transitions of energy systems towards cleaner and increasingly sustainable systems. Examples of better decision making for business actors are hedging for risks of focal or related technologies, in similar or different contexts. Activities like allocating efforts on specific innovation aspects to achieve certain interaction can help in creating certain networks or collaborations, or engaging in lobby activities. These examples can prove useful in strengthening the business actors their performance or competitive advantage.

Acknowledgements

Delft, 25th of April, 2024

Presented before you is my thesis, a culmination of years of dedicated yet fragmented effort to complete my Master of Science in Management of Technology at Delft University of Technology. This period from 2020 to 2024 has undoubtedly been one of the most demanding of my life, encompassing every aspect of my being.

Reflecting on the brighter aspects of the past three years, I am gratified by the personal development of and deepened knowledge, despite wishing the circumstances had been more favourable. Beyond the required dedication and discipline, the unwavering support of numerous individuals has been crucial to the completion of this work.

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Furthermore, I express my deepest appreciation to my family and friends, whose encouragement, listening, and assistance were vital in my journey. A special acknowledgment goes to my father, whose unwavering love and support have always inspired me to strive for excellence.

I hope this work provides you with insightful reading, and to all those who have been part of this journey, my sincerest thank you!

Warm regards,

Casper Linsen

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1 Introduction

The progress of Electrical Energy Storage (EES) technologies like Super Capacitors (SC) and Lithium-Ion Batteries (LIB) is important to the development and implementation of renewable energy technologies and the sustainability of electrical grid systems. EES plays a relevant role in the transition towards climate neutrality by bridging above or below average supply or demand. This research investigates the dynamics, evolutionary patterns, barriers, and drivers by using the Technological Innovation Systems (TIS) framework as proposed by Ortt & Kamp (2022). This study creates a new understanding of interaction between TISs, captured in a conceptualized framework. This framework is demonstrated with help of the TISs of LIB and SC. Therefore, this thesis also creates insights and understandings for both TISs of LIB and SC.

This chapter begins with providing background information on the research topic. The next section describes the problem statement, followed by an explanation of potential contributions of this research. These are stated together with the relevance of addressing the particular research problem. The current stance of literature on the focal topics is briefly reviewed, after which the research questions are formulated. The methods used to perform the research are then explained, followed by how the results can contribute to enhanced understanding of the technologies of SC and LIB, as well as understanding of the interaction of TISs. This chapter concludes with informing about what scope and limitations apply to the research.

1.1 Background

Challenges caused by climate change, drive the development of new, renewable energy sources (RES) and technologies and other climate-neutral technologies (Pathak et al., 2022). The phasing out of fossil fuels is only possible through implementation of radically new technologies (Kamran & Fazal, 2021; Way et al., 2022). Or, as formulated by authors of the IPCC's Sixth Assessment Report "The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation,…" (Pathak et al., 2022). Therefore, effective and efficient innovation is required, accompanied by effective strategies to adapt and diffuse these technologies.

The need for alternatives to conventional technologies, leads to increasing development and implementation of renewable energy technologies. This makes maintaining electric grid stability a challenge. This to make sure that the task of delivering electrical energy is successfully fulfilled (Coppez & Chowdhury, 2010; Mulder, 2014). Many RES are inherently dependent on weather conditions for their power output (Kamran & Fazal, 2021; Mulder, 2014). Weather patterns are unpredictable and cannot be controlled to match the demand for grid power. With an increasing share of energy being produced with RES, variability in weather conditions can result in periods where the energy supply either falls short of or exceeds demand. To manage this mismatch, the implementation of a buffer or energy storage system can provide a solution. EES is such a solution for matching energy supply with demand (Luo et al., 2015).

EES is a technology that converts electrical energy into a form that can be stored and later converted back into electrical energy (Luo et al., 2015). The form of stored energy can vary and different technologies exist for energy transformation and storage, like LIB and SC, hydropower and flywheels (Luo et al., 2015). The storage process aims to address challenges such as oversupply, high demand, blackouts, isolated grids, and power quality issues by allowing energy to be stored and used when needed (Al Shaqsi et al., 2020; Luo et al., 2015).

Recognizing that technologies do not evolve or get developed in isolation, the relevance of a Technological Innovation System (TIS) framework is logical. Supporting elements form over time after invention, such as technology-specific networks, production systems, customers, and other elements or institutional models. The notion of a technological system is first described by Carlsson and Stankiewicz (1991) as "... a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology". Numerous scholars deploy the TIS framework or similar function-based system approaches (Bergek et al., 2008; De Oliveira & Negro, 2019; Decourt, 2019; Hekkert et al., 2007; van Welie et al., 2019; Wicki & Hansen, 2017). These frameworks concentrate on the perspectives of policy makers. Ortt & Kamp (2022) developed and formulated a TIS framework for business perspective.

No TIS studies focusing on either SC or LIB within the TIS framework of Ortt & Kamp (2022) or different TIS frameworks of other authors have been identified in European research. There are no findings of comparative analyses within the TIS framework that study the interactions between the TISs of two or more technologies. The framework as proposed by Ortt & Kamp (2022) has so far solely been applied to individual technologies, without exploring their interactions with other TISs. This highlights a gap in existing research.

1.2 Problem statement

Concerning the focal topic in this research, a twofold problem arises. First, there is a lack of analysis of two important EES technologies LIB and SC utilizing the TIS framework. It is useful and relevant to understand the performance of these technologies in socio-technical contexts, and the TIS framework enables actors to systematically create such understandings. Such analyses can enable actors involved in the technologies to create new insights, strategies and policies that support technology development and accelerate the transition to cleaner energy sources (Bergek et al., 2015; Pathak et al., 2022; Wicki & Hansen, 2017). For business actors active in the EES sector, making well-informed decisions is vital. Improved decision-making can accelerate the development, diffusion, and effective implementation of these technologies. This can accelerate their positive environmental impacts and allows them to develop effective strategies, helping the company's success and contributing to a more stable performance (Ortt & Kamp, 2022). This in turn helps the emerging technologies essential for the energy transition. Both policymakers and business actors could improve their decision-making and strategy formulation processes by analysing the EES technologies LIB and SC using the TIS framework. The current TIS framework includes 'core' building blocks (BBs) and contextual building blocks, referred to as influential conditions (ICs). The ICs help to understand of the technologies' performance and development with regards to influential contexts. The lack of TIS analyses of both SC and LIB for EES, especially with a focus on business actors' perspective, is therefore part of the problem.

Second, understanding how two technologies (such as LIB and SC) interact beyond just competition or complementarity is relevant to better understand the complexities and interdependence of technologies and impacts of certain decisions. Based on literature review, no approach or framework for analysing interaction between two TISs with business actors in mind exists. There is a gap for a framework in TIS analysis that considers the interaction between two TISs, such as those of LIB and SC. Addressing this gap could help understanding these EES technologies and the interactions possible between two TISs better and could provide a new framework to analyse TIS interaction in general, therefore potentially solving the other part of the problem.

1.3 Relevance and potential contributions

This research contributes to existing knowledge on TISs by offering a new methodology to assess the interactions between two technologies. The study also supports businesses in making well-informed decisions by offering a structured approach to analysing a technology's TIS and its interactions, thereby supporting business actors to craft strategies that enhance their competitiveness and resilience. Applying the standardized framework to the cases of LIB and SC demonstrates the method and provides insights for stakeholders and academics interested in these technologies or the framework itself.

Furthermore, the analysis within the TIS framework provides insights into the performance and development of LIB and SC. Not only does it guide research and development to these technologies, it also encourages their adoption. Exploring the competitive and complementary interaction between TISs of LIB and SC potentially uncovers new opportunities for collaboration or hedging. This offers a broader perspective that could reshape strategic planning for business actors, but also policymakers. The study's findings can support policymakers with a better understanding of the strengths and weaknesses of both technologies, enabling the creation of tailored policies that foster a faster transition to sustainable energy. In short, this research could contribute to accelerating the implementation of technologies. For EES technologies, this analysis of the interdependencies within the TISs could help to mitigating climate change, and advancing the energy transition.

1.4 Research questions

This research creates insight into the EES technologies LIB and SC by describing both technologies' performance with the help of the TIS framework of Ortt & Kamp (2022). In addition, the interdependence of both technologies for the current state and historical trajectories is analysed to create insight in how both technologies are interlinked. The results contribute to the existing knowledge of TISs and the EES market.

With that, the main research question for the research is formulated as follows:

How are the Technological Innovation Systems of two Electrical Energy Storage technologies – Super Capacitors and Lithium-Ion Batteries – performing, and potentially interacting with each other?

To answer the main research questions, the following three sub-questions have been formulated:

1. How can the modes of interaction between Technological Innovation Systems (TISs) be conceptualized in a conceptual framework?
2. How are the Technological Innovation Systems (TISs) for each of the two Electrical Energy Storage (EES) technologies Super Capacitors (SC) and Lithium-Ion Batteries (LIB) currently performing?
3. What TIS interactions exist between the SC and LIB TISs?

1.5 Research design

This section informs about the decisions made with respect to the methods applied in the research. The aims of this study are to (i) create an understanding of the focal TIS framework, (ii) to deploy that framework to analyse both EES technologies SC and LIB, (iii) to study if any and if yes, what interaction exist between both technologies' TISs.

1.5.1 Data collection

This research uses qualitative methods for the orientation, interpretation, and understanding of information and concepts. The study begins with a literature review on the TIS framework, TIS interactions and the specific technologies of LIB and SC.

The first sub-question is addressed by reviewing the framework itself and studying the articles on which the framework is based.

The second sub-question is tackled through an analysis of historical reviews and analysis of the BBs and ICs within the TIS framework. The analysis focusses on the general aspects of the specific technologies to identify events and characteristics relevant to include in the study. This primarily descriptive analysis draws from existing literature and reports.

The final sub-question draws on data retrieved in the literature review and second sub-question, as well as the data formulated in the conceptualizations described in the answer to the first sub-question.

1.5.2 Data analysis

The research reviews existing literature, exploring the TIS framework, the concept of EES, and specifically, the socio-technological characteristics SC and LIB. It focuses less on deep technical details and more on how these technologies function within the society, deploying a socio-technical system-thinking approach.

The study conducts a historical review and case studies to identify differences and similarities between SC and LIB. This information is also used to create a profile for the TIS per technology, according to the focal framework. A categorization of system elements and conceptualization of system interactions helps to understand and formulate possible TIS interactions, particularly applied to SC and LIB. A subsequent set of two case studies to interactions between SC and LIB is performed to specific interactions moments in time. This serves to provide a basic understanding of the two focal technologies. Last, a final case study applies the conceptualized framework of TIS interaction to study the current state of interaction between the TISs of SC and LIB.

Data collection spans multiple sources for reliability and validity, with findings critically interpreted to reflect the specific context of technology development and the dynamic field of electrical energy storage.

1.6 Thesis outline

The background information, the problem statement, the research objective and research questions, the research design and the research methods were outlined in this chapter. Chapter 2 presents the results to the literature review, describing the basic principles behind EES, the TIS framework and existing findings on interaction between TISs. Chapter 3 examines the conceptualization of a framework for interaction between TISs, answering sub-question 1. Chapter 4 answers sub-question 2 by analysis of SC and LIB, using a historical event analysis and the TIS framework. Chapter 5 answers sub-question 3 by reviewing the two studied EES technologies (SC and LIB) and discussing the findings of how these two EES technologies interact with support of among others their TISs and the application of the conceptualized TIS interaction framework. Chapter 6 presents the conclusions, a discussion and recommendations.

The research question as presented in section 1.4 is answered per sub-question.
The thesis announces each answer to a sub-question in the style of this text block.

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2 Literature review

This chapter first elaborates on findings and ideas of interaction between TISs. Second, the chapter elaborates on EES technologies, LIB and SC in particular, and why these two technologies are focal in this research. The subsequent part of the chapter reflects on a TIS framework of Ortt & Kamp (2022) proposed to analyse a TIS for business purposes.

2.1 Interaction between TISs

One of the starting points for describing the interaction between TISs and context is the work of Bergek et al. Bergek et al. (2015) devote an article to explore interaction with and between TISs. Their article describes the initial interaction between a TIS and its surroundings as competition and complementation. Competition and complementation occur between technologies, so their TISs positively or negatively influence each other's performance. The two main discussed modes of interaction called 'context interactions', are (1) external links and (2) structural couplings (Bergek et al., 2015). The primary difference between these two is whether or not actors in the focal TIS can control the interaction (structural coupling) or not (external link). External links are considered to be influences from the context of the TIS and can therefore be seen as influences crossing the TIS's boundaries. Bergek et al. indicate that external links may link to 'landscape forces', which could refer to the multilevel perspective. This multilevel perspective is meant to help explain technological transitions (Markard & Truffer, 2008). The concept of external links and structural couplings can be interesting to link with the idea of unidirectional or bidirectional relationships of TISs (Markard, 2020) to capture an even better context and influences among technologies, for a focal technology.

Bergek et al. (2015) conceptualize four different modes of interaction of a focal TIS with context in total. The first mode discussed is an interaction of the focal TIS with other TISs. The article discusses a set of 'horizontal' and 'vertical' influences between TISs. This distinction refers to the position of a TIS and an influencing TIS concerning their supply chain(s). The vertical influence can be regarded as a 'supply chain' influence between TISs up or downstream of the chain. The horizontal influences can be seen as influences between TISs with similar positions in the chain. This similar position would be described as two different TISs working with (partly) similar inputs and outputs within the chain. Although recognizing the significance of understanding influences between supply chains, this study does not describe horizontal or vertical interactions with regards to supply chains of two technologies. This due to the fact that the study focusses on TISs instead of supply chains. A further explanation on supply chain interactions is described in appendix D.

The second by Bergek et al. described mode of influence is one between the focal TIS and the relevant sectors. The third described mode addresses the existing influences between the development of TIS and the geographical context are discussed. The last described mode of interaction is that of a TIS and its political context. Since this thesis only focuses on influences between TISs, the latter three modes are outside the scope of this research and, therefore, not further discussed.

2.2 Electrical Energy Storage (EES) explained

In this research, EES is viewed as a critical component within the broader societal process of delivering electrical power, increasingly sourced from RES. EES serves as essential storage for energy from photovoltaic, wind, and other weather-dependent sources, capturing surplus energy during times of low demand. This section informs about the existing technologies in EES, giving a clear basic oversight of the process of electric power delivery.

As mentioned in the introduction, the growing reliance on RES, which often provide less stable power delivery, poses a significant challenge. This challenge involves ensuring the secure and consistent supply of power while minimizing energy waste. Figure 1 gives a simplified representation of the supply chain of power. The figure provides a visualization of the setup of a typical source to consumer path of electrical power.

Figure 2 gives a representation of current EES technologies divided by their working principles as proposed Rahman et al (2020) and Kebede et al. (2022), who even puts more detail to the overview.

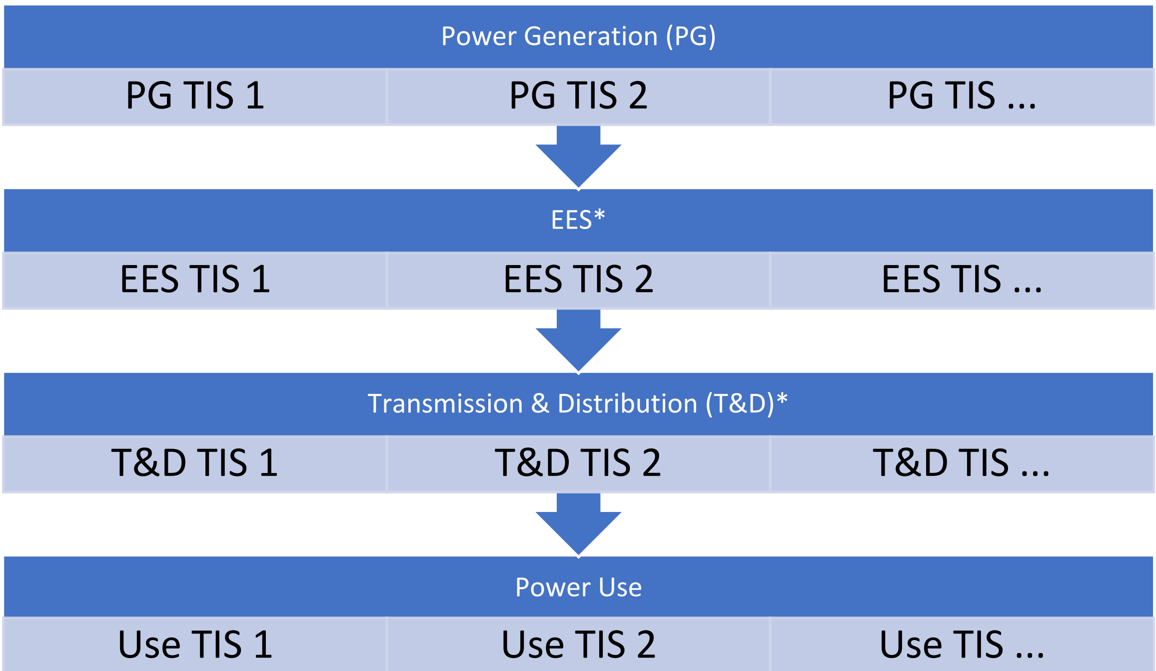

*Figure 1: Simplified representation supply chain electric grid power. *these elements might be switching positions in the chain since EES can be installed before or after de transmission and distribution.*

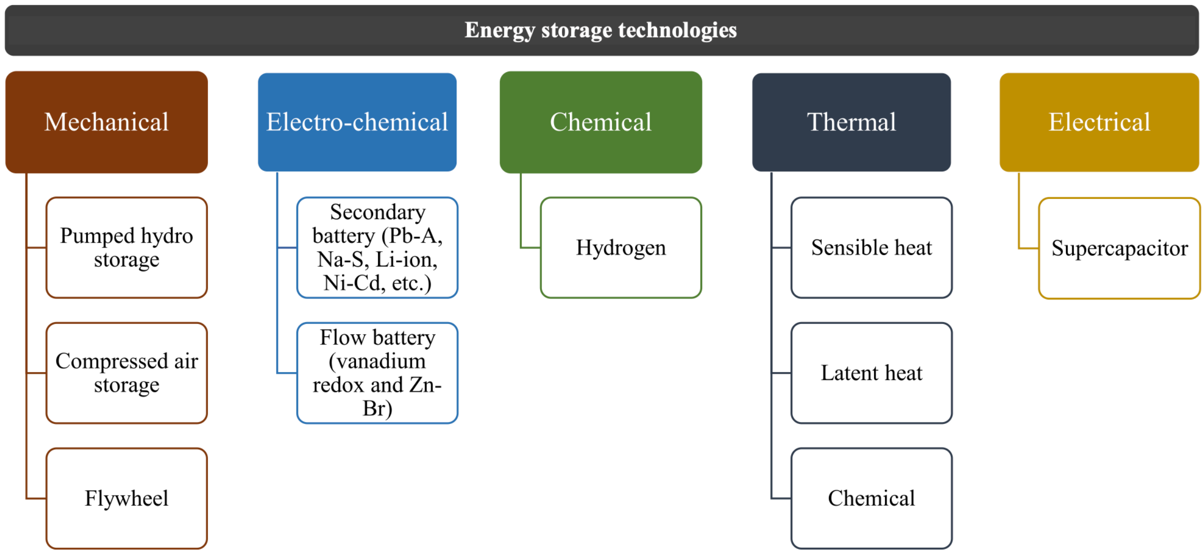

Figure 2: Representation of available EES technologies, divided by working principle (Rahman et al., 2020).

Electro-chemical batteries, like LIB, play an essential role in EES. This research considers them for analysis of the supply chain as one system within EES (secondary batteries). Mechanical EES in the form of pumped hydro storage is the backbone of EES in terms of installed storage capacity, but is difficult to realize for flatter countries with less space like the Netherlands. For situations where that kind of storage is not possible, or where less space for EES is available, LIB forms a good option, which is why it is the second most popular EES technology (Kebede et al., 2022; Rahman et al., 2020).

Flow batteries are an alternative to chemical batteries. Flow batteries are using chemical principles to store energy. The distinction is the movement scale within a system and how the chemistry functions. Where chemical batteries have ions moving in small volumetric spaces through their electrolyte between the anode and the cathode, flow batteries have large volumes (in cubic meters typically) of ionic liquids that flow through a membrane-electrode assembly. EES in the form of pumped hydropower converts electrical energy to potential energy (creating a height difference) and the other way around. The last long-term form of energy storage is the power-to-gas method. Here, an electrolyzer uses electrical energy to create e.g. hydrogen. This hydrogen can be stored and later fed to a fuel cell that creates electricity from the hydrogen.

Different EES technologies align with specific user needs, such as peak power, operational durations, and reaction times. LIB technology for grid EES is more developed than SC, and the potential for SC to advance relies partly on its interactions with LIB. This makes it relevant to review both technologies with respect to each other. Those involved in SC technology have a vested interest in identifying strategies to promote its ongoing development, understanding the dynamics and challenges that influence SC's market presence in relation to LIB. LIB and SC hold a preceding relation in other applications, where mostly LIB but also other EES technologies are replaced by SC. Examples of these are port cranes (Linsen, 2019; Skeleton Technologies GmbH, 2018), automotive start and stop systems (Kebede et al., 2022; Skeleton Technologies GmbH, 2018) and space applications (Gonzalez-Llorente et al., 2020; Sambath Kumar et al., 2018). Last is that for flywheels (FW), being the closest direct competitive grid EES technology to SC, a TIS analysis is performed for the EU landscape (Wicki & Hansen, 2017). This is not the case for SC and LIB. Analysing FW and SC would therefore be easier with the deliverables of this research and existing work.

Two of the often-used distinctions for technical characteristics of EES are energy density and power density (Kebede et al., 2022; Luo et al., 2015; Rahman et al., 2020). These characteristics tell something about the operation time and capacity of EES solutions. This is important for selecting a certain grid EES technology, since different types of requirements for grid EES exist. These differences boil down to basically long-term and short-term EES (*Balanceringsenergie: FCR, AFRR En Noodvermogen*, n.d.). With short term EES, a very quick and short peak performance is required to firmly compensate for quality and sudden gaps of the power on a grid. With longer term EES, a longer lasting gap in too little supply, too large demand, or a combination of both, is bridged. Figure 3 displays a separation of EES technologies over short- and long-term EES.

For further reading on EES in power grids, this research recommends dedicated work of Robyns et al. (2015) on this topic.

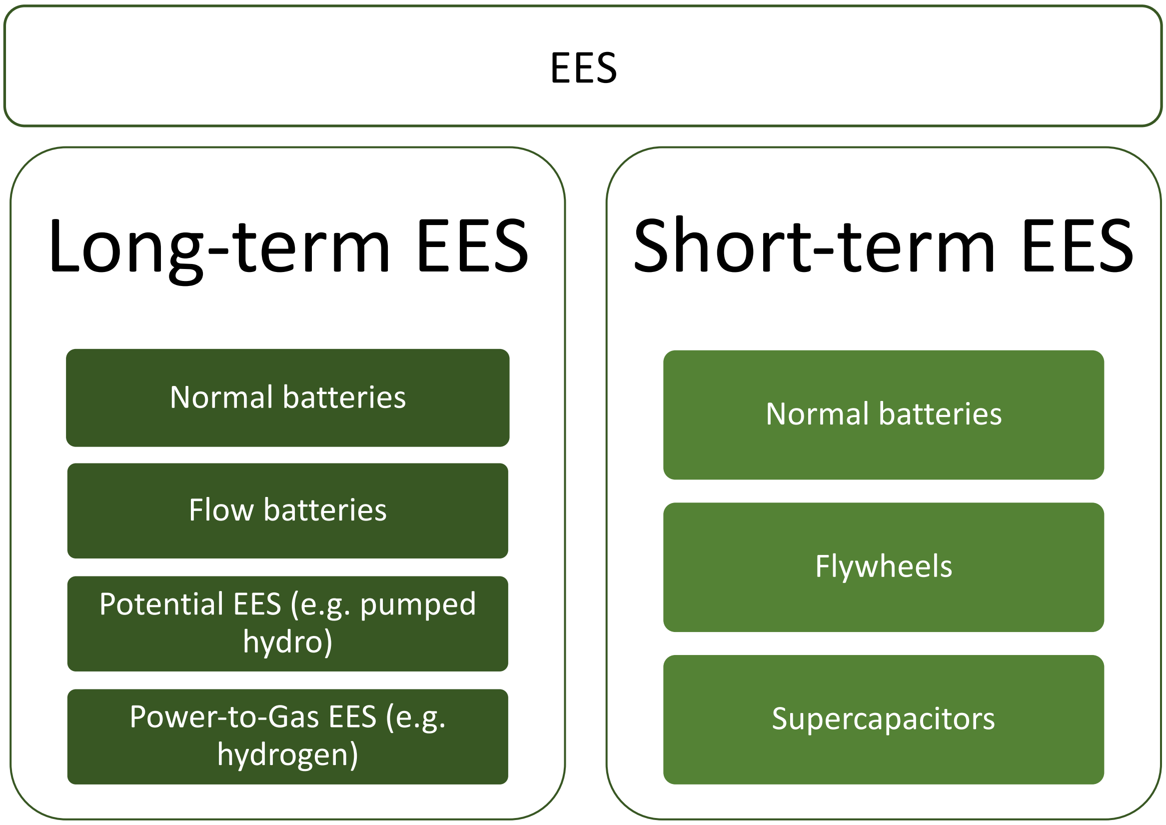

Figure 3: Overview of long- and short-term EES technologies.

2.3 A TIS framework for business

This thesis adopts the TIS framework by Ortt & Kamp (2022) to examine two specific EES technologies. The framework is visualized in Figure 4, illustrating both the direct BBs and the ICs of TISs, aiming to incorporate context when assessing niche technologies. This model is designed to capture the technology-specific innovation system, enriching the analysis with contextual understanding. Appendix A provides the original representation of the ICs and BBs as proposed by Ortt & Kamp.

Building on among others the foundational work of Ortt et al. (2013), the framework serves as an analytical tool for analysing technologies, focusing on the performance of identified BBs. It views these BBs as critical factors for the adaptation and diffusion of new technological innovations. Through this lens, the framework explores and elucidates the key characteristics of LIB and SC in this thesis. This framework distinguishing itself from other models that prioritize a policy perspective for technological development and diffusion. These alternative frameworks often neglect the contextual nuances and fail to address the commercialization of niche technologies from a business standpoint. Additionally, alternative frameworks lack the business perspective.

Contrastingly, Ortt & Kamp's (2022) framework offers a unique framework to the diffusion, implementation, and use of radically new technological innovations from a business actor's perspective, differing from the traditional government or policy-oriented TIS frameworks. By focusing on a company-centric perspective and delineating seven specific TIS building blocks (BBs), it supports business actors with an effective strategy-tool for navigating technology innovation, market dynamics, and the complexities of developing, diffusing, and adapting new technologies. This framework is tailored to provide strategic recommendations for companies, emphasizing the role of technological, social, and institutional actors and factors in the pre-diffusion phase of innovations, thereby filling a critical gap in technology development and business strategy integration.

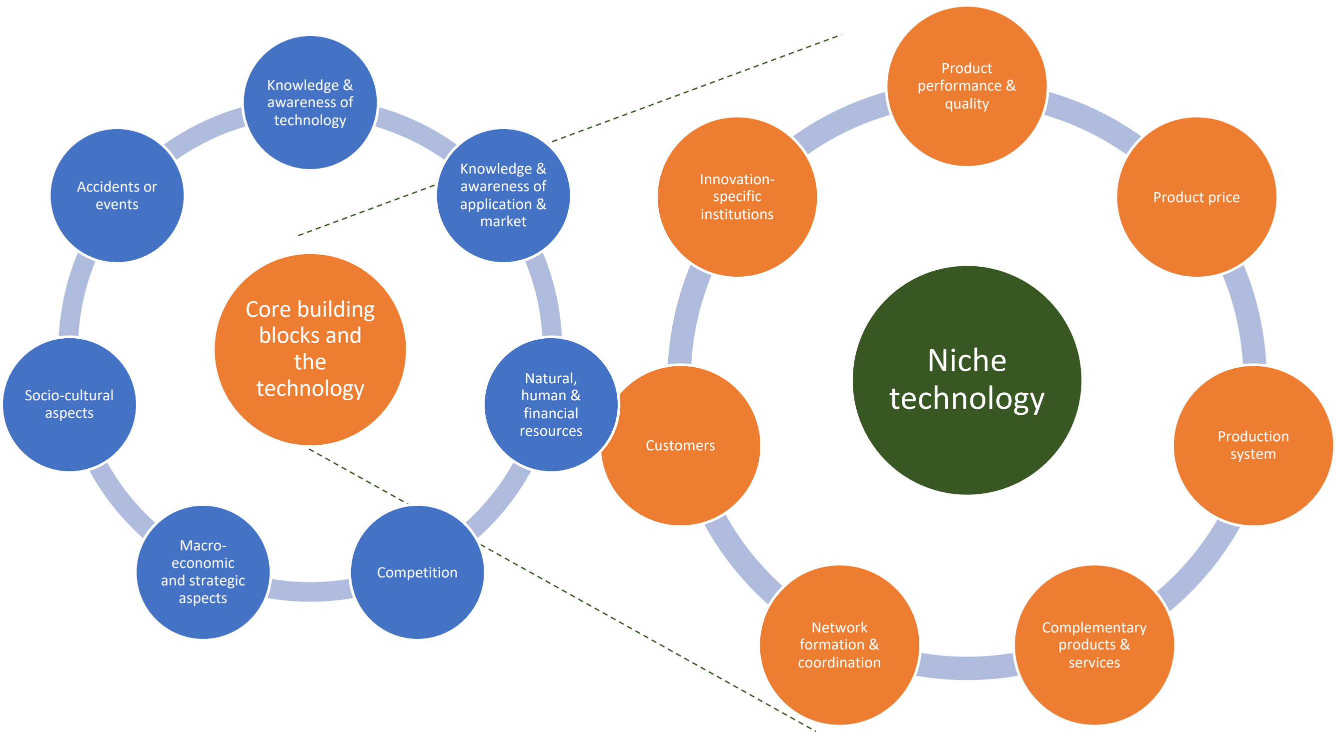

Figure 4: Left: Indirect influencing building blocks in a technology specific innovation system (TSIS). Right: core building blocks to a niche technology.

Ortt & Kamp’s framework is particularly designed for scenarios where a radically new technological innovation has been proven viable but has not yet achieved widespread adoption. It focuses on the adaptation phase between an innovation's initial invention and introduction, and the start of its large-scale diffusion. By taking a company perspective, the framework aims to assist in crafting niche introduction strategies, serving both managers seeking to commercialize their innovations and scholars assessing such strategies. Ortt et al. provide potential business strategies for niche technologies, which are further described in appendix C. These strategies are relevant for business actors and is considered complementary work to the framework of Ortt and Kamp.

Furthermore, the framework offers a new conceptualization of how an understanding of the status and challenges within TIS BBs can inform the timing, scope, and nature of niche introduction strategies. Through an examination of 'influencing conditions' (ICs) that can indicate obstacles within the TIS BBs, the framework identifies potential barriers to the broad application of innovations. This analysis required a broader socio-technical system view to uncover conditions pre-existing the formation of a TIS or market.

Table 1 below describes each BB and IC and cites information from the work of Ortt et al. (2013) and the work of Ortt & Kamp (2022) to describe each BB and IC.

BB/IC	DESCRIPTION	INDICATORS
PRODUCT PERFORMANCE AND QUALITY (BB)	The first TIS building block is a new high-tech product with sufficiently good performance and quality now, or in the near future, when compared to competing products. Target customers should regard the product as a viable option, or as a viable alternative compared to other options. For example, in the case of many sustainable products, environmental performance can be valued highly, but early product versions may suffer from low quality and may be unable to meet the customers’ requirements. Hence, large-scale diffusion can be hampered.	- Relevant functionality - Is a problem being solved - Technological principles - Main components
PRODUCT PRICE (BB)	Product price is an important TIS building block. Often, technological innovations are initially very expensive compared to competitive alternatives, which can hamper their diffusion. The price of a product involves financial and non-financial (e.g., time and effort) costs to acquire and use the product. Acquiring products involves various costs related to selling and depreciating investments in previous products, and it also involves switching costs, i.e., costs involved in switching from one product to another, and transaction costs, i.e., costs to find the right new product and a supplier. For large-scale diffusion, a product is required with a reasonable price (absolutely or relatively compared to other competitive products).	- Price / quality ratio - Price relative to alternatives

BB/IC	DESCRIPTION	INDICATORS
PPRODUCTION SYSTEM (BB)	Another essential TIS building block is a production system that can deliver high quality products in large quantities. Over time, growing experience with the production process and the product itself will increase the product's quality and decrease its production costs (learning by doing). These effects increase the competitiveness of the product. Incompleteness or absence of this building block constitutes a problem for many radically new technological innovations. Creating a large production facility is not only a major investment, it may also take a considerable amount of time to develop and fine-tune such production systems. A lack of production system can block large-scale diffusion.	- Number of factories - Supply of main components / feedstock
COMPLEMENTARY PRODUCTS AND SERVICES (BB)	A fourth TIS building block is the availability of complementary products and services supporting development, production, distribution, adoption, use, repair, maintenance, and disposal of the innovation. Diffusion of the innovation can be hampered when complementary products and services are unavailable, incompatible, or too expensive. Development of complementary products and services can induce multiple innovations in firms that are linked together and therefore motivated to align their strategy. A lack of complementary products and services can block large-scale diffusion.	- Large EES management systems - Workforce for knowledge and installation
NETWORK FORMATION AND COORDINATION (BB)	The network of actors in the supply chain is an important TIS building block. Multiple types of actors are vital for large-scale diffusion of an innovation. Actors can refer to suppliers of parts, actors assembling or producing the product, distributors, and actors providing complementary products and services. The importance of coordination between these actors is highlighted as this coordination not only involves actual collaboration between actors but also involves a shared vision regarding the technological innovation and the TIS surrounding it. A lack of actors or a lack of coordination between them can completely block large-scale diffusion.	- Producers, investors, developers, researchers

BB/IC	DESCRIPTION	INDICATORS
CUSTOMERS (BB)	Customers represent an important TIS building block. A customer segment needs to be identified early on. Potential customers with a need for the innovation should be identified, for example, through a problem solved by the innovation or because they largely benefit from using the innovation. To become actual customers, potential customers should be aware of the innovation, see its benefits compared to other products, and have the knowledge, means, and willingness to acquire and use it. When innovations are developed without involving (future) customers, several customer-related issues may hamper their diffusion. Potential customers may want to use a product but may lack the means to acquire it. They may lack knowledge of a product and can be uncertain about a product and hence perceive risks. Additionally, "users have to integrate new technologies in their practices, organizations, and routines, something which involves learning and adjustments. New technologies are sometimes said to be 'tamed' to fit in concrete routines and application contexts." Obviously, without actual customers, there is no large-scale diffusion.	- Demand for the technology - Clear and proven applications
TECHNOLOGY-SPECIFIC INSTITUTIONS (BB)	Innovation-specific institutions form an important TIS building block. These institutions refer to formal and informal rules such as government policies, laws, standards, and regulations. Such rules can either support or block the development and diffusion of an innovation. Quality norms and property rights can produce trust. A lack of a long-term consistent policy can affect the development and diffusion of innovations. Stable and supporting innovation-specific institutions increase certainty for companies and investors and hence facilitate the development and diffusion of innovations.	- Limiting or stimulating legislation or institutional activity - Monetary stimulation
KNOWLEDGE AND AWARENESS OF TECHNOLOGY (IC)	The first influencing condition 'knowledge and awareness of technology' refers to fundamental and applied technological knowledge. Fundamental knowledge focuses on the technological principles in components of the TIS, such as the product, the production system, and complementary products. Applied technological knowledge is required to develop, produce, repair, maintain, and improve these components. Both types of knowledge are required for TIS formation. These types of knowledge can be developed through research and development or through knowledge creation and experimentation in practice. Education and training are important mechanisms for transferring knowledge of technology across actors. A lack of relevant fundamental and applied technological knowledge by actors in the TIS can hamper TIS formation.	- Technology readiness level analysis

BB/IC	DESCRIPTION	INDICATORS
KNOWLEDGE AND AWARENESS OF APPLICATION (IC)	The second influencing condition 'knowledge and awareness of application and market' refers to the understanding of how, and in which applications, the innovation can be utilized. It also encompasses knowledge of the market structure and the relevant actors involved. This knowledge can be developed through market analysis, experimentation, learning by doing, learning by using, or learning by interacting with relevant actors in the socio-technical system. All actors in the TIS can suffer from a lack of knowledge and awareness of application and market. For example, when potential customers are not aware of the product, or do not know how and for what purpose to use a product, or when they do not know who can supply the product, then TIS formation is hampered. When suppliers lack knowledge of application, they cannot target a customer segment and hence TIS formation is hampered.	- Cases discussed by suppliers
NATURAL, HUMAN AND FINANCIAL RESOURCES (IC)	Another condition influencing TIS formation is the availability of resources. Firstly, natural resources are required. Natural resources to create products, production systems, and complementary products can be acquired by each actor separately or by associations of organizations. Secondly, human resources with appropriate knowledge and competences need to be mobilized. The appropriate knowledge and competences may be acquired via education programs or courses or in practice, via learning by doing. Thirdly, financial resources are needed for the development and application of the innovation, the production system, and complementary products and services. Financial resources can come from different types of actors, such as supplying companies, investors, governmental institutions, or customers. Lack of natural, human, or financial resources hampers TIS formation.	- Information on main components / feedstock
COMPETITION (IC)	In practice, competition refers to an important influencing condition. Especially during TIS formation, innovations based on old technologies compete with those based on new technologies. At the same time, different product versions based on a new technology may compete. When competing alternatives require different components, production systems, complementary products and services, then alternative networks of companies are formed. All of this may create a chaotic and complex pattern of competition between networks of companies. In such situations, uncertainty may increase and TIS formation may be hampered. So, competition can have a large impact on several TIS building blocks. Competition, for example, determines the relative price and performance of a radically new innovation.	- Number of companies - Market shares - Pricing of alternatives

BB/IC	DESCRIPTION	INDICATORS
MACRO-ECONOMIC AND STRATEGIC ASPECTS (IC)	Macro-economic and strategic aspects form important influencing conditions of the TIS building blocks. An economic recession can hamper TIS formation whereas economic growth can facilitate it, for example, by providing funds for incubation activities and consultancy services. The macro-economic situation involves conditions like the market structure and the contemporary way of doing business, and these conditions are often reflected in strategic policies of countries regarding important industries. The combination of these conditions can influence the formation of TIS building blocks.	- News / article research to the market situation
SOCIO-CULTURAL ASPECTS (IC)	Socio-cultural aspects refer to the norms and values held by potential customers and other important stakeholders in the socio-technical system. These aspects may be more informal than the laws, rules, regulations, and policies mentioned as institutions but they can have a large impact on the formation of these institutions and on the behaviour of the actors in the TIS. Socio-cultural aspects can also change over time and can thereby switch from a stimulating into a blocking factor. Socio-cultural aspects can influence the formation of TIS building blocks.	- News / article research to the specific technology
ACCIDENTS OR EVENTS (IC)	Accidents can refer to accidents within the TIS, such as an accident in production or an accident by a product that fails. Accidents can also refer to accidents outside the TIS, such as wars or natural disasters. Both can have a large impact on several building blocks in a TIS. Some accidents may also stimulate TIS formation for radically new technological innovations. Terroristic attacks in Europe in the 1980s represent an example of accidents stimulating the development of a radically new telecommunication innovation. The threat of attacks made US civilians reluctant to travel to Europe while, at the same time, a postal strike hampered communication. This coincidence stimulated the emergence of fax machines for B-to-B communication.	- News / article research to events related to the specific technology

Table 1: Building Blocks and Influential Conditions as described by Ortt & Kamp (2022).

2.4 Concluding the literature review

In this study, the framework from Ortt & Kamp (2022) is used to describe two focal technologies of LIB and SC and their performance. The framework from Ortt & Kamp uses different functions referred to as BBs and ICs, resulting in a more suitable framework for business actors than the preceding frameworks. It is argued here, in line with the preceding work from Ortt et al. (2013) and work from Markard (2020), that attention to the life-cycle model in combination with the TIS framework might be interesting. Markard misses out on considering business actors. For the framework of Ortt & Kamp, understanding technology and its phase in the life cycle could be relevant, for example, due to possible wrong understanding of any business actor about the status of their focal technology, or for helping to understand the interaction between two technologies in different phases of their life cycle. The latter could help to draw interesting connections between two technologies based on life cycles. The focus on a life cycle approach is out of the scope of this research but worth mentioning due to exciting threads in the literature. Appendix B further engages on this topic.

The case studies are performed to explore the focal technologies in more detail, by analysing the technologies SC and LIB with help of the framework from Ortt & Kamp (2022). Past and actual links between both technologies are discussed based on the two cases studies. The results of both the case studies and the analysis of drives, barriers, and interlinks aids a formulation of potential business strategies. This supports business actors active in one of both focal technologies, and actors active in in competing or complementing technologies.

The next chapter engages in conceptualizing a framework for determining and formulating interaction modes for interaction between two TISs. This then serves as a base for further analysis of the potential interaction of the SC and LIB TISs.

3 Interaction between TISs

This chapter embarks on an exploration of the theoretical dynamics between TISs, focusing on the interaction between BBs and ICs of two TISs. The first objective is to categorize the BB and IC of two TISs. This objective creates a basis for a subsequent phase of identifying focus areas, facilitating a manageable scope for the exploration of interactions. The first categorization describes BBs and ICs as on the one hand technological-specific and on the other hand generic BB or IC. The second categorization describes BBs and ICs as fully, partly or not controllable by business actors in a TIS. This evaluation not only unveils the inherent characteristics but also sets the stage for understanding their potential to influence and be influenced by other technological systems. Prioritizing technology-specific and controllable BBs and ICs allows for a focused examination of how technologies impact each other and the potential for business actors to guide this influence. The methodology behind these categorizations is explained in the first section.

The second objective is to delineate the formulation of a manageable amount of modes of interaction. This objective is addressed in the second section. The selection process is guided by a thoughtful consideration of the relevant modes of influence. Chosen modes are judged on their relevance and potential impact on the inter-TIS relationships, thereby offering a convincing rationale for their inclusion. This deliberate selection limits the width of the research on influences between TISs and underscores the depth of analysis and critical thinking applied to uncovering the interaction within and between TISs.

The subsequent sections of the chapter are dedicated to investigating these selected modes of influence within the context of two specific technologies. This investigation is articulated through a detailed explanation of the empirical findings, thereby providing evidence to support the theoretical propositions formulated earlier in the chapter. Each mode of influence is precisely examined, with insights learned from the empirical analysis serving to validate or refine our understanding of the interaction between BBs and ICs in the realm of their TISs.

In articulating the methodological framework for this inquiry, the chapter delineates the approach taken in both conceptual and empirical facets of the study. This includes a clear description of the methodologies deployed in each segment of the research, ensuring that the reader is fully aware of the analytical processes supporting the findings. Each section or chapter of the analysis is methodologically anchored, providing a logical narrative of the journey from conceptualization to empirical validation.

This chapter first will categorize the BBs and ICs based on specified motivations. The next section formulates the different modes of interaction based on the categorizations. The final section of this chapter elaborates on each selected interaction mode.

3.1 Categorization of Building Blocks and Influential Conditions

When considering the full set of BBs and ICs to analyse the interactions between two TISs, a total of 196 distinct modes of interaction emerge, both from an external TIS to a focal TIS and in the reverse direction. Given the impracticality of analysing so many interaction modes within the scope of this research, a selective approach is proposed. This selection process excludes generic and uncontrollable BBs and ICs from the full set considered for interaction analysis. That exclusion provides a more manageable subset of interaction modes.

This section begins with a categorization of technology-specific versus generic BBs and ICs. The logic behind this distinction originates from analysing the influences between two TISs. BBs and ICs are suitable in helping to analyse both the individual performance of TISs and the interplay between distinct TISs. Generic BBs and ICs in two closely related TISs often have overlap and may not be uniquely associated with specific focal technologies. While exploring the impact of such generic and contextual elements is interesting for including more possible modes of interaction from context, this research is dedicated to exploring the interactions between two TISs, excluding the generic contextual influences.

The second part in the selection process categorizes all BBs and ICs as fully, partly, or not controllable by the focal business actors. Focusing only on (partly) controllable factors within a TIS provides makes sense for such actors. Such focus on the subjects that can actually be changed enables them to spent their time and efforts more effective and efficient. This helps to accelerate innovation, deal with challenges and improve pace and quality of formulating strategies. The focal framework's orientation towards the perspective of business actors, with the aim of empowering them with better strategic insights, justifies the emphasis on business actors in this analysis. Business actors frequently act as initiators and decision-makers within a TIS. This implies that they also benefit on knowing what they can control and makes is logical to provide insight in the BBs and ICs for which this is the case.

What makes any BB or IC generic? Generic BBs and ICs share similarities across multiple TISs, regardless of their impacts on a TIS. The characteristics of such generic BBs and ICs are shaped by context rather than technology. These elements uniformly affect all TISs, though their specific impact on a given TIS may vary. What makes a BB or IC technology-specific? Any BB or IC that is technology-specific links directly with the characteristics, inputs, outputs or challenges of the activities within the TIS of the focal technology. These BBs and ICs do not have a society-overarching nature.

The dynamic between technology, its business actors, and a BB or IC calls into question the business actors' ability to control or adapt the BB or IC versus being influenced by it. This links back to the earlier notion of Bergek et al. (2015) to external links or structural couplings. The methodology for assessing the extent of control over BBs and ICs, whether it be full, partly, or not at all, has evolved throughout the process of reviewing all BBs and ICs. Subsection 3.1.15 discusses the development of this approach, providing insights into its conceptualization.

An additional note is made on the effects of market forces directly on BBs. Through the ICs, the market forces are well described for a TIS. I expect some BBs to function independent and others dependent of market forces, but this is something which is not studied in this research.

The following subsections discuss each of the 7 BBs and 7 ICs in total of the framework from Ortt & Kamp (2022). In the discussions, the above characteristics are tested and reviewed per BB and IC. The BBs and ICs are tested from the perspective of business actors in general.

3.1.1 Product performance and quality

As the name of this BB suggests, both the performance and the quality of the technology are focal in this BB. Typically, actors developing, producing and selling a technology are motivated and able to increase performance and quality of the technology. This is done through research and innovation, as well as quality control. Also, the performance is normally unique to a technology, thus making this BB technology specific and actor-controllable. Although striving to have a proper performance and quality, this BB is specific to a technology. The initiative to make this BB perform well for the TIS lies with the business actors.

3.1.2 Product price

This BB is controlled by actors for a new technology when commercially introduced. Actors within a TIS can influence the product price through strategies such as cost reduction in production, economies of scale, and market positioning. The product price can be seen as both specific and generic. Initially it is generic because pricing strategies and considerations are relevant across all TISs, as they are fundamental to the commercial viability of any technology or product. In the beginning a new product has to cope with market prices, disregarding its initially high costs. It can either follow the focal market, or search another market with higher willingness to pay. However, this BB can also be specific because the factors influencing price such as material costs, production complexity, and market demand vary significantly from one technology or sector to another. I argue that this BB is specific over long term, since cost price links to specific characteristics and production processes of the technology. The product price is established by not only the business actors in the TIS, but also by the involved markets. The ultimate decision regarding pricing remains within the control of business actors, who possess the liberty to set the price for a technology at their convenience, including the option to sell at a loss temporarily.

3.1.3 Production system

Actors within a TIS can influence the BB of the production system. They can do so by investing in production technology improvements, scaling up production capabilities, and enhancing process efficiencies. Such actions can lead to better product quality and lower production costs. Actors in the focal TIS depend on other actors and available production techniques in the market for the production systems. Business actors in the focal TIS are in control of the formation of a well performing production system.

The production system is specific to a technology. The challenges and solutions related to setting up and optimizing production systems can differ among different technologies. Topics like the specific nature of production technologies, their sizes, and their regulatory specifications can all influence how a production system is created and deployed. The general goals might be similar across TISs, but the required elements to create and use production systems can be highly specific to the focal technology or sector.

3.1.4 Complementary products and services

The availability of complementary products and services can be influenced by the actors in a TIS. They can for example engage in partnerships and foster technological systems that support the development, production, distribution, use, and maintenance of the technology. Such efforts can drive multiple innovations across interconnected firms. They can also help in overcoming barriers related to the unavailability, incompatibility, or high costs of complementary products and services. Actors in the focal TIS are dependent on other actors in the market of the complementary products and services. The initiative to actually offer the complementary products and services is often not only with the focal business actors but also with business actors in related (complementary) TISs.

While the need of complementary products and services is normally a generic requirement for the diffusion of any innovation, the details of these needs and how they are addressed are rather specific to each technology. The nature of the complementary products and services required varies across different technologies. This makes a complementary part or service sometimes specific, whereas raw material or natural resources like copper are normally generic. But in this definition, complementary products and services are unique combinations of land, labour and capital. For example, the complementary products or services needed for a digital technology like software could be very different from those required for a physical product like electric vehicles. Where the one might need data centres, the other may need a network of charging stations. The requirements of complementary products and services are unique to each TIS.

3.1.5 Network formation and coordination

Actors within a TIS can influence the BB of network formation and coordination. They do so by engaging in the creation and strengthening of for example supply chains, collaborations, and lobbies. How effective various stakeholders (including suppliers, manufacturers, distributors, and service providers) are, is crucial for the large-scale diffusion of an innovation. The initiative to try and improve this BB lies with each of the business actors in the focal TIS. It takes other actors in the network within or crossing the boundaries of the TIS to actually make the improvements happen. This BB is thus not in full control of the focal business actors.

The nature of the network, the types of actors involved, and the coordination challenges are unique to each technology or sector. This makes this BB specific to the technology. Different innovations will require different supply chains, complementary products and services, and forms of collaboration, tailored to the specific demands, technical requirements, and market contexts of the innovation. However, looking at section 2.2, technologies can share supply chains and have commonalities. While the overarching concept of network formation and coordination is a generic need within TISs, the execution and emphasis of this building block are highly specific to the context of each technological innovation. TISs can share supply chains in terms of their function, but will probably differ in their supply chain when it comes to their technological characteristics.

3.1.6 Customers

The actors in a TIS can influence the BB of customers. They can for example identify and interact with the customers in different phases of the technology’s lifecycle, and inform customers about the solution a technology could provide. Business actors actively strive to demonstrate advantages of the technology and try to create customers out of prospects. This indicates that the actual decision power is not solely with the business actors. In the end, the customer decides whether or not to engage further with the TIS.

This BB is specific to the technology because the types of customers and their characteristics, such as their needs, willingness and way of interacting, differ per technology and customer group. The business actors active in a certain TIS deploy different methods by to interact with the customers, led by the specific characteristics of these customers.

3.1.7 Innovation-specific institutions

Business actors within a TIS can influence the BB of innovation-specific institutions only indirectly. They may collaborate with institutions to guide or influence the development of standards, policies, or regulations aligning with their objectives. Business actors can engage with aspects such as quality norms and property rights to foster an environment of trust. These activities can facilitate the advancement of technology. Although business actors in the TIS can actively advocate for or against particular institutions, the final decisions are often made by policymakers, leaving this BB only partially controllable by business actors.

Innovation-specific institutions forms a technology specific BB since the nature of the institutions varies greatly depending on the technological field or sector. Each innovation could require different institutional supports or face unique regulatory challenges. This can make the impact of innovation-specific institutions very specific to the context of each technology. The actual institutions and the strategies for influencing them are tailored to the unique demands and regulatory landscapes of each innovation.

3.1.8 Knowledge and awareness of technology

Business actors have the ability to influence the IC of knowledge and awareness of technology within a TIS. They can do so through supporting research and development activities, facilitating education and training programs, and promoting knowledge creation and collaboration. While a business actor may guide the process of knowledge creation, in an appropriate context it is logical to acknowledge the significant contributions of other individuals or organizations involved. This makes this IC not fully controllable by the business actors in the focal TIS.

The knowledge and awareness of a technology is specific to the technology. The content of the knowledge varies across different technologies and sectors. Each TIS exhibits distinct technological properties and knowledge tailored to its specific components, such as the product, production system, and complementary products. Therefore, the specific knowledge required are unique to each TIS.

3.1.9 Knowledge and awareness of application and market

Similar as to the point above, the IC of knowledge and awareness of application and market can also be influenced by the actors within a TIS. The similar paths can be followed to do so. This IC is also specific to a technology, since the application and market are tailored to the characteristics of the technology and may at best display similarities with strongly related technologies.

3.1.10 Natural, human and financial resources

Actors within a TIS are not capable of directly influencing the IC of natural, human, and financial resources. Indirectly they can, by for example managing resources, investing in human capital, and securing financing. Organizations can for example form alliances to access natural resources more efficiently, create educational programs to enhance workforce skills, or engage with investors and government programs for financial support. But this example does not reflect on the resources itself but rather on the ability within a TIS to create and coordinate networks, which is represented in a BB.

This IC can be seen as generic because the need for natural, human, and financial resources is relevant for the formation and development of any TIS. These resources are fundamental to creating any product and offering complementary any service. The strategies to acquire and manage these resources are applicable across different technological fields. However, the IC of resources is specific because the particular natural resources required, the specific knowledge and competencies needed, and the financial investment necessary can vary greatly among different technologies and sectors. Some innovations rely heavily on rare natural resources (rare earth metals as an example, magnets for electric motors/generators), others may demand highly specialized skills, and still others might require significant capital investment (building a nuclear energy reactor requires significant investments). The strategies for mobilizing these resources, such as through education, collaboration, or funding mechanisms, need to be tailored to the unique challenges and opportunities of each TIS. But such strategies also boil down to the ability to create and coordinate networks.

So, while the availability of resources is a universally influencing condition for TIS formation, the specific nature of these resources and the methods for their acquisition and management are distinct to each technological innovation system.

3.1.11 Competition

Actors in a TIS cannot directly influence the IC of competition. They can influence this IC indirectly by engaging in innovation, differentiation, and strategic alliances to shape competitive dynamics. By developing unique product features, improving performance, adjusting pricing strategies, and forming networks, actors can influence how new and old technologies compete, as well as how different versions of new technologies vie for market dominance.

Competition is generic because competition is a fundamental economic principle that affects all TISs, influencing the development, adoption, and diffusion of technologies across various sectors. The competitive landscape shapes the market environment for all innovations, impacting aspects like pricing, performance, and market share. While competition is a universal influencing condition, its effects and the strategies to navigate it are tailored to the particular characteristics and context of each TIS.

3.1.12 Macro-economic and strategic aspects

Within a TIS, actors cannot directly influence the IC of macro-economic and strategic aspects. Actors can indirectly contribute to shaping the economic and strategic environment in which a TIS operates, through strategic planning, lobbying efforts, and participation in policy development. For example, they can lobby for policies that support innovation, seek incentives for research and development, or steer their business strategies to leverage economic conditions favourably. But these are activities that do not directly control the IC.

This IC is generic because macro-economic conditions and strategic aspects, such as market structures and economic trends, affect all TISs regardless of the specific technology or sector. Such conditions provide a context within which all TISs operate, influencing the availability of resources, the market demand for innovations, and the overall direction of industry development. Macro-economic and strategic aspects influence the landscape within which all TISs operate. Their specific effects and the strategies for navigating these effects are tailored to the unique circumstances of each technological innovation system.

3.1.13 Socio-cultural aspects

Actors within a TIS can influence the IC of socio-cultural aspects, though often indirectly. Since direct influence is not possible, we deem this IC as not controllable by actors, since the influence will take place via other BBs or ICs. Actors can engage in public education campaigns, collaborate with community leaders, or leverage media to shape societal norms and values towards more favourable perceptions of new technologies. Doing so, they can help form the socio-cultural landscape to support the development and adoption of innovations.

This IC is both specific and generic. It is generic because socio-cultural aspects such as public opinion, cultural norms, and societal values play a role in the adoption and diffusion of technologies across all TISs. These aspects universally affect how innovations are perceived and accepted by potential customers and other stakeholders. The socio-cultural aspects are specific to a geographical area because the norms, values, and cultural attitudes. They can influence the acceptance of a technology and this can vary significantly from one community, region, or country to another, and even within different segments of the same population. In analysing any TIS, this IC is evaluated not based on its cause or origin, but rather on its current state and impact on the target technology. Based on the definitions provided at the start of this section, this approach categorizes the IC as generic.

3.1.14 Accidents and events

Actors within a TIS have limited control over the IC of accidents and events, as many of these occurrences are external and unpredictable. However, actors can influence how to respond to such accidents or events. Through preparedness, resilience, and innovation, actors can prevent and otherwise mitigate the impacts of accidents. They can also potentially use these events as catalysts for innovation and development.

This IC can be considered both specific and generic. It is generic in that accidents and events can affect any TIS, regardless of the technology or sector, by impacting its building blocks and overall functionality. The need for resilience and adaptability in the face of unforeseen events is a universal challenge across all TISs.

Some TISs may be more prone to certain types of accidents or external events due to the nature of their technology, their role in society, or their operational contexts. The specific innovations or adaptations that emerge in response to these events will be highly tailored to the needs and opportunities of the affected TIS.

While the occurrence of accidents and external events is a generic factor that any TIS must deal with, the specific impacts and the responses to these impacts are unique to each TIS, influenced by its particular context and the proactive measures taken by its actors. Yet, the accident or event itself and its risk is something beyond the control of actors. The cause of an accident or event caused by the focal technology is technology-specific, but the results of any accident or event is generic according to the definitions given in the beginning of this section. Since the IC does not consider the cause, but only the phenomenon and its results, this IC is considered generic.

3.1.15 Discussion on the BB and IC analysis

The previous 14 subsections discussed each BB and IC of the TIS framework from Ortt & Kamp (2022). Table 2 provides an overview of the results per BB and IC according to their subsection number. The results are provided as 'actor-controllable', 'requires third party action', 'technology specific' and 'generic'. The first latter two terms are explained in the beginning of the section. The second term of required third party action, is new. This element is reviewed per BB or IC, since it provides extra information on the degree of control that the business actors in the focal TIS can exert on the BB or IC. Where action from a third party is required to change the status of a BB or IC, the controllability of the actor is changed from 'yes' to 'partly', since there is now also control from the third party.

The BBs and ICs previously considered uncontrollable can be re-evaluated. In this analysis, the approach adopted involves assessing the possibility for business actors to engage in an arena (such as offices, marketplaces, universities, etc.) with the objective of altering the BB or IC. Where such intervention proves impossible, the BBs or ICs was classified as not in control of business actors.

BB/IC	*Actor-controllable*	*Requires third party action*	*Technology specific*	*Generic*
Product performance and quality	*yes*	*no*	*yes*	*no*
Product price	*yes*	*no*	*yes*	*no*
Production system	*partly*	*yes*	*yes*	*no*
Complementary products and services	*partly*	*yes*	*yes*	*no*
Network formation and coordination	*partly*	*yes*	*yes*	*no*
Customers	*partly*	*yes*	*yes*	*no*
Innovation-specific institutions	*partly*	*yes*	*yes*	*no*
Knowledge and awareness of the technology	*partly*	*yes*	*yes*	*no*
Knowledge and awareness of the application and market	*partly*	*yes*	*yes*	*no*
Natural, human and financial resources	*no*	-	*yes*	*no*
Competition	*no*	-	*no*	*yes*
Macro-economic and strategic aspects	*no*	-	*no*	*yes*
Socio-cultural aspects	*no*	-	*no*	*yes*
Accidents and events	*no*	-	*no*	*yes*

Table 2: Overview properties BBs and ICs

3.2 Selection of different modes of interaction

This section addresses the selection of different modes of interaction. Why is this selection made? First, it provides structure for the study and provides focus to investigate the interactions within the given timeframe. Second, it enables the free selection and discussion of more relevant and interesting modes of interaction, instead of having to address each single mode of interaction.

For both the focal and interacting TIS, the analysis is restricted solely to those BBs and ICs that are entirely or partly within the control of the business actors. It is deemed necessary to categorize these controllable elements into three distinct categories. This due to the set of potential modes of interaction originating from the controllable BBs and ICs, which present too many different modes to make an analysis feasible in this study.

Each category will represent a set of BBs or ICs, or combined. The categories are used to discuss their interaction. This provides a narrower set, and enables a more structured approach to formulating interactions of the categories. This approach provides an orderly method to analyse the related BBs and ICs, by limiting interaction between three categories, instead of the nine controllable BBs or ICs per TIS. The narrow set of three categories reduces the possible number of interaction modes from 81 to 9, which is a feasible number to continue the analysis with.

The categorization of the technology specific and controllable BBs and ICs into three categories, is based on the core characteristics and relationships that each group represents in the context of a TIS. Three categories are presented and discussed in the following three paragraphs, being Product Attributes, Market and Value Chain, and External Environment.

The BBs directly related to the focal technology's direct characteristics are arranged under the Product Attributes category. This category holds the two BBs of product price and product quality and performance. These BBs describe solely the technology and embody important characteristics, which strongly influence the interaction between customers and the technology within a market.

The technology does not exist in isolation from the market. It has elements that enable the production of the technology, complement the technology, buy and sell the technology, and support the technology in other ways. The category Market and Value Chain categorizes the BBs of production system, complementary products and services, network formation and coordination, and customers. This category embodies the controllable BBs that describe the interaction of the TIS with the environment.

The remaining BB and 2 ICs that can be influenced by business actors are the external entities and attributes that either or not enable the development and diffusion of the technology. The category External Environment includes the BB technology-specific institutions and the two ICs of knowledge and awareness of the technology, and its application. This category represents for example the perception, regulation and support of third parties or institutes which are relevant to the TIS.

This categorization within the TIS framework offers a simplified framework for interacting elements in the dynamics of technological innovation. The three categories yield the following combinations of interaction between two TISs:

1. Product Attributes to Product Attributes
2. Product Attributes to Market and Value Chain
3. Product Attributes to External Environment
4. Market and Value Chain to Market and Value Chain
5. Market and Value Chain to Product Attributes
6. Market and Value Chain to External Environment
7. External Environment to External Environment
8. External Environment to Product Attributes
9. External Environment to Market and Value Chain

These interaction modes are further refined by concentrating exclusively on unidirectional interaction from one TIS to another TIS.

A selection where unidirectional interaction of two TISs asks for methods of determining which of the two TISs exerts the influence can be made according to the interest of the user. One more mature, developed TIS is more likely to exert influence on a less developed (niche) technology's TIS. Such selection is based on the higher probability of influence exerted by a more mature TIS on a smaller, less developed TIS, rather than the reverse scenario. This further implies business actors in the niche TIS having to cope with interactions from the more mature TIS. The maturity of a TIS is in this study based on the state of the BBs and ICs of the TIS.

For users interested in the potential and power of a smaller (niche) technology's TIS, it is however interesting to study the reverse scenario of how the smaller one interacts on the more mature TIS. This can aid them in positioning in the market and formulating appropriate strategies.

3.3 Explanation of different modes of interaction

The previous section explained the stance on analysing the TIS interaction, and informed about the selection procedure and categorization of nine interaction modes. Figure 5 displays these interaction modes by visualizing two TISs, the relevant BBs and ICs, brackets to indicate the categories, and the directions of interaction between categories. This section describes the nine modes of interaction and further explains them to help understanding of the dynamics between TISs. Each interaction mode is addressed in a separate subsection. For each mode, at least one example of interactions between the category its BBs and/or ICs are presented. The goal is to delineate and clarify these interaction modes, examining their effects in shaping the TIS of a technology.

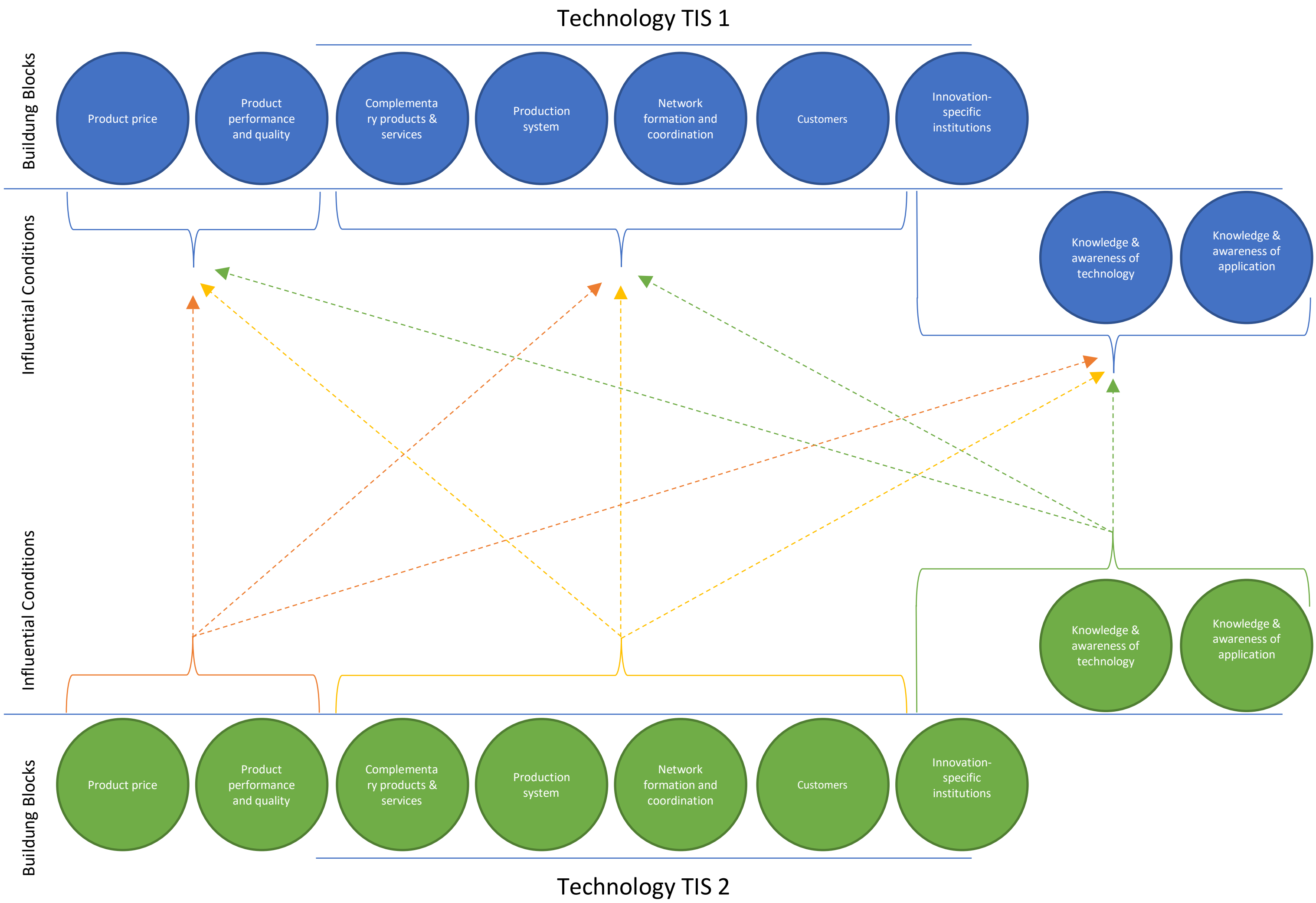

Figure 5: Visualization of interactions between the categories of technology-specific BBs and ICs of two TISs.

3.3.1 Product Attributes to Product Attributes

This interaction mode is very well described by looking at the interaction between the price BB of one TIS and that of another. In market entry and competition, the pricing strategies of mature technologies have an influence on the pricing approaches of niche technologies. This interaction is supported by factors such as consumer expectations, cost benchmarking, and competitive pressures, which together shape the pricing landscape of new technological entrants. Mature technologies often set benchmarks for what consumers perceive as acceptable prices for technological solutions. These benchmarks inform consumer expectations and require new technologies to strategically align their pricing.

The competitive landscape shaped by mature technologies challenges niche technologies to justify their market value, making pricing strategies that reflect the innovation's value necessary. This may involve pricing adjustments to either match with established market norms or distinguish the niche technology through its value propositions that justify a different pricing model. These pricing considerations are important for successful market diffusion and adoption of niche technologies. This highlights the complex interactions between incumbent technologies and the innovative potential of new entrants. Such competitive pricing has been researched for both producers as for distributors (Shipley & Bourdon, 1990). Figure 15 provides a visualization of the interaction between these categories.

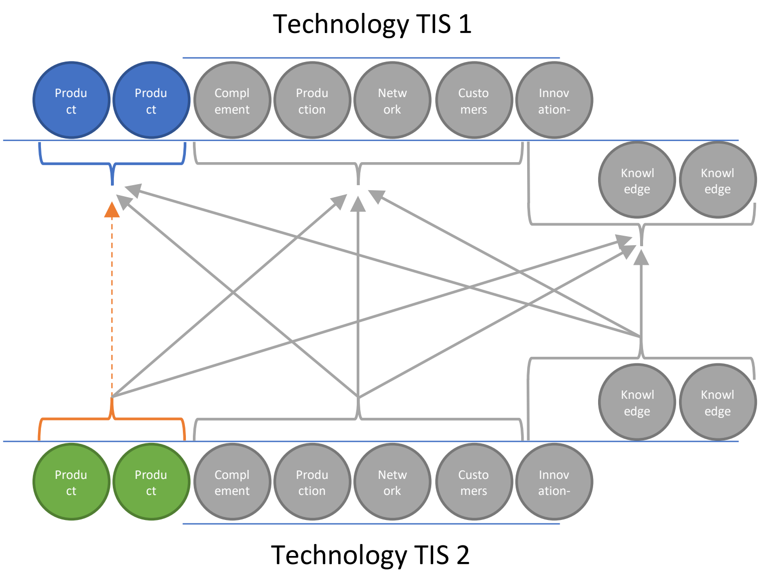

Figure 6: Visualization of interaction between the product attributes categories of two TISs.

3.3.2 Product Attributes to Market and Value Chain

The pricing and performance of a mature technology not only impacts the pricing strategy of a niche technology but also extends its influence to aspects of the market and value chain, specifically affecting customer perceptions and the development of complementary products. When a mature technology is established in the market at a certain price point, it sets a general expectation among (potential) customers regarding the price-performance ratio of similar technological solutions. This expectation influences how customers see the value of newer, niche technologies, and can affect their willingness to pay if the price differs significantly from the general norm. The customer base of a niche technology may be directly shaped by the pricing models of incumbent technologies, as consumers judge the value of the new technology in the context of what they expect or are used to pay.

The price of mature technology can foster or hamper the development of complementary products for the niche technology. Complementary products are essential to create a complete solution that meets customer needs. Manufacturers of these complementary products observe their markets, including the pricing strategies of both mature and emerging technologies, to make strategic decisions regarding their own product development and pricing. If the niche technology were to be priced higher due to an influence of the mature technology's pricing which is especially the case in the occasion where a mature TIS is supplier to the niche TIS. This could scare complementary product manufacturers due to concerns about market size or consumer willingness to pay in a complete, higher-priced solution. Figure 7 provides a visualization of the interaction between these categories.

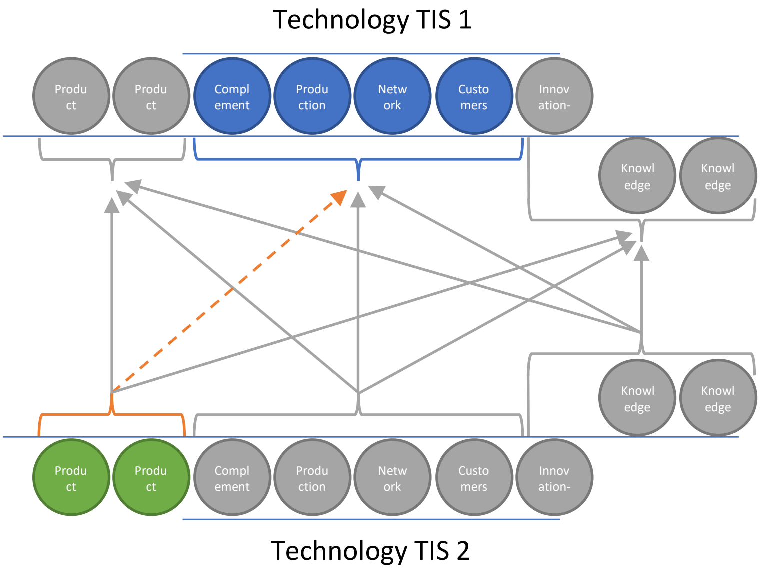

Figure 7: Visualization of interaction between the categories of product attributes and market and value chain of two TISs.

3.3.3 Product Attributes to External Environment

The price and performance of a mature technology can have a nuanced, albeit indirect, influence on the innovation-specific institutions and the broader knowledge base surrounding a niche technology and its applications. A direct interaction of the mature technology’s price and performance characteristics with the external environment of a niche technology is often limited and not very clear.

This limited direct interaction is due to the nature of the external environmental components. Innovation-specific institutions like regulation, norms and policy are in general formulated by policy makers and follow the broader societal, economic and technical trends. They do not necessarily consider specific characteristics of another technology. In similar fashion, knowledge of a technology and its application is influenced by a broad set of factors, in which specific characteristics of another technology form one of the many other factors that can influence education and general understanding of the public.
One indirect influence can for example be found on bad safety aspects of a LIB TIS (product quality) leading to knowledge on this aspect of the technology and its application (LIB TIS) leading to safety regulations in a related TIS of electric vehicles (EVs). This interaction is further addressed in subsection 3.3.7. Figure 8 on the next page provides a visualization of the interaction between these categories.

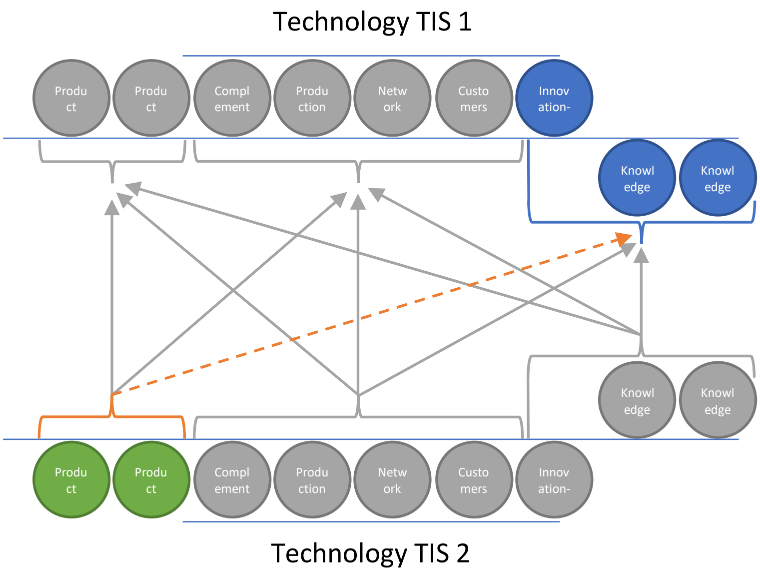

Figure 8: Visualization of interaction between the categories of product attributes and external environment of two TISs.

3.3.4 Market and Value Chain to Market and Value Chain

The direct interaction between the market and value chain of a mature technology and that of a less developed niche technology is complex in nature. BBs in this category, being the complementary products and services, production system, network formation and coordination, and customers, inhibit a considerable potential for interaction. This especially is the case from the mature technology's perspective. Here too, the nature of both technologies determines the nature of the interaction.

For example, production systems for incumbent technologies can offer valuable insights and even support the niche technology. Mature technologies have often dealt with adaptations in their market and value chain, potentially offering niche technologies a leap forward by not having to reinvent such aspects. It is also possible for actors in the value chain of the mature technology to try and get involved in the market and value chain of that of the niche technology. In such interactions, actors can either attempt to compete or to collaborate with the niche technology.

An example of competition for resources is detailed in Section 2.1, which explains about the demand for silicon in the manufacturing of PV panels and the potential implications for other technologies that also rely on silicon as a key input, as discussed by Bergek et al. (2015). Similar competition for complementary products for production systems can be imagined for production systems, particularly in the manufacturing of high-tech semiconductor chips. ASML, as one of the few global suppliers of advanced semiconductor manufacturing machinery, faces constraints in its delivery capacity (*Strong Demand at ASML Points to the Coming Chip Upswing*, 2024; Toby Sterling, 2024). Consequently, different TISs that depend on such machines for semiconductor production might directly impact each other's production systems through the acquisition of these machines. The limited availability of such manufacturing equipment could lead to a situation where the acquisition choices of one TIS influence the production capabilities and efficiency of another, illustrating a direct competition for essential resources within the semiconductor production system domain.

The development and market strategy of niche technologies are influenced by the landscape shaped by mature technologies, especially through complementary products and services that can provide either insights or warnings for growth. Challenges such as competition for essential resources like production machines and the need for niche technologies to offer distinct advantages to transition consumers' trust highlight the complex dynamics of market entry and competition. Historical instances of disruptive innovations, such as the digitalization of music and video content, illustrate the potential for swift shifts in consumer bases. However, the direct adoption of elements that led to the success of mature technologies remains uncommon, emphasizing the need for niche technologies to strategically innovate and differentiate themselves.

In reviewing this subsection, three modes of direct interaction were addressed between mature and niche TISs. First, the interaction between the production systems highlights how mature TISs can offer crucial insights and practices to niche TISs, aiding in their operational optimization. Second, the competition for complementary products and services impacting production systems underscores the challenges niche TISs face due to resource competition with mature TISs, especially for exemplary inputs like silicon or specialized machinery. Finally, the transition of customer bases from mature to niche technologies reveals that the potential market shifts depend on the niche offering's unique advantages and characteristics. Figure 9 provides a visualization of the interaction between these categories.

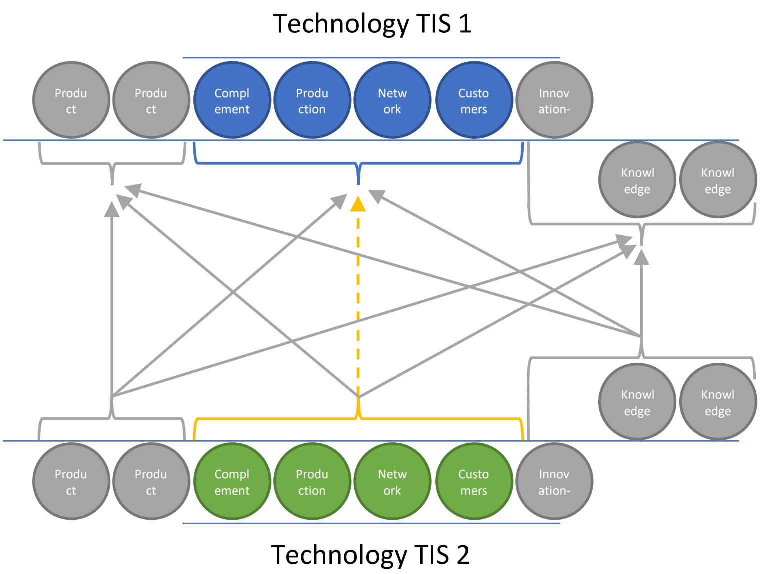

Figure 9: Visualization of interaction between the market and value chain categories of two TISs.

3.3.5 Market and Value Chain to Product Attributes

This interaction mode between mature and niche TISs illustrates the direct impact of organization within the value chain such as network formation and coordination on product pricing strategies. As an example, the semiconductor industry is considered. Incumbent companies such as Intel have long dominated the sector, benefiting from well-established supplier networks that gave them significant advantages in terms of production costs, efficiency, and scalability. These networks, created over years of operation, allow mature companies to negotiate better terms, achieve economies of scale, and access cutting-edge manufacturing technologies at lower costs.

For niche semiconductor companies entering the market, the established networks present both a challenge and a standard. This dynamic, where the network formation and coordination influence the product price BB of a niche TIS, becomes clear as these newcomers straddle the competitive contexts.

To remain competitive, niche companies must not only create technological innovations but also evolve their supply chain strategies to effectively manage costs and set competitive prices. The goal to maintain competitive pricing is strengthened by market demands for cost efficiency, significantly influenced by the pricing strategies of industry leaders. Herein lies the question: does this scenario present a direct influence, considering that the pricing strategies of both technologies are encapsulated within their product price BB and are partially crafted through their efforts to forge efficient and effective supply chains? The scenario described does show a direct influence. Mature semiconductor companies with efficient supply chains set cost standards for the industry. Niche companies entering the market must adapt their pricing to meet these standards, directly influenced by the established cost efficiencies and market expectations set by the mature companies. This creates a direct impact on how niche companies manage costs and set their product prices.

Similarly, the shift from traditional to smartwatches illustrates how customer expectations from mature TISs directly affect niche TISs' product development and characteristics. Companies such as Apple have set new standards for smartwatch functionality and characteristics, leading to a direct customer to product performance and quality interaction. New entrants focusing on health monitoring features in their smartwatches are compelled to meet or exceed these benchmarks to gain consumer acceptance. These instances highlight the direct influence of mature TISs' networks on niche TISs' pricing and the impact of established consumer expectations on niche product quality and performance. Figure 10 provides a visualization of the interaction between these categories.

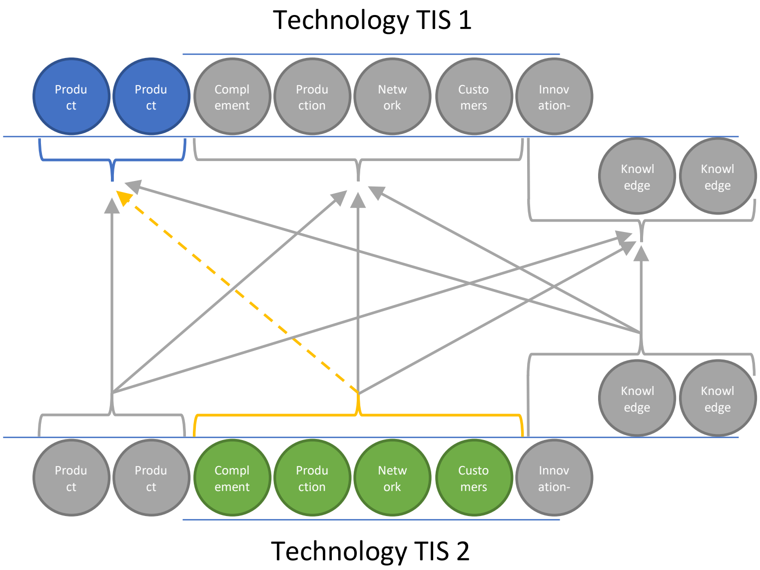

Figure 10: Visualization of interaction between the categories of market and value chain and product attributes of two TISs.

3.3.6 Market and Value Chain to External Environment

It is thinkable that scenarios exist where this type of interaction presents itself. For instance, a scenario could involve a mature TIS incorporating a niche TIS as either a complementary product or within its production system. In such cases, the BBs related to the production system or complementary products of the mature TIS would naturally have a direct impact on the knowledge of the application of the niche technology. This could also contribute to the specific knowledge of the niche technology, especially if its performance and quality are studied during its application. I expect that interactions of this type exist where the niche technology participates in the value chain of the mature technology. I also expect that interactions with the innovation specific institutions and regulations will be impacted indirectly through other BBs or ICs of the niche TIS. Figure 11 on the next page provides a visualization of the interaction between these categories.

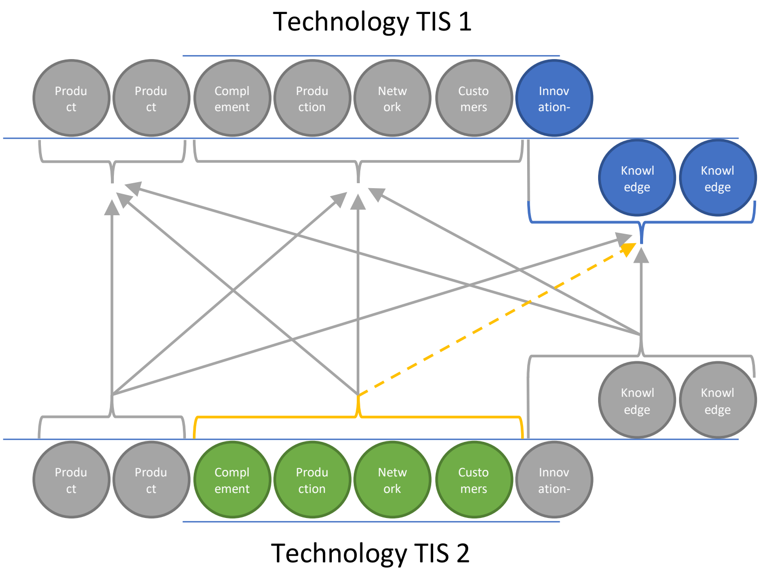

Figure 11: Visualization of interaction between the categories of market and value chain and external environment of two TISs.

3.3.7 External Environment to External Environment

This interaction can by exemplified by the interaction between the IC of awareness of technological advancements in the one TIS and the BB of innovation-specific regulatory frameworks in another TIS. This interaction underscores how the perception and understanding of technologies can influence the specific institutions of another TIS. Awareness of the potential and impact of a technology is fundamental to the formulation of policy and regulation. On the contrary, the existing regulations and policies can influence the focus and directions of the development of new knowledge of technologies.

One example of the above mode is the example of LIB applied in EVs. The knowledge and awareness of the technology of LIB (one TIS), and particularly its risks, directly leads to specific regulations regarding safety for EVs (another TIS) (Nicky Smol, 2023). Figure 12 provides a visualization of the interaction between these categories.

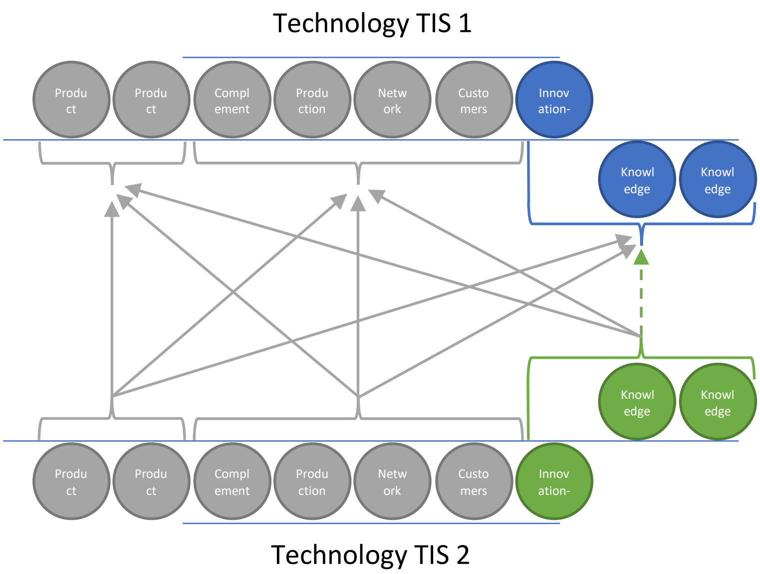

Figure 12: Visualization of interaction between the categories of external environments of two TISs.

3.3.8 External Environment to Product Attributes

When examining how the external environment of a more mature TIS interacts with the Product Attributes of a niche TIS, it becomes clear that this relationship is likely and mostly indirect. Direct interaction between the external factors associated with a mature TIS, such as regulatory policies, industry standards, or cultural norms, and the specific qualities of a niche product (like its performance, quality, or price) does not typically occur in a straightforward manner. Instead, the mature TIS's External Environment influences the broader market and regulatory landscape, which then impacts the development, positioning, and perception of the niche TIS's Product Attributes. For example, environmental regulations developed in response to issues within mature industries might encourage innovation in eco-friendly materials or processes in niche sectors, affecting product development indirectly. Thus, while the external conditions set by mature TISs do shape the innovation pathway of niche technologies, they do so through a series of indirect influences that eventually affect product attributes. Figure 13 provides a visualization of the interaction between these categories.

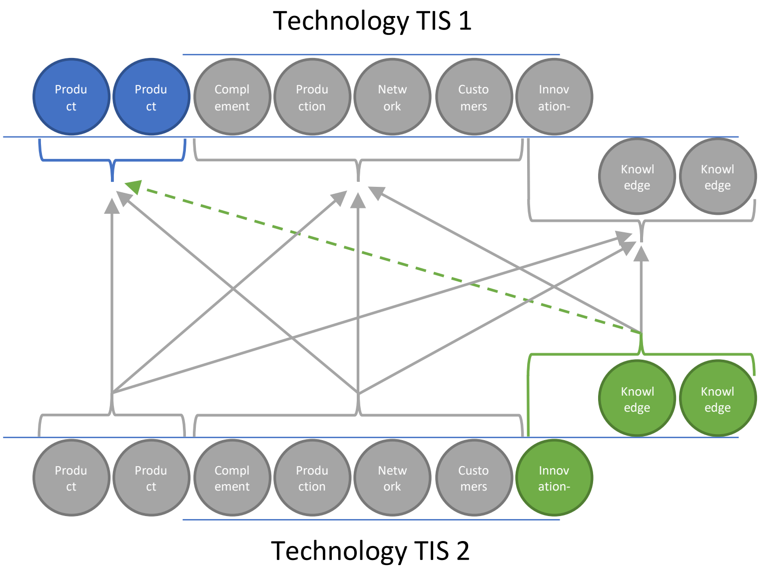

Figure 13: Visualization of interaction between the categories of external environment and product attributes of two TISs.

3.3.9 External Environment to Market and Value Chain

The influence exerted by the innovation-specific institutions of a mature TIS can have a significant and direct impact on various BBs within the Market and Value Chain category of a niche TIS. This interaction becomes clear when policy measures, whether positive or negative, affect the level of knowledge within the mature TIS regarding the technology or its applications. These changes can directly influence the complementary products, the efficiency of the production system, or even the formation of networks in a niche TIS. For instance, enhanced understanding or regulatory support within a mature TIS can facilitate the formation of strategic partnerships, aiding a niche TIS in establishing robust networks supported by new knowledge.

Furthermore, mature TISs that view niche TISs as competitors might seek to actively influence policies in a way that supports their existing systems or undermines customer confidence in the niche TIS (in that case it might become technology-specific to the niche TIS). Such strategies allow technology-specific institutions linked with mature TISs to directly impact the customer base of niche TISs. Actions such as advocating for strict regulations that niche technologies might struggle to meet, or promoting public scepticism about the effects or safety of niche innovations, serve as direct channels through which the established institutions can affect the market dynamics and customer trust surrounding emerging technologies. Figure 14 on the next page provides a visualization of the interaction between these categories.

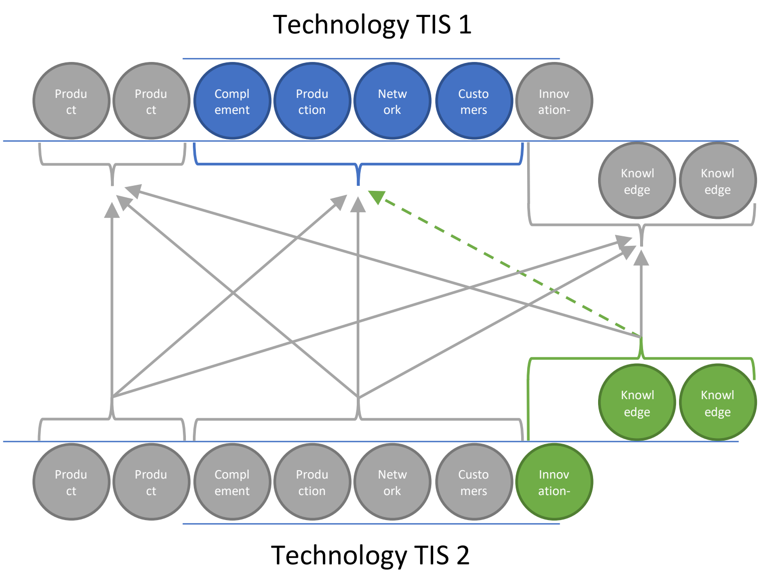

Figure 14: Visualization of interaction between the categories of external environment and market and value chain of two TISs.

3.4 Concluding the conceptualization of a TIS interaction framework

This chapter explains the process of conceptually designing the TIS interaction framework central in this thesis. The first section affirms the potential amount of different interaction modes when considering direct interactions between any BB or IC from one TIS to that of the other TIS. These 196 different modes did not provide a feasible set of modes to study in this research.

To provide a feasible set of modes to study in this research, a further selection of relevant BBs and ICs is proposed. For a TIS interaction, with a TIS framework that focusses on a business actors' perspective, it is important to consider those elements in a TIS that are specific to the technology and controllable by business actors. These BBs and ICs that are controllable and technology-specific are regarded for further analysis of interaction. However, the limited number of BBs and ICs still results in a set of 81 different modes of interaction. Hence, the BBs and ICs are collected in three categories, being (i) product attributes, (ii) market and value chain, and (iii) external environment. Product attributes entail the first two BBs of product price, quality and performance. The subsequent category of market and value chain stands for the four BBs of complementary products and services, production system, network formation and coordination, and customers. The last category, external environment, describes the last BB and the two ICs, being innovation-specific institutions, knowledge of the technology, and of the technology's application.

With now considering a feasible amount of nine different interaction modes, the next chapter will provide a brief historical analysis of the two EES technologies SC and LIB. Subsequently, the TISs of both technologies are analysed and provided for a systematic and detailed understanding of both technology's status and performance. Last, the drivers and barriers for both SC and LIB are discussed. The information of the next chapter serves as foundation for the onwards study to the interactions between the TISs of SC and LIB.

4 TISs of EES technologies

For the Dutch market of EES solutions, no prior analysis for its TISs exists. This chapter analyses the TISs of two EES technologies. The first section describes the approach for analysing the TISs before analysing the TIS of SC for EES in the second section. These sections are then followed by the third section, in which the TIS of LIB as an EES technology is described. These results are relevant for chapter 5, in which the interaction modes as described in previous chapter 3 are applied to the case of LIB and SC. The final section of this chapter

4.1 TIS analysis approach

To analyse the TISs of SC and LIB, the research follows the framework created by Ortt & Kamp (2022). This framework is addressed in section 2.3 of this thesis.

The European market, instead of just the Dutch market, is considered in the analysis of both TISs. The European and Dutch market have high interdependence making the consideration of both a more realistic context to analyse. Examples of such interdependence can be related to the energy market of both focal technologies (Bosco et al., 2010).

Sections 4.2 and 4.3 start by introducing the technology and its developments over time. The technology's invention and adaptations over time are historically briefly addressed. The sections proceed by visualising the performance of the TIS's BBs and ICs, using three different colours for the factors. Red, orange and green will respectively indicate an incomplete/incompatible, partly incomplete/incompatible, or complete/compatible BB or IC. The description of the BB or IC its performance is discussed along with the indicators related to the performance of the BB or IC.

The following section first addresses the analysis of SC and the TIS of this technology.

4.2 TIS of Super Capacitors (SC)

This section answers sub-question 2 for SC

This section describes BBs and ICs related to the TIS of Super Capacitors (SC). SC is a relatively new technology in EES for national grid purposes.

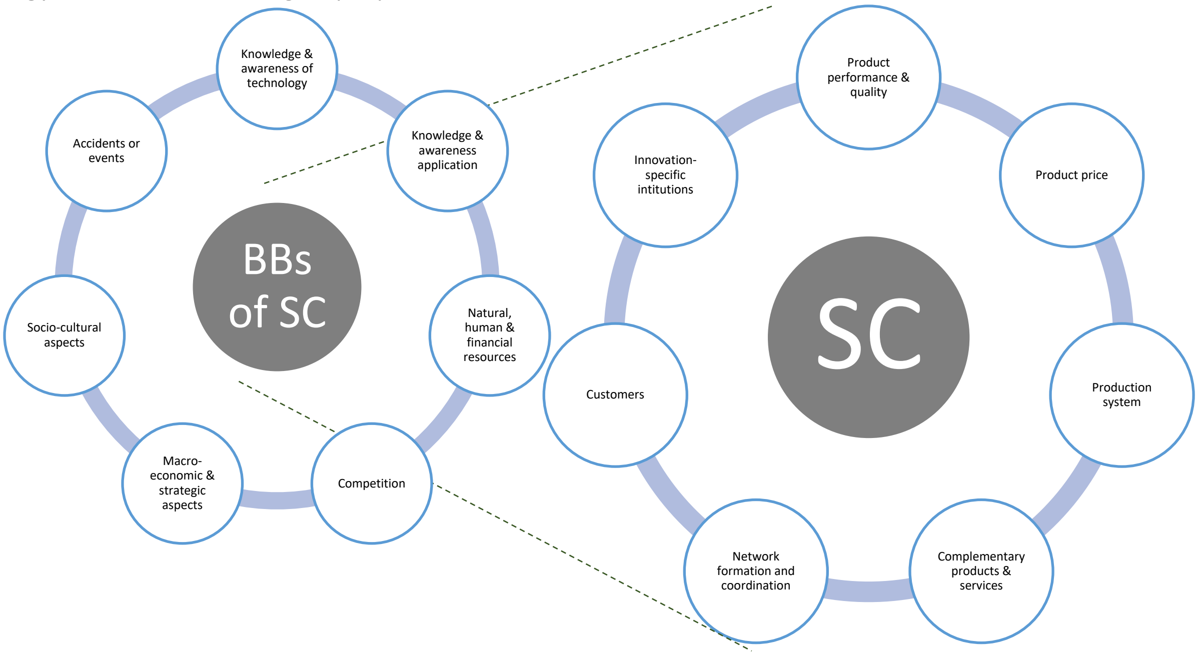

Figure 15: Visualisation of TIS of SC without status of BBs and ICs, according to model of Ortt & Kamp (2022)

Figure 15 provides a visual representation how the factors in the model of Ortt & Kamp (2022) are represented in the situation for the SC TIS. Figure 17 at the end of this section will provide a visual representation of the SC TIS with indicating the status of each BB and IC. In that case, a green, orange or red BB or IC represents a supporting, neutral or hindering factor.

The roots of the capacitor technology are found in the invention of the so-called 'Leyden jar' in 1745. This initial product differed significantly from the more recent products. The original product incorporated actual water jars. The first application supported the knowledge development for SC significantly, and was later on succeeded by more advanced and complex SC products. The first notion of regular solid capacitors dates back to 1876. This regular solid capacitor was created for the alleged preceding market demand for the functionality of capacitors in radio receivers. (Ho et al., 2010)

The later invention of the double-layered SC took place in 1957, but that initial invention by General Electric never made it to market due to impracticalities. Later discoveries in 1962 and 1970 by another company made the product suitable for market introduction, and nowadays, it is the root of almost all developments in the SC TIS. General commercialization followed in 1978. (Ho et al., 2010; Miller, 2007)

Figure 16 displays the path of inventions towards SC technology.

The technology and principle behind SC are increasingly understood. Although SC technology will have gone through an adaptation phase and are familiar with large-scale diffusion in general, this is not yet the case for SC in EES. With two hampering factors, the situation for the SC TIS is not yet fully supportive of its performance. Combined with observations of European manufacturers for SC technology and market initiatives to demonstrate SC, the SC TIS for EES seems to be in the adaptation phase.

4.2.1 Product Performance and Quality

SC in EES is a relatively new high-tech product, providing a sustainable method to manage ultrashort power peaks. It offers a comprehensive electrical system perspective, stability, and reliability over short periods. As discussed in this research, SC's functionality is multifaceted, which is also discussed by Espinar and Mayer (2010). In EES, SC serves both function as a buffer for power surges and as a stabiliser to, for example, smoothen demand and supply curves. This versatility supports and enables adaptation and diffusion of RES technologies, which are inherently less stable power sources than traditional systems (Mulder, 2014).

The current price-quality ratio of SC is exceptional for certain applications, outperforming alternatives in terms of durability, security, and response time for increased cyclic use in demanding environments. This can justify the higher price for SC compared to other options, positioning it as a cost-effective choice in the long run.

Capacitors store energy by creating a voltage difference between two separated conducting areas, resulting in potential energy storage. SC enhances the capacity of standard capacitors significantly by increasing the area of the conductors, resulting in enhanced storage capabilities. Therefore, a capacitor's capacitance is expressed in farads by dividing the charge (in coulombs) by the potential (in volts). In EES applications, SC are combined with equipment that enables the transformation of electrical energy flows from alternating current (AC) to direct current (DC) and vice versa, as SC operates exclusively with DC, while power transmission and distribution are predominantly AC-based.

Unlike other energy storage technologies, SCs do not transform electrical energy into a different form but store it as electrical potential. This characteristic makes SC ideal for rapid energy discharge (resulting in significant power capacities limited by the resistance of gear and connected equipment), though less suitable for long-term energy storage. SC necessitates specific transformation equipment for effective use in EES, which includes a range of complementary products discussed later in this chapter.

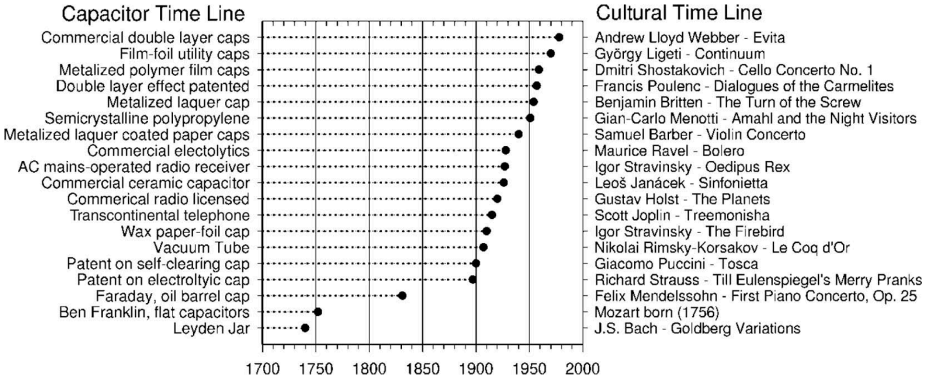

Figure 16: Capacitor time line with corresponding cultural time line for reference (Ho et al., 2010)

With the enhancement of SC as cleaner, safer, and more durable technologies, their competitiveness and influence are growing in comparison to LIB. This growth is supported by a broader set of challenges in the energy transition, where SC is finding a better technological fit. Consequently, this has a negative influence on the LIB TIS.

4.2.2 Product price

When looking at SC solutions compared to the pricing of other technologies, such as EES applications, it becomes clear that SC depends on whether the price is attractive to a customer or not. Within EES, SC technology is currently only interesting for its price when looking at 'peak power applications'. SC technology is much more expensive for longer-term energy storage, where power is less relevant (Al Shaqsi et al., 2020, pp. 300–301).

4.2.3 Production system

Production in The Netherlands and the European Union

In the Netherlands, no complete production systems or parts of the production system are in place to produce supercapacitors. This absence does not imply that extensive scale adaptation and diffusion in the Netherlands would be impossible. This could result from the fact that there exist links between stakeholders in this system in the Netherlands and at least one manufacturer abroad in Germany. This manufacturer, Skeleton Technologies, controls a large part of the supply chain of their SC. (Skeleton Technologies GmbH, 2018)

A scale-up (NAWA Technologies) in France aims to achieve similar production capacity performance levels. However, their technological advances aim to perform better than the already high performance of the SC from the German company (NAWATECHNOLOGIES, n.d.). EIT InnoEnergy describes one more European manufacturer, C2C, based in Portugal (EIT InnoEnergy, n.d.). This company is in an even earlier phase than the two companies as mentioned above. NAWA and C2C do not yet have commercialize products ready for EES when analysing their available documentation. Relatively lower demand caused by, among others, the LIB TIS influences this factor.

4.2.4 Complementary Products and Services

With large-scale adaptation and diffusion, a sociotechnical system must be able to perform without severe barriers to the performance of the technology. Therefore, complementary (supporting) products and services should be in place to support the performance of the sociotechnical system itself. This subsection describes the complementary products and services required for the product's production, adaptation, and use. Together with SC, these elements create the sociotechnical system for SC. (Ortt et al., 2013)

For SC for EES, complementary products are available. One example is voltage transformation equipment. This transformation equipment is often widely available from other systems and must be used to charge and discharge SC in a controlled manner. The same applies to existing and further developed or diffused technologies, such as lead-acid batteries for EES. The knowledge to produce such transformation gear is thus advanced. Only the configuration of such systems is specific to a certain EES technology.

SC cells are assembled using functional elements such as processed carbon, milled and sheet aluminium, and binding agents. These components are available, and none are unavailable to the SC technology. Thus, no shortage hampers large-scale development and diffusion.

Developments in nanotechnology are helping the formation of graphene, which in turn helps the improvements of SC (Liu et al., 2015). This strengthens the competitiveness of SC, negatively influencing the LIB TIS.

4.2.5 Network Formation and Coordination

Looking at the largest manufacturer of SC in Europe, Skeleton Technologies, it is interesting to observe the few suppliers the company relies on. Little information is available on this aspect from the other two European manufacturers, but they appear to follow a similar path. The network still requires development to reach full self-organising capabilities, and many entities still organise through the push of manufacturers or third parties (like incubators). For other producers, the supply of components and feedstock operates as desired.

Based on experiences in the Dutch market, the organization of actors on the demand side for EES applications of SC is emerging but is not yet fully established. This observation is related to the next factor, customers.

The lack of customers impacts the organization of financial resources, rendering this factor neither supportive nor obstructive. Therefore, Figure 17 indicates the factor as orange.

4.2.6 Customers

Potential customers mostly seem to lack knowledge of the benefits of SC for EES and are, therefore, hesitant to inquire or step into applications with SC involved for EES. Also, the incumbent technologies like LIB are more attractive due to their multifaceted advantages and application possibilities. This makes the factor not yet supportive of the TIS. This finding is based on my market exploration in The Netherlands in 2019. Where SC have much more appealing advantages over other technologies, conventional and established technologies are often used instead, as in the case of port cranes. This is proven by pilot projects and sometimes changing an industry (Skeleton Technologies GmbH, 2018).

4.2.7 Innovation-specific institutions

The factor of institutional aspects is indirectly influenced by the initiative of institutions to stimulate RES. This will directly stimulate the use of SC related to RES products or complementary systems to RES. NL has no clear set of direct rules or laws that govern the development, deployment, and use of EES, or SC as EES. This neither hampers nor helps technology, in my opinion. However, it is believed that the stimulation of RES indirectly stimulates the use of SC for EES. This factor supports the SC EES TIS.

4.2.8 Knowledge and awareness of technology

Much knowledge of SC technology remains with the companies that develop SC systems, of which three are identified in Europe. The production of SC systems deals with patented technologies and methods for producing components, and these patents limit others from learning from already existing findings. At the same time, it activates competition to put more effort into innovation, thus discovering new ways of adding advantages to the technology.

The main challenge of SC technology remains to improve its weaknesses compared to conventional solutions such as LIB technology. Increasing energy storage capability is one of the main challenges for SC technology. Recent advancements in research prove that the technology can reach parameter levels of LIB technology. This, however, brings new challenges, such as stability issues and performance challenges to overcome. Hence, there cannot yet be a viable alternative for the LIB applications that performs the same or better on all parameters. SC technology must make profound leaps forward to keep up with demand soon. (Ho et al., 2010; Sambath Kumar et al., 2018)

This factor partly blocks the TIS. Technology is proven for specific power-demanding applications. On the other hand, there is a long leap to overcome the differences compared to competing technologies. Opportunities to improve exist (Sambath Kumar et al., 2018), but they must be introduced in workable forms.

4.2.9 Natural, human, and financial resources

Until now, there seem to be no problems with the availability of natural, human, or financial resources. The main components of SC (aluminium and carbon) are abundant on Earth (Royal Society of Chemistry, n.d.). Market leaders have no problem attracting capital to develop (Skeleton Technologies GmbH, 2018), and no blockades are observed.

4.2.10 Knowledge and awareness of the application and market

Knowledge of the application of SC in EES is growing but remains insufficient. Introductions to markets, through exhibitions or marketing, are beneficial. However, achieving certain standard levels of understanding the potential of SC demands more intensive initiatives or activities, and additional time. In the realm of niche development and management, efforts continue to integrate this technology with other systems. Compared to reference technologies, this results in relatively limited knowledge spread of using SC for EES. Being self-informed or self-taught about the applications tends not to occur outside universities or knowledge institutes. This perspective derives from personal experience discussing the use of SC in EES for port cranes in the Port of Rotterdam in 2018. At that time, the stakeholder was not interested in exploring further options, likely due to a lack of interest and knowledge about the potential benefits of cooperation. Websites of these manufacturers illustrate the available knowledge about applications where SC is used in EES.

4.2.11 Competition

SC experiences competition based on several applications (Energy Storage NL, n.d.). Competition comes from older, more established technology, such as flywheels in the Netherlands, and from LIB and other forms of batteries. However, where flywheel technology is more comparable in an application, LIB and other batteries are supposedly more often deployed for longer-term energy storage because of their more mature systems.

4.2.12 Sociocultural aspects

Regarding socio-cultural aspects, there are no blocking mechanisms observed. The lack of regulation on SC might hinder its TIS performance because systems such as these might operate at critical levels. Operating at critical levels would require meeting specific standards (as prescribed by regulations), which would not be possible due to the lack of such a regulation. On the other hand, there is a widespread urge to move towards 'clean energy systems,' which is an advantage for SC since the technology and composition of SC fit in perfectly.

4.2.13 Macroeconomic and Strategic Aspects

No economic problems or challenges exist for SC at the time of writing. The challenge might be the threat of inflation and increases in the price of raw materials. However, the demand for RES (and supporting SC systems) is expected to weigh more in the coming decades and thus push the performance of the SC TIS. The worldwide efforts to transition to cleaner energies make the environment for application in different fields of technologies like SC currently very friendly.

4.2.14 Accidents or Events

No accidents or incidents with SC for EES have been found to have occurred.

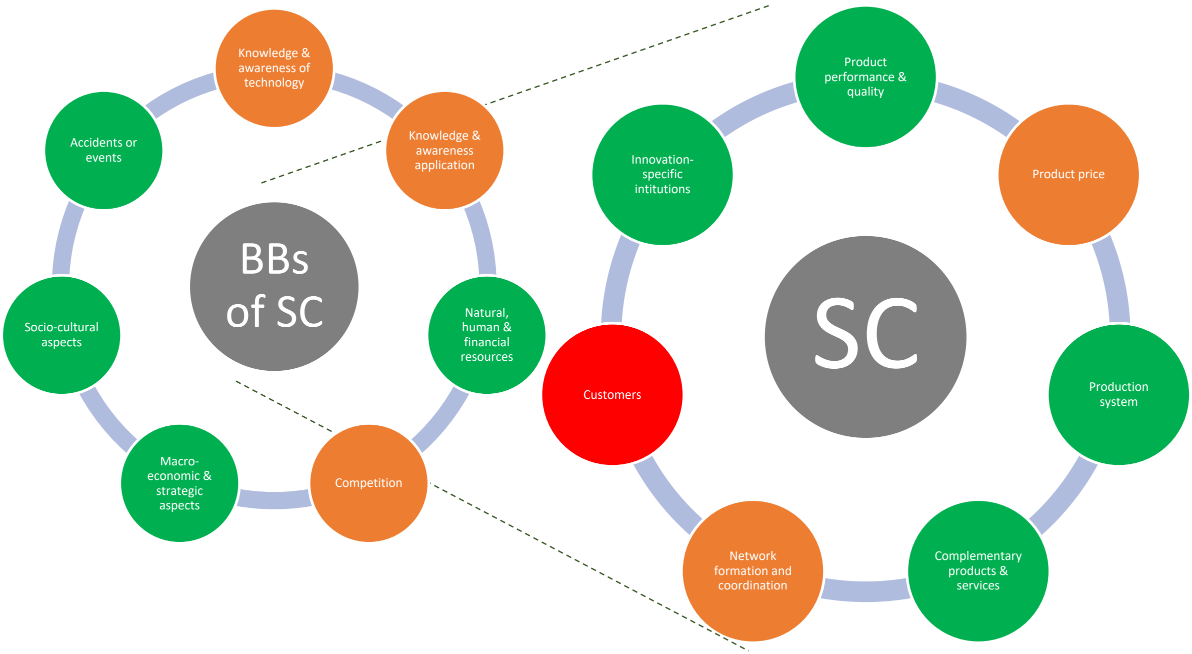

Figure 17: Visualisation of TIS of SC with status per BB and IC, according to model of Ortt & Kamp (2022)

4.3 TIS of Li-ion batteries (LIB)

This section answers sub-question 2 for LIB

This section describes the BBs and ICs related to the TIS of LIB. LI is a well-known and explored technology in the field of EES for national grid purposes.

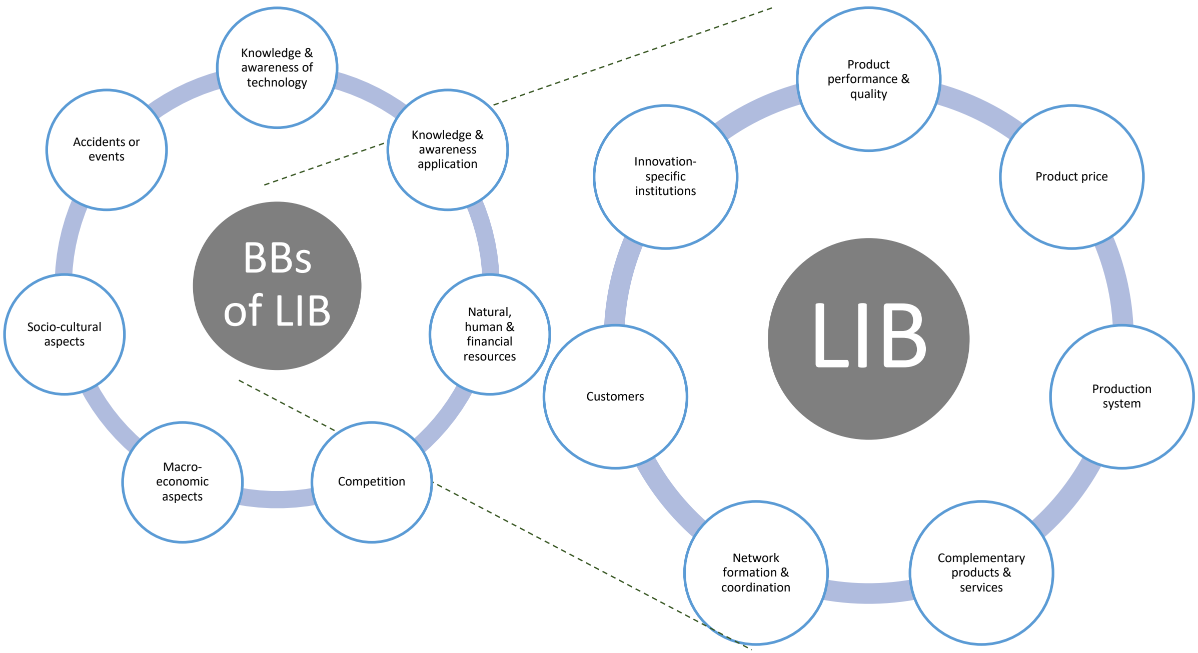

Figure 18: Visualisation of TIS of LIB without status of BBs and ICs, according to model of Ortt & Kamp (2022)

Figure 18 provides a visual representation of how the BBs and ICs from the Ortt & Kamp (2022) framework are visualised in the situation for the LIB TIS. Figure 21 at the end of this section will provide a visual representation of the LIB TIS with indicating the status of each BB and IC. In that case, a green, orange or red BB or IC represents a supporting, neutral or hindering factor.

The orange-coloured BB and ICs for the TIS of LIB in EES are not hindering the system but do pose a threat to the system. In the following subsections, each BB and IC is discussed, and the market situation for the orange-coloured BB and ICs is explained, discussing why there is a threat.

LIB are increasingly used for EES. With the findings from exploring the performance of the LIB TIS for EES and the observations in the information sources from various market research companies, the TIS is considered to have just reached the early stabilization phase.

The invention of LIB, as considered in this thesis (LI rechargeable batteries), dates back to 1976 (Boisvert, 2021; Deng, 2015). Although the first mentions of the rechargeable battery date back to 1803, no means existed at that time to prove full working technology (*Electropaedia History of Science, Technology and Inventions. Key Scientists and Engineers and the Context and Explanations of Their Contributions*, n.d.). It lasted until 1983 for the prototype to be developed and demonstrate the technology. A successful prototype followed in 1985, after which, in 1987, a patent was filed for a fully functional LIB known today for its application in many different fields. (Deng, 2015; Yoshino, 2012)

The innovation phase for LIB, from its invention in 1976 to its introduction in 1983, is followed by a short time of technology adaptation. In 1991 and 1992, large multinationals Sony and Toshiba took on the further developed LIB technology by graduates applying it in their products, where LIB replaced older rechargeable battery technology or made rechargeable battery technology possible by improved technological characteristics. This marks the general start of large-scale diffusion for LIB technology.

Based on reviewed historical events preceding LIB technology (*Electropaedia History of Science, Technology and Inventions. Key Scientists and Engineers and the Context and Explanations of Their Contributions*, n.d.; Whittingham, 2012), Table 3 and Figure 19 are created and provided below. These figures put preceding development in perspective to the timeline given for SC technology in Section 4.2.

For LIB technology as deployed for EES, its diffusion parallels that of RES. Also, according to the analysis of factors within the LIB TIS, this technology is deemed to be in its large-scale diffusion and transitioned into the stabilization phase for EES applications. Currently, there are few significant barriers, and the maturity of the LIB technology in other applications has led to a broad understanding of its capabilities, making it more straightforward to deploy. LIB EES technology is expected to evolve in direct relation to the share of RES in the energy mix (T. Chen et al., 2020; Diouf & Pode, 2014), and this share also appears to be stabilizing, based on the interconnection between the two, as outlined in the introduction. Figure 20 represents the share of RES in electricity production and indicates exponential increases over the recent years. This suggests that EES is likely to follow this pattern soon, assuming the continuation of the RES trend as visualized, in line with the previously discussed demand for storage

Event no.	Year	Description
1	1800	First battery: Volta cell discovered
2	1803	Components of rechargable battery described by Ritter
3	1836	Volta cell evolved in first practical battery: Daniel cell
4	1859	First practical rechargable Lead-Acid battery by Planté
5	1866	Leclanche cell, forerunner of modern dry-cells
6	1882	First alkalin battery developed
7	1890	Nickel-cadmium rechargable battery developed
8	1899	First patent to competitive nickel-cadmium rechargable battery
9	1949	Zinc magnese dry cell battery developed
10	1977	Li-ion rechargable battery

Table 3: Events per year preceding LIB technology

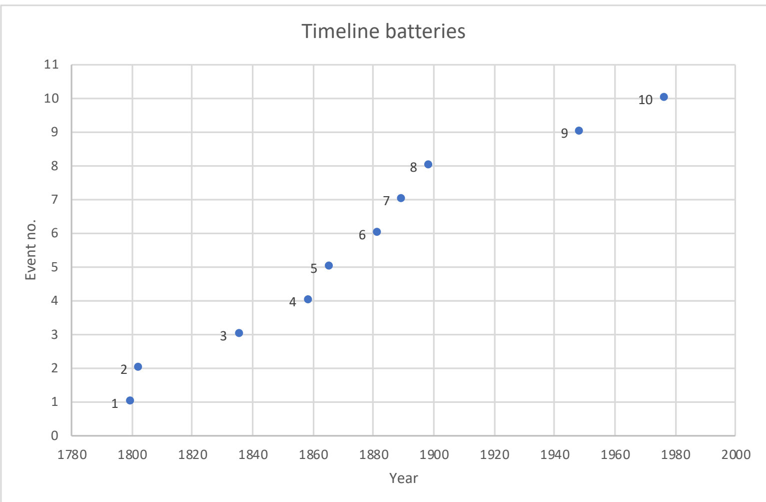

Figure 19: Events per year preceding LIB technology, visualized

SC was the first invention of a device to store electrical energy. The invention proved to have the potential to store electrical energy and will have initiated further research into developing such devices. Capacitors served in experiments on other phenomena in electricity, which supported further development, such as the battery (Volta, 1782). Knowledge spill overs from discovering and experimenting with the capacitor that led to the invention of the chemical battery seem to have contributed to the development of LIB technologies. This can be seen as a positive influence of the SC TIS on the LIB TIS.

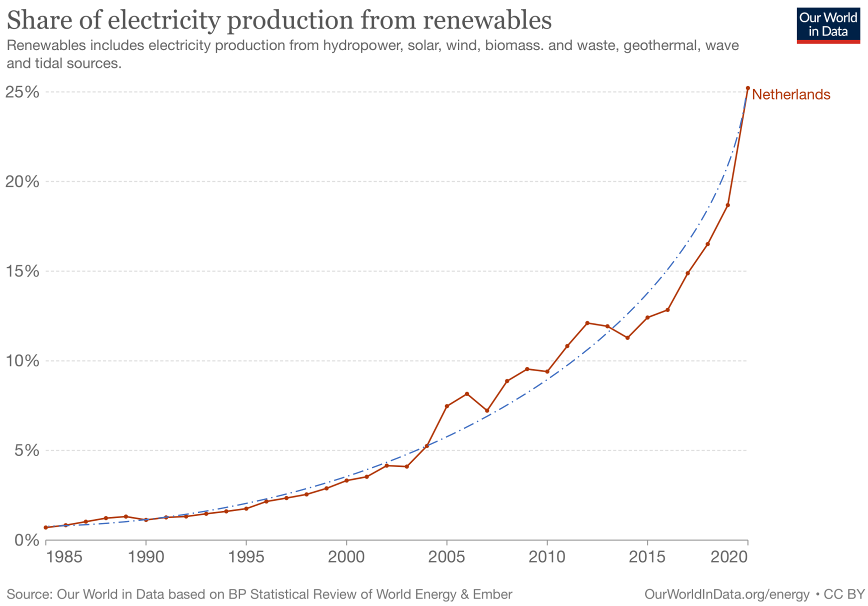

Figure 20: Share of RES in Dutch energy mix with trendline

4.3.1 Product Performance and Quality

The drive to reduce CO2 emissions leads to unprecedented electrification of sectors. Concurrently, the storage of electrical energy via LIB is increasingly popular. LIBs are deployed for other areas, such as grid stabilization and electric vehicles. The LIB EES TIS is (firmly) related to the speed at which we deploy weather-dependent RES (Schill, 2020).

LIB provides EES for longer-term periods with little energy loss per unit of time. LIBs have better energy densities than weights, volumes, and money spent compared to direct competitors (e.g. SC, other chemical batteries or hydro storage). The functionality of the technology is found in buffer EES, peak shaving EES, or grid stabilisation. LIB provides ideal storage of electrical energy and suitable for intermediate levels of power storage. The technology supports flexibility of the grids by offering energy and power reserves. Efficiency-wise, the technology can be regarded as one of the best-performing options. (Espinar & Mayer, 2010)

LIB use a chemical reaction to store energy with. In short, charged electrons move out of the battery when a LIB discharges. The reaction inside the battery is one in which molecules are split up into (partially) positively charged ions. In this reaction, electrons are freed and move out of the battery through an anode. When a typical LIB is charged, this reaction is reversed. Charged electrons move into the battery, and with available ions, they join and form different molecules. Like many other EES technologies, LIB uses equipment to transform AC to DC and vice versa.

4.3.2 Product price

LIB is currently the most mature and opted-for technology for most EES applications. The price-quality ratio is only outperformed by pumped hydropower. When trends continue, LIB technology has the potential to become the cheapest mid- and long-term EES technology. However, power-demanding applications are more costly than technologies like SC and flywheels. (Al Shaqsi et al., 2020)

Furthermore, the cost of the environmental impact should be considered increasingly for technologies like LIB, which are known to pose a challenge when they are removed at the end of life (Fan et al., 2020). When these costs are included in the product prices, the BB can be negatively impacted and hampered (Gutsch & Leker, 2024).

The next factor discusses how a more extensive production system influences price and hampers the SC TIS.

4.3.3 Production system

The Netherlands does not know the production facilities LIB cells (EUROPAGES, n.d.). However, there are some research production lines where several technological advancements are on schedule (van der Heijden, 2021). Most of the initial actors for LIB TIS are those parties who integrate LIB cells into their solutions.

In Europe, more and more production facilities arise. In Europe, there is an incentive to invest more in battery technologies (BATTERY 2030+, n.d.; BNR Webredactie, 2021) which will support the production systems. Most production systems exist in Asia and the United States, but for the coming decade, Europe and the United States expect the most significant increase in production capacities (Campagnol et al., 2022). In 2024, reasonable production initiatives of the actual cells (Murray, 2024) and the raw materials (Palata, 2023) are planned in Europe.

The more significant sales and broader application of LIB have led to a more extensive global production system, which pushes the price and production power. This does not help the SC TIS.

4.3.4 Complementary Products and Services

Components required to set up an EES system with LIB seem widely available in the market. This availability might be because LIB is used in many other sectors and is better known. No hampering events are observed.

More complementary products and services exist and are tailored for LIB due to its larger sales and establishment, which negatively influences the SC TIS. On the contrary, most complementary products are relatively quickly adaptable to SC, making it not too big of an issue.

4.3.5 Suppliers and network of organizations

No signs of a weak current supply chain with LIB production are found. This is reaffirmed by established systems, which currently perform well. However, threats do exist for the near future, where the supply of raw materials might hamper diffusion as demand increases. (Colthorpe, 2021; Sharova et al., 2020)

The LIB supply chain its smooth operation is threatened because of the increasing demand from multiple areas for the technology on one side and geopolitical and availability risks on the other. (Bernhart, 2022)

The establishment and significant sales of LIB technology make it possible to have more supplies and a better-established network of organisations around LIB, negatively influencing the SC TIS.

4.3.6 Customers

Customers for the technology can be pretty widespread, both in the EES applications and in other application fields of LIB (Grand View Research, 2021; Mordor Intelligence, n.d.). Growth for the LIB market in EES is predicted to have a stable growth rate over the coming period, ensuring the performance of this factor (Grand View Research, 2021).

4.3.7 Institutional Aspects

There is an increasing set (and demand) of standards for LIB for EES, and none are set yet. Most of the rules and standards come from general electrical applications. The governmental plans in the Netherlands are positive for LIB, which are in line with energy transition plans. From the European initiative, there is the investment program (BATTERY 2030+, n.d.) which supports these systems and others.

4.3.8 Knowledge of technology.

The knowledge of LIB is complete to support the system's performance, also through the widespread use in other markets. This is based on the competitive landscape, in which manufacturers are fragmented and the landscape is not dominated (Grand View Research, 2021; Mordor Intelligence, n.d.). Advancements in LIB technology in other sectors, such as electronic devices and electric vehicles, make the technology widely familiar and understood.

4.3.9 Natural, human, and financial resources

The availability of raw materials and the methods of production or mined pose challenges to the performance of the LIB TIS. The COVID situation has, in recent years, resulted in problems with supplies to Western markets from Asia. This did expose the risks and vulnerability of the supply chain of, among others, LIB (Cary Springfield, 2021). In more extended periods, some experts forecast deficits influencing the technology, even after the end of COVID. Cobalt is currently still one of the critical ingredients in LIB. Although fewer amounts are needed for LIB, an increasing total market volume increases cobalt demand. Also, the labour required with conventional methods of mining has been disputed over the past few years. However, the local governments of the countries where cobalt comes from work to improve conditions. Another complicated topic on cobalt is that it is produced as a by-product. This currently makes investing directly in cobalt difficult. Human and financial resources appear to be the only barrier to the system. (Campagnol et al., 2022; Desai & Nguyen, 2021; Fan et al., 2020)

4.3.10 Knowledge and awareness of the application and market

There is sufficient knowledge on applying LIB in different fields, among which the field of EES is evident, as existing projects through the Netherlands prove (Energy Storage NL, n.d.). Advancements in LIB technology in other sectors, such as electronic devices and electric vehicles, make the technology widely familiar and known.

4.3.11 Competition

The initial applications of LIB made the technology quickly ready for application in EES. Besides countries where hydropower is present and easy to deploy, LIB takes the lead regarding EES. This technology has no serious competition in its market-leading role (Al Shaqsi et al., 2020; Coppez & Chowdhury, 2010).

Logical competition in the past, due to a better fit of LIB, resulted in more emphasis on (chemical) LIB compared to SC. Since the technological fit of LIB has been much better and broader over the last years, LIB have found more applications and a higher degree of development. This is due to existing complementary technologies and knowledge enabling LIB to have highly suitable characteristics for various applications.

4.3.12 Sociocultural aspects

There are remarks on the sociocultural aspects of LIB. In general, LIB have minor limitations regarding its use for EES. Some guidelines are published to advance planned directives for more extensive EES solutions based on LIB (*Lithium-Ion Accu's: Opslag En Buurtbatterijen*, n.d.).

A social issue is the use of cobalt, for which human laws are sometimes violated in retrieving it. An effort is being put into improving the situation and administering situations in and around the cobalt mines. The macroeconomic aspects favour LIB, and threats could not be identified.

4.3.13 Macroeconomic and Strategic Aspects

Similar to the analysis for the factors of the SC TIS, no serious economic problems or challenges exist for LIB at the time of writing. The challenge might be the threat of inflation and increases in the price of raw materials. The demand for RES (and, with that, the supporting LIB systems) is expected to increase in the coming decades. The worldwide efforts to transition to cleaner energies make the environment for application in different fields of technologies like LIB currently very friendly.

4.3.14 Accidents or Events

LIBs are known to be sensible for minor defects or changes in conditions. Extreme pressure differences, temperature changes, or charge/discharge currents/voltages can severely threat and potentially damage an EES system with LIB. Although safety systems are widely available and fit LIB systems well, the resulting problems and effects can be extremely severe and difficult to control when a failure occurs. Examples are uncontrollable temperatures, which result in fires accompanied by toxic gas development and pollution. This is positively influencing the SC TIS. SC technology is known for its safe and clean operation (when correctly applied).

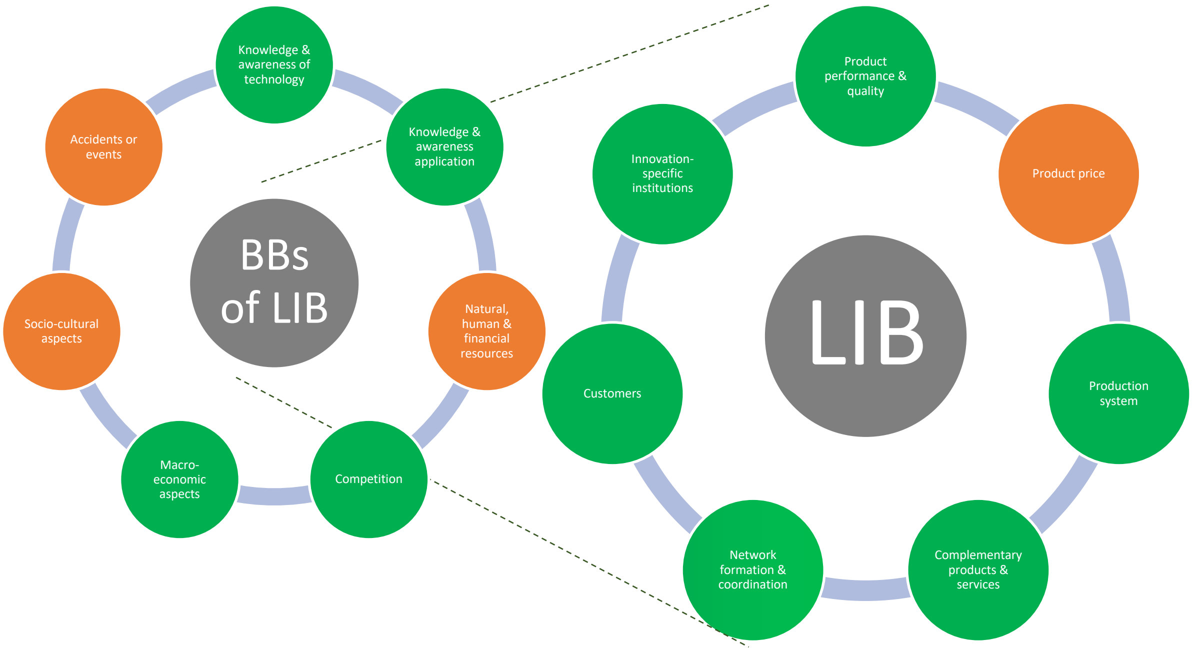

Figure 21: Visualisation of TIS of LIB according to model of Ortt & Kamp (2022)

4.4 Drivers and barriers in EES for the technologies SC and LIB

This section elaborates on the drivers and barriers for LIB and SC, also based on preceding findings. First, drivers for LIB are discussed, followed by its barriers. Next, drivers for SC are discussed. The section concludes with the barriers for SC.

4.4.1 Drivers for LIB

The increasing use of LIB for EES in the power grid can be attributed to several driving factors. The most prominent these is the serious increase in production with and consumption of RES. Possibly coming from the climate change event (IC), this creates a favourable context for LIB. In this context, the macro-economic aspects (IC), together with the knowledge and awareness of both the technology and its application (2 ICs) result in a good performance of the TIS, expressed in sufficient customers (BB). More applications drive economies of scale, influencing both the production system (BB) and product price (BB). The intermittent nature of wind and solar energy is discussed at the beginning of this thesis, together with the increasing need for EES related to those natures. LIB offer a solution for bridging this gap between supply and demand.

Furthermore, advancements in battery technology and manufacturing processes (IC of knowledge of the technology) have significantly reduced the cost of lithium-ion batteries (product price BB). This has made them an economically viable option for large-scale energy storage. The gradual maturation of the electric vehicle market has also played a key role in this respect, as it has spurred investments in battery production and research, leading to economies of scale and further cost reductions (Fleischmann et al., 2023). This also highlights influence of two different TISs where LIB is applied in.

4.4.2 Barriers for LIB

Alongside the aforementioned driving factors, there are considerable barriers to the use of LIB for EES. One of these is the issue of battery degradation. LIB do have a long cycle life, yet their performance inevitably deteriorates with repeated charging and discharging. This occurs faster compared to some other technologies. This limits their operational life, making them less suitable for applications that require long-term, reliable EES (Al Shaqsi et al., 2020).

Also, the use of LIB at grid scale brings safety concerns with it. While rare, LIB can, under certain circumstances, catch fire or explode. This presents a significant risk, particularly when dealing with large-scale battery installations. Events (IC) with LIB in other applications such as electric vehicles expose these risks, like the recent spontaneous fire of an electric car at a parking lot (Leesberg, 2023) and the alleged cause of a fire aboard onboard a ship being a LIB powered electric vehicle (Krishanta, 2023).

Finally, the supply of raw materials needed to manufacture lithium-ion batteries, such as lithium, cobalt, and nickel, is a significant barrier. These resources are finite and concentrated in a few countries, creating potential supply chain vulnerabilities. The extraction and processing of these materials also pose environmental challenges, raising questions about the sustainability of large-scale lithium-ion battery deployment. A larger business actor (the company Bosch) within the network are already indicating the presence of this barrier (Kit, 2023).

These challenges have an effect on the ICs of natural resources, socio-cultural aspects, and accidents and events. The aforementioned accidents and events pose a threat to the quality and performance of the technology, but are relative to the amount of applications manageable. Natural resources and socio-cultural aspects of mining raw materials of LIB, together with increasing demands, drive the price of the technology.

4.4.3 Drivers for SC

SC also have the driving factor of the increase in supply of and demand for RES, similar as mentioned in subsection 4.4.1 for LIB and its ICs. SC propose an exciting potential for EES in the power grid, pushing a set of unique characteristics and attributes. This can be accounted to the knowledge of the technology (IC). Among the primary drivers for their use is the remarkably high-power density they offer, which surpasses that of other EES, allowing for very rapid charge and discharge times. This makes SC particularly suited to applications requiring a quick release of energy, such as for smoothing power supply or compensating for short-term fluctuations in renewable energy generation.

In addition to their high-power density, SC have an exceptionally long lifespan, capable of enduring millions of charge and discharge cycles without significant degradation. This offers a high degree of reliability and reduces maintenance requirements over the lifetime of the energy storage system. This adds to the ICs of knowledge of the technology and its applications. Furthermore, unlike traditional batteries, super capacitors can operate effectively across a wide range of temperatures and conditions, which increases their security, reliability, versatility and adaptability to different environments and applications.

4.4.4 Barriers for SC

The adoption of super capacitors in the power grid also faces several barriers. The energy density of super capacitors is considerably lower than that of conventional batteries such as lithium-ion. This means that while they can deliver or absorb energy very quickly, they cannot hold as much energy per unit volume, making them less suited for long-duration storage applications. Additionally, the public is not as aware of the technology of SC and its application (ICs) as is the case with for example LIB. Therefore, it is making competition (IC) with other EES options harsher, resulting in less customers (BB). Also, knowledge (IC) of how to increase the technology's energy density is developing.

SC as an emerging technology in the field of EES also face barriers related to system integration and standardization. Grid operators and planners may be unfamiliar with how to optimally integrate SC into existing infrastructure. (Al Shaqsi et al., 2020)

The high initial cost of super capacitors (price BB) presents a significant challenge. Although they can be cost-effective over their lifetime due to their durability and low maintenance requirements, the upfront investment required is generally higher than for other energy storage technologies. This has limited their deployment particularly in the developing parts of the world where capital investment can be a constraint. Knowledge (ICs) should develop further to make SC competitive, by enabling larger productions systems (BB) to foster economies of scale and to reduce product price (BB), resulting in more customers (BB).

5 Application of standardised framework TIS interaction

This chapter answers sub-question 3

In the previous two chapters, both the explanation of a framework for reviewing TIS interactions and the analysis of two related TISs are presented and discussed. In this chapter, the interaction between the SC and LIB technologies are first discussed supported by two cases, after which a subsequent section addresses the interactions between the TISs according to the framework as formulated in chapter 3. The first section elaborates on these two cases. Their description supports the further application of the conceptualized framework on their TIS interactions in multiple ways.

Describing and analysing these cases of interaction between LIB and SC, or their preceding technologies, helps to develop insights and understandings of their dynamics and interactions. This is relevant before analysing and describing the interactions of their TISs with use of the conceptualized framework. Historical information helps to identify and study possible trends and patterns, which might be relevant to the current state of the technology today. Anticipating on the analysis with the conceptualized framework, two things are relevant. First, the historical context in describing the cases helps to link the theoretical conceptualized framework with the real world scenarios, indicating the applicability and relevance of that framework. Second, these cases help to identify specific real-world factors, important to the interactions between LIB and SC or their preceding technologies. Such findings support the further application of the theoretical conceptualized framework. Finally, the formation of the current TISs of LIB and SC did not happen in isolation, but interacted with other technologies and their systems, and with mechanisms of markets and developments. Before applying the conceptualized framework, discussing the historical cases offers a baseline with which the results of the application of the framework can be compared.

The theoretical approach in chapter 3 considered nine modes of unidirectional interaction from one more mature TIS to a younger niche TIS. In this chapter, the application of the framework on the cases of the mature TIS of LIB and the adapting TIS of SC lets go of the unidirectional approach. The second section of this chapter will, per interaction mode, discuss the bidirectional interaction if applicable.

Before continuing this chapter, Figure 22 provides a visual overview of the conceptualized TIS interaction framework, with the BBs and ICs for the TISs of SC and LIB shown. The interaction framework is indicating the status of each BB and IC. A green, orange or red BB or IC represents a supporting, neutral or hindering factor.

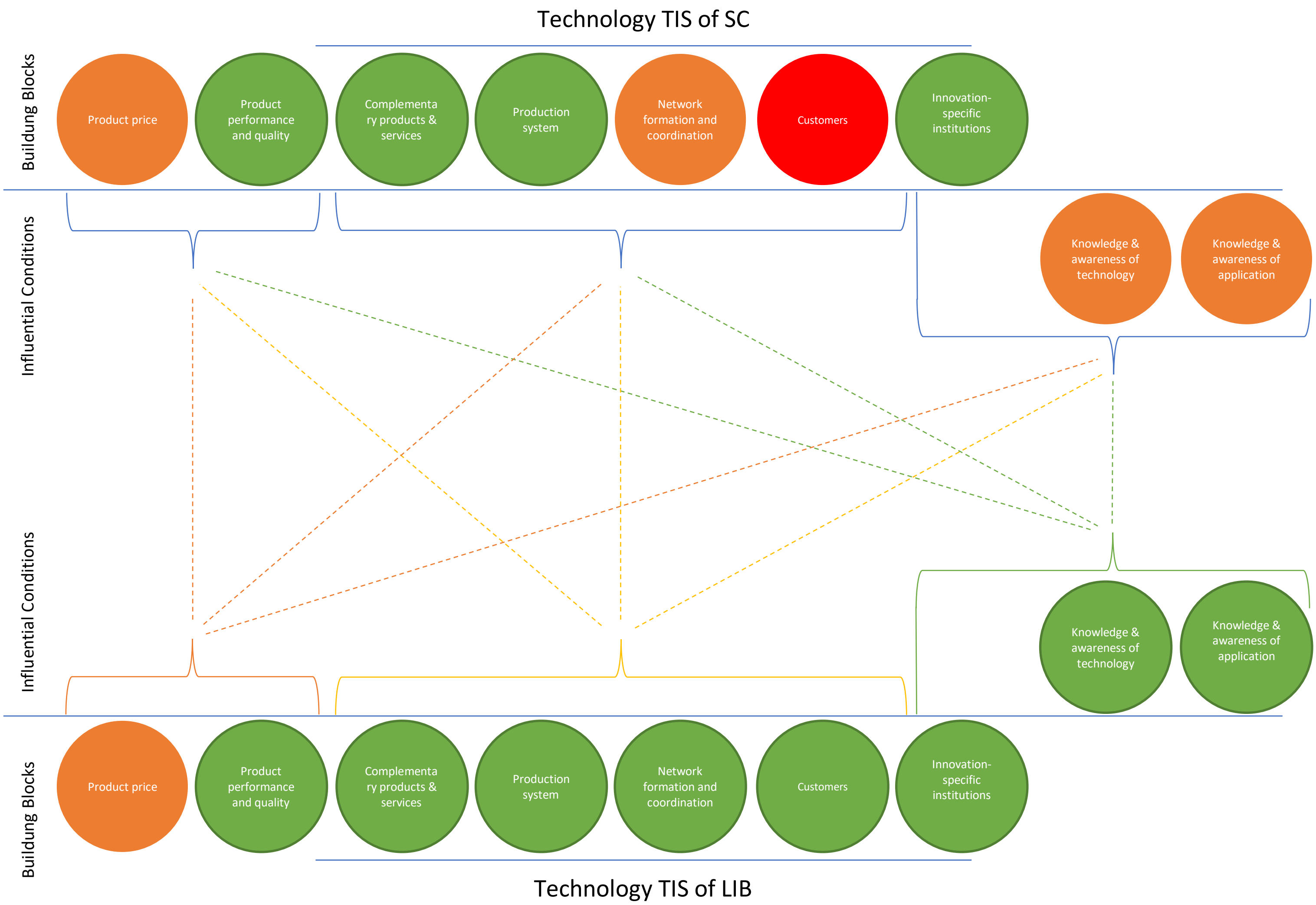

Figure 22: Visualization of interactions between the categories of technology-specific BBs and ICs of two TISs, with status per BB/IC.

5.1 General findings interaction LIB and SC

This section addresses the general findings of the interaction of LIB and SC in two cases. These cases were discovered through the initial analysis of the both TISs of SC and LIB. The first case discusses the historical case of Morse devices. The historical case does not directly involve LIB and SC, but their predecessors. The interesting dynamics in the Morse case and the highly probable relevance of the predecessors to the invention of both LIB and SC, led to the decision to include it in this case description. The second case discusses the current stance challenges in the LIB TIS, and how these affect the SC TIS. The first case discussed in subsection 5.1.1 is likely caused by the dynamics of the core characteristics of both technologies (product attributes) and the application's wants and needs. The second case discussed in subsection 5.1.2 presents itself in a more contextual pressure of foreseen and unforeseen risks and challenges of a technology, motivating both TISs to undertake actions, as will be discussed further on.

5.1.1 Morse Case

Figure 16 and Figure 19 display the timelines of the SC and LIB development events relatively. In the 1840s, the first large-scale application for general preceding battery technology was found in Morse telegraph systems. The change in complementary products and services for the 'Morse code device' TIS greatly impacted its development (*Electropaedia History of Science, Technology and Inventions. Key Scientists and Engineers and the Context and Explanations of Their Contributions*, n.d.; History.com Editors, 2009). Capacitor technology preceding SC technology first saw its successful large-scale production in 1936 for application in radios (Ho et al., 2010).

The first large-scale application of battery technology in Morse code devices, was caused by the demand for different characteristics for energy storage in the systems. With capacitors as the incumbent technology back then, it was challenging for batteries to compete. However, after proof of their functionality, it became velar that the requirements for Morse devices suited batteries more naturally than it did capacitors. These early developments indirectly influence today's TISs of SC and LIB.

As previously described, the development of Morse code was a positive impulse for the battery TIS at the time and vice versa. Figure 23 gives a visualisation of such a cycle.

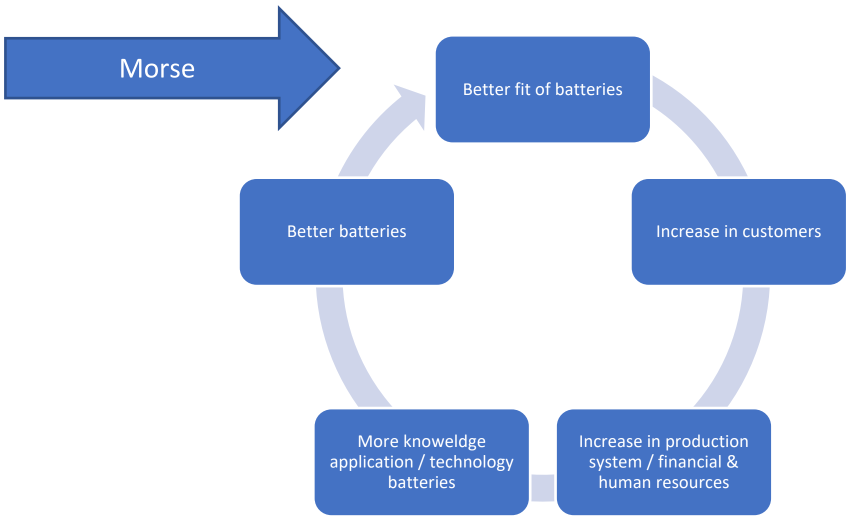

Figure 23: Example of reaction within battery TIS after Morse opportunity.

Changes in the performance affecting by one of the TISs also impact the other TIS. Where in the Morse case batteries outperformed capacitors, the reverse is also thinkable nowadays in an example of peak-power applications, where SC can be superior to LIB technology (Ho et al., 2010; Miller, 2007). In such cases, the technological fit of one TIS wins over the other TIS.

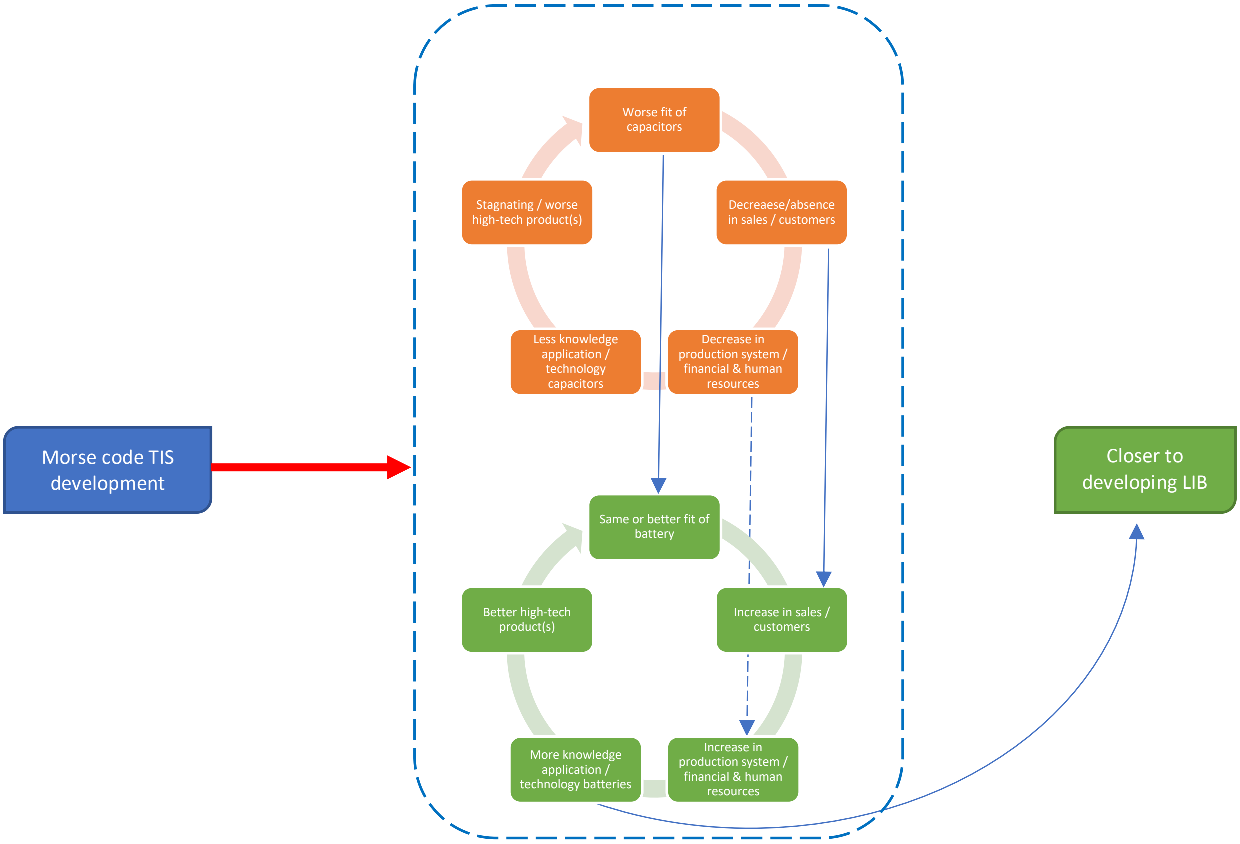

Figure 24: Event in Morse TIS causing favorable conditions for normal batteries compared to SC TIS. Contributing to development LIB TIS.

Figure 24 displays a schematically representation of the influence of the Morse TIS on the TISs of capacitors and batteries in the past.

Here, an external TIS relevant to the performance of the focal TISs made a particular step or experienced a specific event, influencing the performances of both focal TISs. In the case of Morse, the demand for the technology rose. This was partially enabled by energy storage through batteries, which raised demand and interest for this technology. The increased interest in battery technology partially shadowed the capacitor technology.

As displayed and discussed above, the influence can be best described as one coming from a TIS up or downstream in a supply chain. It is competition between batteries and capacitors for energy storage in the Morse TIS.

Conceptually, it could have been the case that a technological breakthrough for capacitors occurred right before or during the accelerating diffusion of Morse technology. In such a case, changing and improving technical specifications could have made capacitor technology the optimal solution. In the current field of EES for RES, the technological superiority of LIB over SC still exists. However, the balance is shifting as the LIB and SC TIS develop.

5.1.2 LIB footprint and risks case

Events caused by actions within a focal TIS can also influence other TISs. It can be the case with technologies in similar applications that one technology experiences an event which creates a negative image for that technology. LIB applications have experienced events in which the image of the technology's safety was impacted.

The result of such events is that some applications start exploring alternative technologies like SC for it. This causes, on a short cycle, a situation as displayed in Figure 25. Here, another TIS like that of SC benefits from the weakening TIS of LIB, and a window of opportunity is created or becomes more likely. A longer cycle is exemplified in Figure 25 and can be described as one where the LIB TIS regenerates, learns from adverse events, and improves the technology. Alternatively, there might not be any improvements possible, which could lead to a strongly diminishing TIS. The LIB accident visualized Figure 25, can be substituted with negative interactions between any TIS and its context. Specifically, for LIB, this is for example the case with the questionable conditions at the cobalt mining.

Conceptually, it could have been the case that policymakers, societies or academics deemed batteries poisonous or dangerous, and therefore strongly undesirable. Such an event could lead to negative (innovation-specific) institutions for the LIB TIS, which potentially benefit the SC TIS and would have hampered or blocked further development of the LIB TIS.

Between the LIB and SC TISs, complementation also exists as a hybridization of the two technologies. Researchers are actively researching how to combine the advantages of both technologies and preferably eliminate the disadvantages. A review of the developments and progress in such developments exists. It concludes that the challenges for developing such hybrid products are understood, but the knowledge and, in addition to that, the technology on how to tackle such challenges still lacks. (Ding et al., 2018)

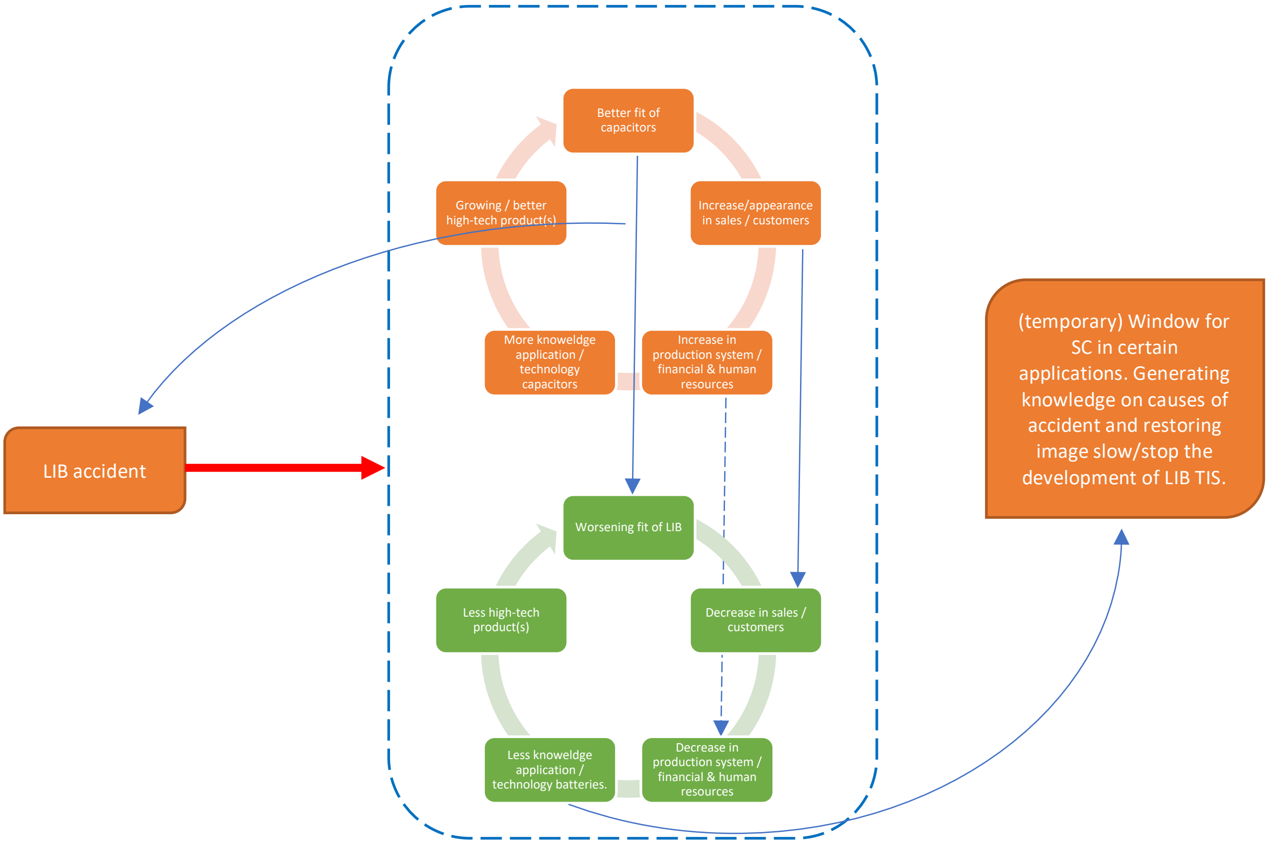

Figure 25: Event in LIB TIS causing favorable conditions for SC TIS.

5.1.3 Concluding both cases

The earlier problem in the telegraph/Morse TIS formed an opening for general battery technology in the 1840s. The telegraph TIS influenced the general battery TIS, which later impacted the learning and application of battery technologies. This potentially contributed to the earlier development of the LIB TIS, and may have drawn more attention, effort, and input to the whole battery technology and related technologies relative to the capacitor technology. The latter can have contributed to the current quality, performance and prices of both technologies.

With LIB occupying more applications and being a more dominant part of systems, a more developed LIB TIS exerts an influence on the SC TIS, constraining the exploration of knowledge of the application for SC. Applying SC technology in existing applications, such as port cranes, is very interesting. However, due to existing and widespread usage of LIB not yet occurring, excluding the demonstration projects (Linsen, 2019; Skeleton Technologies GmbH, 2018). The technical characteristics of the focal technologies in each TIS are different, making one technology a better fit for an application than another. LIB can store energy for a more extended period, while SC can release more power with a longer lifetime and less temperature sensitivity (FutureBridge, n.d.; KEMET, 2019).

The LIB TIS for EES knows earlier adaptations and already experiences an almost complete and supportive TIS enabling large-scale diffusion. Knowledge of SC applications may have lagged due to an earlier start and higher adoption of LIB TIS, and it can be seen that SC market leaders' applications focus on existing applications to replace LIB (C2C New Cap, n.d.-a; NAWATECHNOLOGIES, n.d.; Skeleton Technologies GmbH, 2018). In that focus, SC-related actors seem to focus on the differences between technologies, amplifying the advantages of SC over LIB EES.

A logical sort of lock-in exists, making LIB the more exciting option. This creates a context for SC TIS in which the development of the TIS becomes more challenging (Bergek et al., 2015). The TIS of LIB is expected to have evolved and developed more because of (i) the relative ease of creating better energy storage with the working principles of LIB batteries, (ii) the more intense steps in developments for batteries when compared with SC technology, (iii) the higher degree of attention, effort, and input for (the roots of) the LIB TIS, and (iv) generally more interesting technological characteristics. Differences in technological characteristics opposed to SC technology were naturally crucial in the development path of LIB. With better and new techniques arising, SC is gaining on LIB technologies.

In an economic context, another form of lock-in might be considered due to the maturity of TISs. Well-developed TISs, such as that of LIB, typically know wider applications and, consequently, have access to greater financial resources. This increased capital availability facilitates more extensive and rapid research and development activities compared to those possible within a less developed TIS like SC's, assuming equal financial incentives or constraints apply to both technologies.

In terms of financial incentives or constraints, it is possible that a less mature TIS could receive more subsidies due to its relatively limited capacity for self-sufficiency and competition against more established technologies. Besides these financial aspects, another factor to consider is the available capital for niche technologies, specifically in terms of profit margins. An emerging technology such as SC, utilized in specific applications, might enjoy a mono- or oligopolistic status due to fewer companies producing the technology and more active patents. This scenario allows SC to establish higher price points, potentially yielding above-normal profits.

On the other hand, a technology that is larger, more widely applied, and more diffused, like LIB, faces a broader market with more producers which typically equates to normal profits and heightened competition. In contrast, SC, as a nascent and smaller technology, may be able to generate relatively higher profits. These additional profits provide SC with greater flexibility to invest a larger proportion of capital into research and development or other activities conducive to growth, thereby enhancing its resilience and competitive stance over time.

Problems that arise from factors such as accidents or events and the availability of natural resources (Y. Chen et al., 2021; Desai & Nguyen, 2021) change factors in the LIB TIS from supportive to less supportive, leading to problems. This influences the TISs of other similar or 'neighbouring' technologies that do not share similar problems but were initially less attractive to apply. Such dynamics can lead to, for example, hybrid solutions with the same advantages of LIB but strongly reducing or even excluding the problems (Al Shaqsi et al., 2020; C2C New Cap, n.d.-b).

The last paragraph in previous section 5.1.2 raises some interest since this is a complementation via hybridization of two TISs which used to compete before. This links to the hybridization strategy for niche technologies described by Ortt et al. (2013). It might be interesting to review the competition or complementation of technologies, whether or not it is complementation from the old (replaced) technology or a new non-related technology. Also, it is interesting to review whether or not the complementing technology fulfils a similar function in the process as the focal technology.

5.2 Application of theoretical framework TIS interaction

This section systematically addresses and indicates each interaction mode as formulated in section 3.3. The indication per mode is based on descriptions from the previous section, and the findings in chapter 4. It does so by reviewing both the SC and LIB analysis and considering the influence mode as an influence from LIB to SC and from SC to LIB.

5.2.1 Product Attributes to Product Attributes

One of the in the previous section described interactions between the SC and LIB TIS and their preceding technologies, is that the mature LIB TIS benefits from earlier developments, and with that has set standards in expectations and prices for EES applications earlier on. This leads to the business actors within the SC TIS to consider their own prices with the prices of LIB in mind, when the did enter or are entering markets with new solutions. Such interaction can be seen as Product Price BB of LIB influencing Product Price BB of SC. No support of such considerations was found for the case of LIB and SC, but this is a likely part in the process of determining pricing in any technology.

When it concerns the obvious and straightforward considerations, these could be direct interactions from the LIB product attributes on the SC price BB. The price can for example be lowered until normal profit conditions and minimal earnings requirements are reached. No direct alteration in the price of either technology was observed. It is observed how prices of LIB interact with business actors in the SC TIS to argue for their product attributes and defend their prices when compared to LIB (KEMET, 2019; NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018). It is likely that in competition with LIB, business actors of SC could change their price. It is more possible that they engage in informing and educating the customer on both their technology and the LIB technology its up- and downsides (Linsen, 2019). Such discussions as described also influence different aspects than just the product attributes.

5.2.2 Product Attributes to Market and Value Chain

As discussed in the above for prices, customers of LIB also interact with business actors in the SC TIS to argue for their product attributes and defend their product attributes when compared to LIB (KEMET, 2019; Linsen, 2019; NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018). The product price in combination with its performance and quality (TIS of SC) directly interacts and influences with customer segments within the TIS of LIB, able to become customers of SC. Such interaction is likely to also exist in reverse order, but was not observed. The SC TIS also exerts an influence in specific applications of LIB and the formed networks in those collaborations. Examples are as the case of substitutions of LIB with SC in port crane power systems and several short term power applications in the grid (Linsen, 2018; Skeleton Technologies GmbH, 2018). When replacing specific applications, the SC TIS also interacts with the complementary products in such applications previously complementary to LIB. It was not observed, but it is likely that in these instances actors that provide such complementary products or services are being influenced. Initially they will also have been complementary to the LIB, and after application of SC also consider to become complementary to SC.

The reverse interaction from the TIS of LIB on that of SC is possible, but probably less likely. With LIB being the more developed, diffused, and therefore more applied technology, there are more applications in which SC can substitute LIB than in reverse. In scenarios where SC have replaced numerous applications traditionally dominated by LIB, and should LIB experience a significant advancement in its development, it is thinkable that LIB could then emerge as the underdog yet superior option to SC. In such instance similar interaction as currently from SC on LIB is then more likely in reverse.

Product attributes influence markets and value chains of LIB and SC in both directions. A perfect example for the LIB TIS its market and value chain being influenced is made with the raw materials required for SC. These raw materials are very clean and safe, which is positive for the product quality of SC. This is not the case for LIB and influences their customer, the production partners, and the providers of complementary products and services. Customers and such actors within the SC and LIB TIS are influenced by product characteristics of the opposite TIS will adapt their decision making by considering clean SC with or more harmful LIB both with their specific characteristics (Luo et al., 2015; Rahman et al., 2020). Production partners are influenced in both ways by such product characteristics and will try to organize collaboration to create knowledge on how to create among others cleaner and safer LIB. Providers of complementary products and services on own initiative or at request attempt to organize and mitigate such downsides of the technology, by for example offering recycle plants that deal with end-of-life challenges for LIB (Gutsch & Leker, 2024).

Another example from the aforementioned Morse case, and the preceding technologies of LIB and SC, is how qualities of the battery lured customers away from the capacitor market. Here, the product attributes of the battery directly impacted the market and value chain of the capacitors.

Finally, a related technology characteristic of assembling SC influenced the value chain of the company Tesla. An SC company was acquired partially due to its ability to produce SC with unique technical advantages from which the directly the knowledge and production system for LIB of Tesla could benefit from (Alvarez, 2019).

5.2.3 Product Attributes to External Environment

Product attributes of both SC and LIB interact with the external environment category. The case studies prove that for example SC business actors actively search for applications where LIB is deployed for its attributes, and analyse if SC is a more viable option to apply, adding to the knowledge and awareness of its applications (NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018).

What is interesting is the fact that both technologies perform research to create knowledge enabling the harnessing of the positive attributes of the opposite technology. And it tends to be, that both technologies move towards developing a new kind of SC innovation that literally implement lithium-ions to harness the strengths of both technologies (Ma et al., 2015; Sun et al., 2020; *SuperBattery | Skeleton*, n.d.).

The above example shows how the influence of for example the LIB its strong characteristics, can motivate creation of knowledge about the SC technology, potentially leading to new production methods and networks and improving its own product attributes. The same can be said for the opposite direction from SC influencing LIB via this route.

Competitive pressure on the LIB TIS regarding its footprint and end of life challenges from, among others, the SC TIS its product attributes, may lead to knowledge creation within the LIB TIS on how to deal with this (Gutsch & Leker, 2024). LIB probably also experience innovation-specific regulation regarding the end of life challenges from within its TIS or from its context, but these influences are out of this thesis' scope.

5.2.4 Market and Value Chain to Market and Value Chain

This interaction has a several obvious interactions. One is the interaction, where customers move between the TISs of LIB and SC. This can be through direct engagement with the customers of the opposite TIS, of which no proof is found. Alternatively, this can be by first being influenced by existing or changed product attributes of the opposite TIS, after which the customer moves to that particular TIS. In such caste, there is interaction from the opposite TIS' product attributes on the customer in the focal TIS, after which that customer moves to the opposite TIS. In such case, the only interaction is the move of the customer from the one TIS to the other. Such switching of customers has been achieved with for example engine-related systems, where customers moved from LIB to SC (C2C New Cap, n.d.-b; Skeleton Technologies GmbH, 2018). For example, customers of LIB for the particular system of uninterrupted power supplies, may decide to move to SC technology when convinced of a better price-performance ratio and with the right context. This indicates it is required for that customer to first interact with the opposite technology its attributes or external environment (or both) before moving.

Suppliers of complementary products and services within the LIB TIS also learnt to interact with networks of the SC TIS, such as the customers and production actors. The latter two actors seek for complementary products such as transformation or safety gear. Such gear can be similar to the gear used with LIB, and therefore at first hand easy to attain at the suppliers of the LIB TIS. Over time and with interaction between the aforementioned parties, the suppliers of complementary products and services also embed into the SC TIS. This interaction with suppliers of complementary products and services was also addressed in the first paragraph of subsection 5.2.2.

Another example of interaction in this category, but also in the category of both market and value chain, and external environment to external environment from the LIB TIS with the SC TIS, is the event of the company Tesla acquiring a leading SC company (Alvarez, 2019). This acquisition was made to embed the technology for producing dry cells into the production systems of Tesla's LIB. Tesla is also active in EES solutions, but it is not clear if this technology had impact on those solutions. After acquiring the required knowledge and systems, the SC company was sold again (Schmidt, 2021).

The above example realms in the other interaction modes too. The SC production system is acquired by a LIB producer and therefore directly interacts with the value chain of the LIB producer. However, it was essentially about the acquired knowledge which could lead to transformation of the LIB TIS.

5.2.5 Market and Value Chain to Product Attributes

The most likely interaction here is the customers of the LIB TIS, that are also potential customers to the SC TIS, influencing the product attributes such as price and other relevant specifics of the SC TIS. For any technology's product attributes that compete for existing customers in either opposite TIS, product attributes are influenced by the expectations and willingness of those existing customers. This dynamic is also described in the cases in subsections 5.1.1 and 5.1.2. The business actors in the SC TIS understand this interaction and attract the customers in the incumbent LIB TIS by providing them with relevant information through explanations on performance, quality and price characteristics for their specific application as discussed in subsection 5.2.2.

The reversed order is also possible, but less likely and not as pressing as for the described order. The LIB TIS is more mature and therefore established when it comes to pricing and its characteristics. With the SC TIS adapting, there is a larger influence from the customers within the LIB TIS that are also potential customers to the SC TIS when reviewing the product attributes.

5.2.6 Market and Value Chain to External Environment

The complementary products and existing value chain of LIB has inspired actors within the SC TIS and supported the increase in their knowledge of the technology's applications. This is the result of analysis of the customers' applications of LIB and reviewing those that are also interesting for SC. These potential applications are documented and shared as knowledge within relevant actors in the SC TIS (C2C New Cap, n.d.-b; NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018). This logical process for business actors is likely also present with the earlier cases in subsections 5.1.1 and 5.1.2.

There is also a slight interaction here with the case described in the final 2 paragraphs of subsection 5.2.4, of Tesla acquiring the SC company Maxwell, where (the knowledge of) the production systems is absorbed in the knowledge of the LIB technology, and that knowledge is developed.

5.2.7 External Environment to External Environment

The example of Tesla buying an SC company in the final 2 paragraphs of subsection 5.2.4 demonstrates that interaction between LIB and SC also exists when considering the focal interaction mode of this subsection. As discussed in that example, when reviewing the actual transaction, it is basically the knowledge of the SC production technique being acquired by a LIB business actor. Knowledge of the technology of SC impacted the knowledge of LIB in that case, when reviewing the motivation for the acquisition (Alvarez, 2019; Schmidt, 2021). For the cases of SC and LIB the preceding and prevailing knowledge of the applications of LIB has interacted with the knowledge of the applications of SC by giving a set of applications already in which LIB functions (NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018). This gives a suitable reference for actors in the SC TIS to test those applications and see if SC forms a suitable alternative to LIB in an application.

5.2.8 External Environment to Product Attributes

The business actors within SC possess and explain the product characteristics partially based on the knowledge and the product-specific institutions of LIB (NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018). Specific institutions like subsidies and support measures often apply to both LIB and SC. If not, they have to adapt their attributes such as pricing or explanation of the advantages compared to the investments required, to keep strategically aligned with each other.

LIB has more risk for accidents (leading to hampering institutional aspects) and the knowledge of LIB highlights the interim inescapable need of harmful and dubiously sourced raw materials (Y. Chen et al., 2021; Deng, 2015; Fan et al., 2020). These aspects are exploited by business actors in the SC TIS explaining the better product quality and performance regarding these aspects, and justifying the probable price difference. Additionally, awareness of the weaknesses of LIB, where SC excel, resulted in SC business actors to promote their product attributes for applications that highlight these strengths (C2C New Cap, n.d.-a; NAWA Technologies, 2019; Skeleton Technologies GmbH, 2018).

5.2.9 External Environment to Market and Value Chain

Knowledge of the application of a technology, such as that of LIB, can more directly interact with the customers and actors in the market of SC to assist them create useful new combinations of their technology. Ready knowledge of application of LIB saves actors in the SC TIS the step of studying the opposite TIS, and instead use the existing knowledge. Such existing knowledge can also include the broader EES market as discussed in the literature review chapter 2 of this thesis. Both TISs can and do probably apply knowledge from the opposite TIS to their market and value chain, as also discussed in subsection 5.2.4. As with the interaction mode discussed in previous subsection, there is interaction between the LIB's external environment and the market and value chain of SC. Technology specific institutions and knowledge of the technology of LIB reaffirm customers and formed networks within the SC TIS to keep focus on their strengths and weaknesses.

5.2.10 Discussion on the described interactions for LIB and SC

In short, it is believed that there is bidirectional interaction between the TISs of LIB and SC because of the following reasons:

- In certain applications, performance of either LIB or SC fits the customer better
- Risks and accidents of LIB
- Socio-cultural challenges of LIB
- Resource challenges of LIB
- Price and product positioning of SC

For these two technologies I believe the most important interactions are addressed in this section. In both TISs, business actors compete based on price, performance and quality. Applications are searched and selected based on the best fit, and for these applications business actors of especially the SC TIS advocate for their technology's advantages over the characteristics of LIB. Risks, accidents, and challenges with resources and socio-cultural aspects that impact the LIB TIS are leading to new characteristics and insights for LIB, which directly impacts the TIS of SC in various ways and through various aspects. It encourages actors in the SC TIS to promote the strengths of SC where LIB has weaknesses. These interaction links are slightly thickened in Figure 26.

The impact of the developments of batteries (preceding LIB) in the Morse case, was a sudden development of the battery TIS, and a serious stabilization or decrease in the development of the capacitor TIS, preceding SC. Unforeseen accidents and developing issues with sourcing of raw materials are barriers in development to the LIB TIS, and create opportunity for alternative technologies like SC.

The impact of today's risks and challenges with LIB are favourable to the TIS of SC, which happens to be a cleaner product regarding its materials and production. Additionally, it motivates the development of 'hybrid' SCs (so-called Super Batteries by one actor), with advantages of LIB and SC combined. The risks and challenges with LIB logically hamper the development of its TIS. Apart from increasingly stringent regulation, it takes time to create knowledge of the technology on how to deal with or prevent these issues. For those reasons, knowledge factors in the external environment category of the more developed LIB TIS slightly interacts with both the market and value chain of SC, and its knowledge elements in the external environment of the SC TIS. These interaction links are slightly thickened in Figure 26.

The higher price and specific characteristics of SC (high power density, low energy storage density) make it that the majority of the available customer segments opt for other technologies such as LIB. Such interactions, where price and performance of LIB draws away potential customers from the SC TIS, are also indicated by a much thickened line in Figure 26. Also, the link between both TISs their market and value chain categories is highlighted, due to their occasional shared complementary elements, customers and networks. The developments within the field of SC technologies take time, but are promising (Ma et al., 2015; Sambath Kumar et al., 2018; Sun et al., 2020). Over time, these new insights, together with suitable and enabling value chains, may enable the TIS of SC to experience less barriers and to increase its market share.

Last, it deserves special attention in any analysis of TIS interaction, to mind the direction of interaction in between TISs. Also, the order of interactions that can exists, are rather complex dynamics.

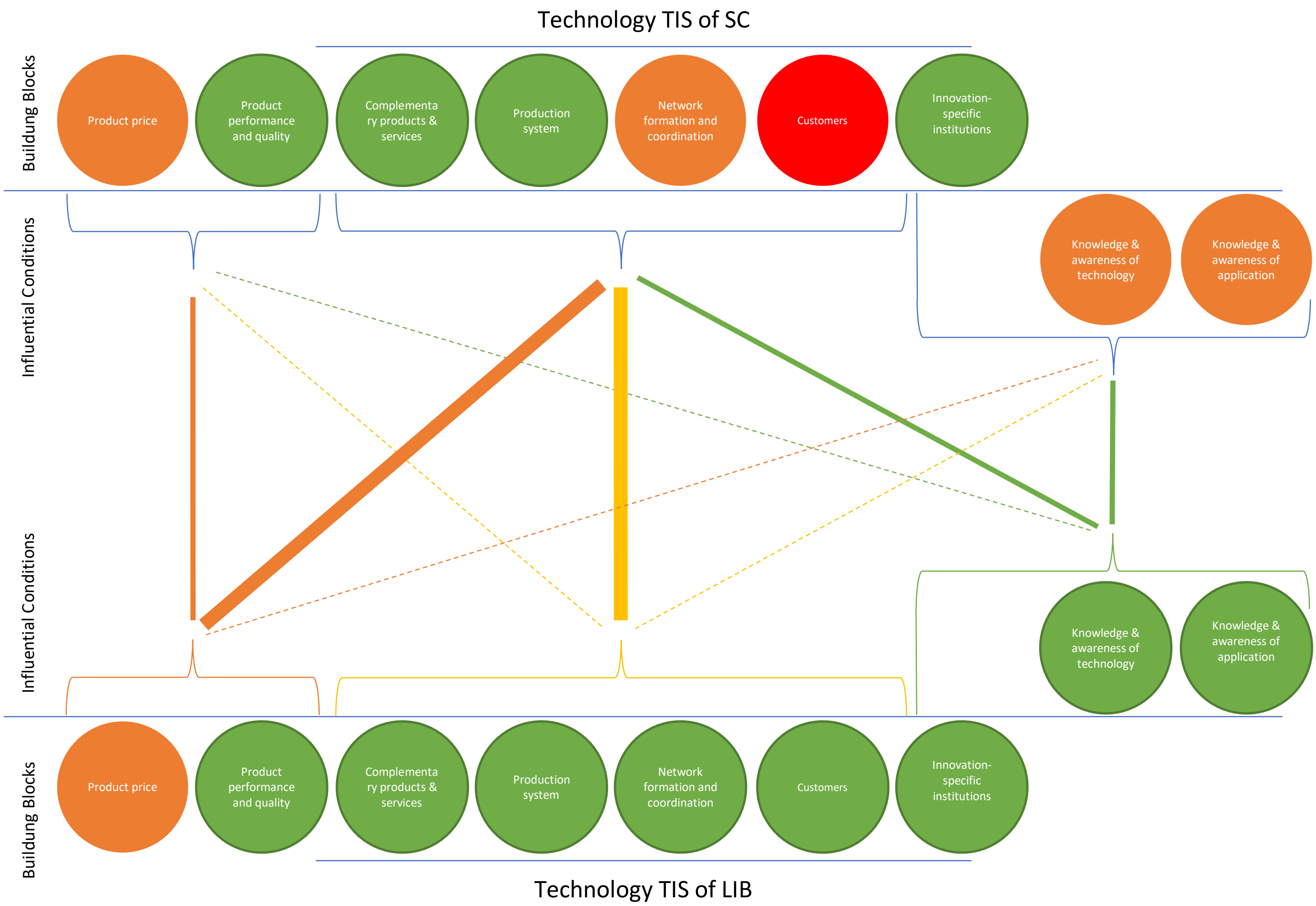

Figure 26: Visualization of interactions between the categories of technology-specific BBs and ICs of two TISs with status per BB/IC and highlighted interactions.

6 Conclusions, Discussions, and Recommendations

The previous chapters address the objectives of this thesis. In this chapter, I conclude the thesis by addressing the conclusions, discussing the results and providing my recommendations for next steps and future research. This chapter consists of three sections, each discussing the aforementioned parts per section.

6.1 Conclusions

This thesis creates insight on four themes. The first theme is the review of the current stance of literature on both EES technologies LIB and SC, on the available knowledge of TIS interactions, and on the TIS framework of Ortt & Kamp (2022). The second addressed theme is the formulation conceptual framework for addressing interaction between two TISs, based on TIS framework of Ortt & Kamp (2022) specially drafted for the perspective of business actors. The third theme is the analysis of the performance of the EES technologies LIB and SC, by applying the TIS framework. The final theme is the discussion of interactions between the focal EES technologies, and the application of the earlier conceptualized framework on interactions between the TISs of LIB and SC.

The results contribute to the existing knowledge of TISs, their interaction, and the EES technologies LIB and SC. With that, the main research question for the research is formulated as follows:

How are the Technological Innovation Systems of two Electrical Energy Storage technologies – Super Capacitors and Lithium-Ion Batteries – performing, and potentially interacting with each other?

The main research question is answered with support of the following three sub-questions, which are per sub-question answered.

1. How can the modes of interaction between Technological Innovation (TISs) Systems be conceptualized in a conceptual framework?

The adopted TIS framework of Ortt & Kamp consists of 7 core BBs and 7 contextual ICs. These core BBs together represent the core of the socio-technical system around the technology, referred to as the TIS, and are influenced by the contextual influencing conditions (ICs). In studying potential modes of interactions between two TISs, a selection is made in the BBs and ICs to drastically reduce the otherwise 196 possible interactions directly between BBs and ICs of two TISs. Generic and uncontrollable BBs and ICs are excluded, resulting in focus on the controllable aspects for business actors. Since the set of seven BBs and two ICs still result in too many possible modes of interactions to address in this thesis, these remaining aspects are categorized in three distinct categories. This reduces complexity and enables further discussion of the potential modes of interaction between two TISs. The three categories per TIS are Product Attributes, Market and Value Chain, and External Environment.

The possible interaction modes in the TIS interaction framework are Product Attributes to Product Attributes, Product Attributes to Market and Value Chain, Product Attributes to External Environment, Market and Value Chain to Market and Value Chain, Market and Value Chain to Product Attributes, Market and Value Chain to External Environment, External Environment to External Environment, External Environment to Product Attributes, and External Environment to Market and Value Chain. These interaction modes can determine pricing and marketing strategies, create expectations, set benchmarks, or influence development of complementary elements. Competition and collaboration within production systems and value chains can put pressure on either technology to innovate and express their technological value. External factors such as regulation or knowledge are also influenced through price and performance characteristics of technologies and activities within their TISs, which in turn shapes these external factors.

2. How are the Technological Innovation Systems (TISs) for each of the two Electrical Energy Storage (EES) technologies Super Capacitors (SC) and Lithium-Ion Batteries (LIB) currently performing?

The SC TIS is found to perform less optimal than the TIS of LIB. Based on the results, the TIS of SC seems to have a bad performing customers BB, and hampered BBs and ICs when it comes to product price, network formation and coordination, competition, and knowledge and awareness of the technology and its applications. The SC technology is therefore deemed to be in its adaptation phase. Strategies should aim to improve knowledge with customers, find unique combinations that stress the advantages of the SC technology, and innovate to reduce prices or increase performance of the product based on the customer's needs.

Meanwhile, the results of the analysis of the LIB TIS show a relatively well performing technology with some upcoming threats accompanying its increased deployment. The state of the TIS seems to enable the technology to diffuse on larger scales. No BBs or ICs fully block the technology's developments. Threats mainly present themselves as risks and accidents that occur with the use of LIB in EES. Also, harmful raw materials for components and dubious mining practices of the raw materials pose a challenge. Increasing pressure from society and institutions slowly but steadily motivates the TIS to adapt and comply to new regulations and expectations.

The aforementioned findings for SC and LIB stress the importance of dedicated strategies that focus on increasing knowledge and awareness of SC as a technology on its own, and strategies that focus on solving the challenges for LIB.

3. What TIS interactions exist between the SC and LIB TISs?

The conceptualized framework is applied to study the interactions between the TISs of SC and LIB for EES. Both obvious and deeper interactions are observed. The more obvious interactions are a result of competition, in which business actors promote the technical characteristics of both technologies and search for customers to which these characteristics match with their needs. For SC, business actors also engage in studying cases where SC can outperform LIB, and promote SC to potential customers as such. Characteristics of SC, such as pricing and awareness of the technology and its applications with potential customers in, among others, the LIB TIS, deserve more attention to improve. This leads to less customers in for SC as well. Concurrently it seems that the aforementioned challenging aspects of the LIB TIS lead to new insights in both the LIB and SC TIS, leading to direct interaction. Such situations and new insights offer the business actors in the SC TIS to promote strengths of their technology, especially on similar aspects where LIB falls short. In addition, it is therefore also no surprise that business actors are attempting, in collaboration with knowledge institutions, to develop technology based on both LIB and SC that can combine the best of both technologies.

Simultaneously, the historical Morse case shows how preceding technology of LIB poses challenges to the preceding technology of SC, and how events and developments of complementary systems impacted the development and acceptance towards LIB and SC. Such dynamics highlight the need to both understand technical characteristics, as well as the contexts, in which a technology develops.

6.2 Discussion and recommendations

The presented results of this thesis serve as a first system approach analysis of the TISs of SC and LIB by use of the framework of Ortt & Kamp (2022). The framework of Ortt & Kamp (2022) includes context but is limited when it comes to including effects from TIS interactions. The conceptualized framework for analysing TIS interaction, based on their framework, can be seen as a starting point in TIS interaction models for business actors. It is believed such interaction models are also relevant for other concerned or involved actors. The accuracy of the categories with which interaction modes are reviewed would benefit when considering their specific BBs/ICs instead of the categories. That simplification possibly leads to loss of such specific elements and attention for them. The timeframe of this thesis motivated the decision to create the generalized categories in the conceptualized framework to describe TIS interaction.

The background of this thesis and the results of the literature review in chapter 2 show the importance of EES for the energy transition, and what advantages LIB and SC provide. Additionally, the principles of electrical energy value chains are explained to provide the reader with a basic understanding of this system. The literature review concludes by explaining how technologies can be analysed with application of a TIS framework. Explanation of the framework of Ortt & Kamp (2022) enables the reader to understand their framework and potentially adapt it themselves. The aforementioned information, together with the introduction of the thesis, enable the reader to understand the background and value of this research relative to the current gaps in literature and challenges in the energy transition.

This research is first to address the specific and important topic of TIS interaction from the study of Bergek et al. (2015). The contributions to their findings are the conceptualized TIS interaction framework and its application on the cases of LIB and SC. Based on the notion of TIS interaction from Bergek et al., future research should study the further effects on TIS interaction from the TISs their supply chain relatedness.

6.2.1 Implications for academics

Academics using TIS frameworks to study technologies may benefit from the conceptualized framework for analysing TIS interaction in chapter 3. The results in that chapter enable academics to use the interaction framework to study interaction between two TISs in a basic approach. It also allows them to comment the conceptualized interaction framework and refine it to enhance its quality. This can lead to an improved use of that framework.

The analyses of both TISs of LIB and SC in chapter 4 demonstrates the use of the TIS framework Ortt & Kamp (2022). The description of both TISs allow academics to study the findings and use them as a source to their own work. It is possible for academics to further compare the results with other (sustainable energy) technologies and study different interactions. They can also update the findings of the TISs from chapter 4 over time, and develop a timeline of the developments to increase the accuracy and understanding. Additionally, academics can compare these findings with other related sustainable energy technologies their analysis. This can lead to improved or new insights.

The results allow academics to review and possibly correct the set of interactions between both TISs. Furthermore, academics can use the findings to support their own future work within TIS interaction, within EES technologies or other logical and related areas.

6.2.2 Implications for (business) actors

Business actors can learn how the framework of Ortt and Kamp (2022) can be used to assess the performance of focal or other technologies. These actors can by applying the framework study how different aspects of a system can have different impacts on a technology. Using the conceptualized TIS interaction framework from chapter 3 the business actors can analyse the interaction between two technologies. This systematic approach supports them in understanding the interaction modes between competing or complementing technologies.

The results of the TIS analysis of LIB and SC allow (business) actors involved in either of both technologies to review the current state of both technologies, and consider these in their activities. For niche or emerging technologies (such as SC), further application of frameworks as presented by Ortt et al. (2013) and Ortt & Kamp (2022) can assist in the further development and diffusion. The results also demonstrate how to use the TIS framework to other focal technologies of the business actors.

The business actors can with the new insights from chapter 5 determine where to put more focus within their focal technologies, to either study a specific interaction in their field of business, or to motivate certain interaction to achieve particular results. The conceptualized TIS interaction framework offers a guideline to the (business) actors to study interactions less based on feeling and reasoning, and based more on a structural analysis approach, and with that act more effective and efficient. More effective strategies and decisions of (business) actors involved with sustainable energy technologies (like SC or LIB) enhances the effective and efficient functioning of them and their systems of innovation, marketing and policy making. These improvements help improving the development and diffusion of such technologies. This in turn impacts the transition towards cleaner energy technologies.

By involving the insights or methods of this thesis, improved strategy formulation for business actors can be described in various ways. For example, they can have improved hedging for risks of focal or related technologies, in similar or different contexts, further securing their activities. Activities like allocating efforts on specific innovation aspects to achieve certain interaction can help in creating certain networks or collaborations, or engaging in lobby activities. This in turn can strengthen performance or competitive advantage.

6.2.1 Recommendations for future research

This thesis provides new insights in the TIS interaction between the technologies of SC and LIB by applying the framework of Ortt and Kamp (2022) and the conceptualized TIS interaction framework. The conceptualized TIS interaction framework underwent certain simplifications that may or may not leave out interesting information such as other interesting modes of interaction. Analysis of the interactions between LIB and SC can be expanded to other relevant and relating technologies, or completely new sectors, to further test and understand the TIS interactions and a possible framework for it. Testing the conceptualized TIS interaction framework on other technologies makes sense, due to the probability of different technologies having different characteristics, and therefore having different mutual interactions.

Future research should therefore focus on refining such interaction models due to the simplifications of the proposed TIS interaction framework. Additionally, current TIS frameworks, such as that of Ortt and Kamp, lack specific or explicit focus on TIS interaction. Refining a TIS interaction framework can be done by study the roles of individual BBs or ICs in the interaction, instead of the broad categories used in this research. Adding more specificity possibly increases the understanding of effects and interactions between TISs, and enables better documentation of these interactions. Furthermore, the framework of Ortt & Kamp could benefit from including findings from this research or the authors could draft a finetuned framework, with regards to TIS interaction. Business actors are interested in understanding their competing or complementing related technologies, for which TIS interaction studies are fundamental.

The TIS analysis in this research shows that the SC TIS performs less optimal compared to the LIB TIS, mainly due to limited availability of customers. Reviewing the performance of the TISs over time is paramount to its accuracy. An intensified and actual analysis of the TIS of SC or LIB can increase the quality and reliability of the results.

With new analyses lies a chance to include other research methods, such as different analysis of more articles and inclusion of patent analysis. It deserves the recommendation for future research, to update the TIS analysis of both LIB and SC, and optionally other related technologies too. This not only improves the accuracy of the results, but can also provide actors with reliable insights and enable the formulation of better strategies, to for example aid the further development and larger scale diffusion of SC.

The application of the conceptualized TIS interaction framework on the TISs of LIB and SC provides a structured approach of their interactions. The application of the conceptualized TIS interaction framework on other technologies can provide values both the knowledge of those technologies, as well as the framework itself as also briefly mentioned before. Analysing interaction with the framework between different technologies, with different characteristics, life phases, and geographical boundaries, can test and strengthen the universality and adaptability of the TIS interaction framework. It also allows improvement of the framework. Last, it offers a more profound and structured understanding of interaction between two TISs.

As discussed by Bergek et al. (2015) and discussed in appendix D, studying the interaction between related TISs in their supply chain is recommended. In different positions relative to one another, TISs will experience different dependencies and therefore hold different characteristics when it interacts.

Studying such interaction with special attention to supply chain characteristics, can provide valuable information on how a position in a supply chain can help or hamper the development of a TIS. Knowing the impacts of dependencies or relations based on the aforementioned might also help business actors to reassess their current and future strategies. As a simple example, threatened complementary parts for a focal TIS might in time also threaten the stability of the focal TIS. Future research could enable to discover such threats (or opportunities) and enable actors to act.

Another recommendation that stands a bit more apart from the research's findings embodies my particular interest in a potential combination of a life cycle approach with the TIS framework such as that of Ortt & Kamp (2022). As cited from the conclusion of the literature review and further discussed in appendix B, attention to the life-cycle model in combination with the TIS framework might be interesting. Markard (2020) misses out on considering business actors. For the framework of Ortt & Kamp, understanding technology and its phase in the life cycle could be relevant. This for example due to possible wrong understanding of any business actor about the phase of their focal technology, or for helping to understand the interaction between two technologies in different phases of their life cycle. The latter could help to draw interesting connections between two technologies based on life cycles. As observed with the interaction between the cases of LIB and SC, the life cycle of the technologies in a specific application can change, when both the technology's TISs compete and lead to a moving customer base, resulting in a diminishing or disappearing TIS in that application. The focus on a life cycle approach is out of the scope of this research but worth mentioning due to exciting threads in the literature.

Last, the BBs or ICs their statuses might be reassessed after performing a TIS interaction analysis. A BB or IC on its own might seem to perform well or unwell in its own context. However, when placed in the context with another TIS, the focal BB or IC could be under such an influence, that the information for indicating its status now or in the near future can be altered, changing the assessed status of the BB or IC. It is recommended to further investigate such a phenomenon.

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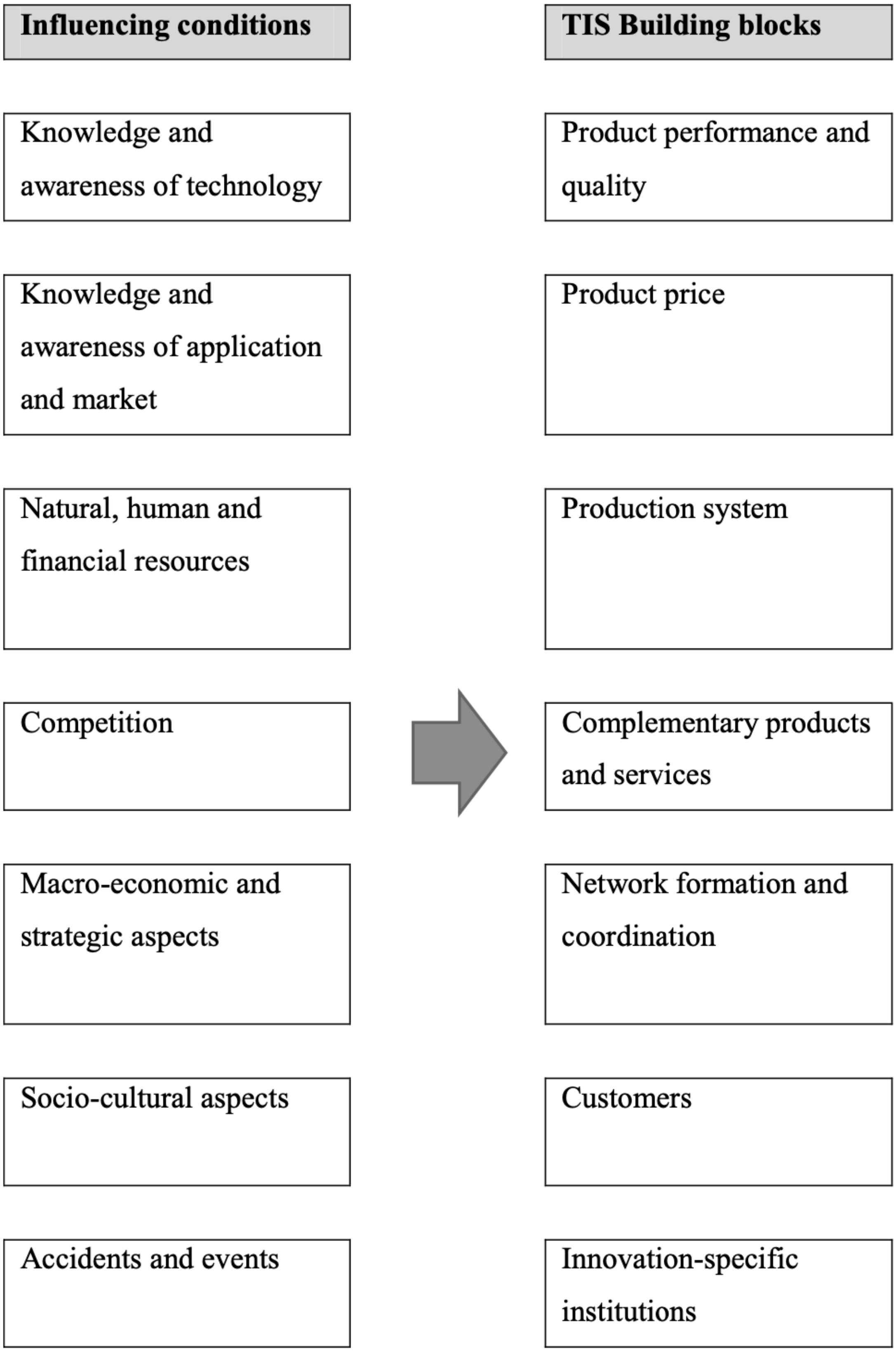
Appendix A

TIS framework as proposed by Ortt & Kamp (2022).



Appendix B

Elaboration on models of Ortt & Kamp (2022) and Markard (2020)

Today, the TIS interaction for energy technologies can be considered to involve the decline of the TISs in conventional energy systems (often based on oil and gas). I reviewed papers discussing similar principles for TIS interaction. These principles involve technological decline, which is also deemed necessary (Markard, 2020; Markard et al., 2020). Where the considered framework for the TIS analysis in this thesis can accurately be deployed to track TIS evolution as well (Ortt & Kamp, 2022), I expect that both this framework and the framework from Markard (2020) can well be deployed for addressing TIS decline too. Both frameworks use a comparable barrier-identification method and already show to be able to analyse the decline of, for example, nuclear energy (Markard et al., 2020). It is obvious that a declining TIS is being replaced by other TIS(s).

Markard (2020) addresses three points which are in my view interesting to consider in addition to the model of Ortt & Kamp (2022), being (i) technology varieties, (ii) development pace, and (iii) expectations. Technology varieties might be considered in addition to the 'competition' block, indicating how unique the focal niche technology is compared to the context. The pace of development goes for both the focal niche technology and the competition and complementary products and services. As discussed, the pace of development should at least keep up with the focal technology to prevent any resistance to development. Pace of development can potentially be described by analysing how many adaptations of a niche technology follow up on each other, and how quickly they do so in the general adaptation phase, in line of the work of Ortt et al. (2013).

Similarly, competition could either lack pace (creating opportunity for new technologies) or have a better pace (creating barriers for new technologies). In the development pace, it is interesting to distinguish whether or not focal or competing technology improves radical or incrementally (Markard, 2020). Finally, expectations could be added to 'innovation-specific institutions', although this might not be necessary. Ortt & Kamp might consider the same aspect but describe it as trust.

Appendix C

Ortt et al. (2013). Highlighted cells concern strategies for niche technology of Super Capacitors as discussed in the research.

Generic niche strategies	**A market situation in which they can be adapted to introduce a high-tech product or system**	**Description of the niche strategy**	**Cases and references**
1 Demo, experiment and develop niche strategy	Knowledge of the technology is lacking, which affects the product's availability because the functionality is not provided with sufficient **quality**.	A niche strategy can be adopted to demonstrate the product in public in a controlled way, so the limited performance quality is not a problem. As part of the strategy experimenting with the product is essential to develop the product further, for example in a research environment.	Telegraphy was demonstrated in multiple cities before it was put into use [Dordick, 1990] [Huurdeman, 2003] [Winston, 1998]. Video telephony was demonstrated on multiple world exhibitions before marketable products emerged in the 1960s [Baird, 1971] [Ortt, 1998].
2 Top niche strategy	Knowledge of the technology is lacking and that affects the availability of the product for a reasonable **price**. Knowledge of the technology is lacking and that affects the production system with which controlled production of products with a constant and good enough **quality and reasonable price** is possible. Resources for the product or the production are lacking or very expensive and that affects the product's **price**.	A niche strategy can be adopted where hand-made products can be made to order, in small numbers, for a specific top-end niche of the market. A skimming strategy can be adopted in which the top niche of customers is supplied first with a special product.	The first cars were made-to-order and crafted by hand for a top-niche of the market [Eckermann, 2001] [Setright, 2004]. The strong fiber Dyneema was hand-made and used in a special niche before large-scale production was possible [Hongo & Phillips, 1997] [Mulder, 1992].
3 Subsidised niche strategy	Knowledge of the technology is lacking and that affects the availability of the product or the production system and that in turn affects the availability of the product for a reasonable **price**. Resources for the product or the production are lacking or very expensive and that affects the product's **price**.	A niche strategy can be adopted where the product is subsidised if the use of the product by a particular segment of users is considered as societally relevant or important.	Video telephony for deaf people was funded by EU budgets [Ortt, 1998] [Dickson & Bowers, 1974]. New clean energy technologies are subsidized [Caniëls & Romijn, 2008] [Kemp et al., 1998].

Generic niche strategies	A market situation in which they can be adapted to introduce a high-tech product or system	Description of the niche strategy	Cases and references
4 Redesign niche strategy	Knowledge of the technology is lacking and that affects the availability of the product or the production system and that in turn affects the availability of the product for a reasonable **price**. Resources for the product or the production.are lacking or very expensive and that affects the product's **price**. Knowledge of the application of the product is missing or socio cultural aspects affect the availability of appropriate institutional aspects (laws, rules and standards) and thereby hamper diffusion. Socio-cultural aspects affect the availability of suppliers or customers.	A niche strategy can be adopted where the product is introduced in a simpler version that can be produced with the existing knowledge, less use of resources and therefore for a lower price A niche strategy can be to explore an application where institutional aspects are more favorable. Mostly leads to redesign. A niche strategy can be to explore an application where suppliers or customers have no resistance to produce and use it. Mostly leads to redesign.	Furniture design after WW2 was adapted because resources such as steel and wood were scarce and needed to rebuild countries. The first personal computers were apart from the first professional applications used as kind of typing machine rather than using their full potential [Windrum & Birchenhall, 1998]. The contraceptive pill was introduced for skin irregularity because approval as a contraceptive was controversial [Junod & Marks, 2002].
5 Dedicated system or stand-alone niche strategy	Knowledge of the technology is lacking and that affects the availability of complementary products and services.	A niche strategy can be adopted where the product is used in stand-alone mode or a dedicated system of complementary products and services is designed (e.g., a local network when an infrastructure is not available on a wider scale).	Telephony was first used to contact the telegraph office, as a means for intra-company communication, and as a dedicated burglar alarm when the telephony infrastructure was not yet available [Huurdeman, 2003] [Dordick, 1990].
6 Hybridi-zation or adaptor niche strategy	Knowledge of the technology is lacking and that affects the availability of complementary products and services. Resources are lacking and that affects the availability of complementary products and services.	A niche strategy can be adopted by which the new product is used in combination with the old product and thereby all existing complementary products and services can be re-used. Or an adaptor/convertor is provided to make the product compatible with existing complementary products and services.	Hybrid car is a way to create fuel efficient cars when the infrastructure to use fully electric cars is not yet available [Jefferson & Barnard, 2002] [Wakefield, 1998].

Generic niche strategies	**A market situation in which they can be adapted to introduce a high-tech product or system**	**Description of the niche strategy**	**Cases and references**
7 Educate niche strategy	Knowledge of the technology is lacking and that affects the availability of suppliers or customers	A niche strategy can be adopted aimed at transferring the knowledge to suppliers. An educate and experiment (pilot) niche strategy can be adopted aimed at increasing customer knowledge.	Bell labs organised conferences to transfer knowledge regarding semiconductors and transistor technology to manufacturers such as Raytheon. Bell also stimulated universities to develop this knowledge [Brinkman et al, 1997].
8 Geograp-hic niche strategy	Knowledge of the technology or its application is lacking and that affect the availability of appropriate institutional aspects (laws, rules and standards) Resources are lacking affecting the availability of the product or complementary products and services. Socio-cultural aspects or macro-economic aspects affect the availability of suppliers, customers and appropriate institutional aspects. Accidents and unexpected events affect the availability appropriate institutional aspects.	A niche strategy can be adopted where institutions (laws and rules) are relatively easy to arrange or are less strict. A niche strategy can be adopted in another geographic area where resources, suppliers or customers are available. A niche strategy can be adopted in another geographic area where suppliers are available and not hampered by these unexpected events or accidents.	After some terrible accidents Nobel was forced to move the production of Dynamite to the UK, that also stimulated the creation of a new market segment [Brown, 1998].
9 Lead user niche strategy	Knowledge of the application of the product is missing and that affects a clear view on customer applications, specific product requirements and customer segments by suppliers. Socio-cultural aspects, Macro-Economic aspects or accidents and unexpected events affect the availability of suppliers or customers.	A niche strategy can be adopted finding innovators or lead users. These lead users can co-develop the product and innovators are willing to experiment with the product.	Sport equipment developed by top sporters themselves [Herstatt, & Von Hippel, 1997].
10 Explore multiple markets niche strategy	Knowledge of the application of the product is missing and that affects the availability of a clear view on applications, usage patterns and product benefits by customers.	A niche strategy can be adopted in which multiple customer applications can be explored. Visibility of the first applications might stimulate explorative use in new applications.	At first it was unclear in what type of applications memory metal could be used [Kauffman & Mayo, 1996] [Kumar & Lagoudas, 2008].

Appendix D

Bergek et al. (2015) conceptualize four different modes of interaction of a focal TIS with context in total. This appendix briefly discusses the described interactions between supply chains.

The first mode discussed is an interaction of the focal TIS with other TISs. The article discusses a set of 'horizontal' and 'vertical' influences between TISs. This distinction refers to the position of a TIS and an influencing TIS concerning their supply chain(s). The vertical influence can be regarded as a 'supply chain' influence between TISs up or downstream of the chain. The horizontal influences can be seen as influences between TISs with similar positions in the chain. This similar position would be described as two different TISs working with (partly) similar inputs and outputs within the chain.

Vertical interactions between TISs can be seen as either complementary or competitive relationships between suppliers and buyers within a specific TIS. An illustration of this is the relationship between a rubber feedstock TIS and a car tire TIS, where both entities benefit mutually from the success of the other. This dynamic ensures that a high-performing rubber manufacturer enhances the car tire TIS and vice-versa, facilitating its advancement.

An additional example provided by Bergek et al. involves a photovoltaic (PV) panel manufacturer contracting a silicon producer, demonstrating how vertical interactions can influence the development and efficiency of TISs based on the specifics of their agreements. This relationship between the PV panel manufacturer and the silicon producer epitomizes vertical interaction, with potential impacts depending on the contract's nature.

Bergek et al. further introduce the concept of horizontal interactions, which arise when two TISs share similar resources or outputs. For instance, if an aerogel TIS, which also uses silicon, faces a reduced silicon supply due to the exclusive contracts between the PV panel and silicon producers, it exemplifies a horizontal interaction influenced by vertical agreements in the silicon market.

Both horizontally and vertically relatable EES technologies are identified in section 2.2. A comparable view on relations between TISs is used here as discussed by Bergek et al. (2015). The vertically relatable EES technologies and their TISs form a process in the chain in which EES plays a role. Figure 1 gives a visual representation of the vertical chain relations considered for the proposed research. A notion is that EES technologies are existent between use, and transmission & distribution. However, these are not considered in this research. Figure 2 and 3 show the horizontal relations between different EES technologies that the proposed research considered for this research. Some technologies are on both sides of the system since these technologies can fulfil both functions.