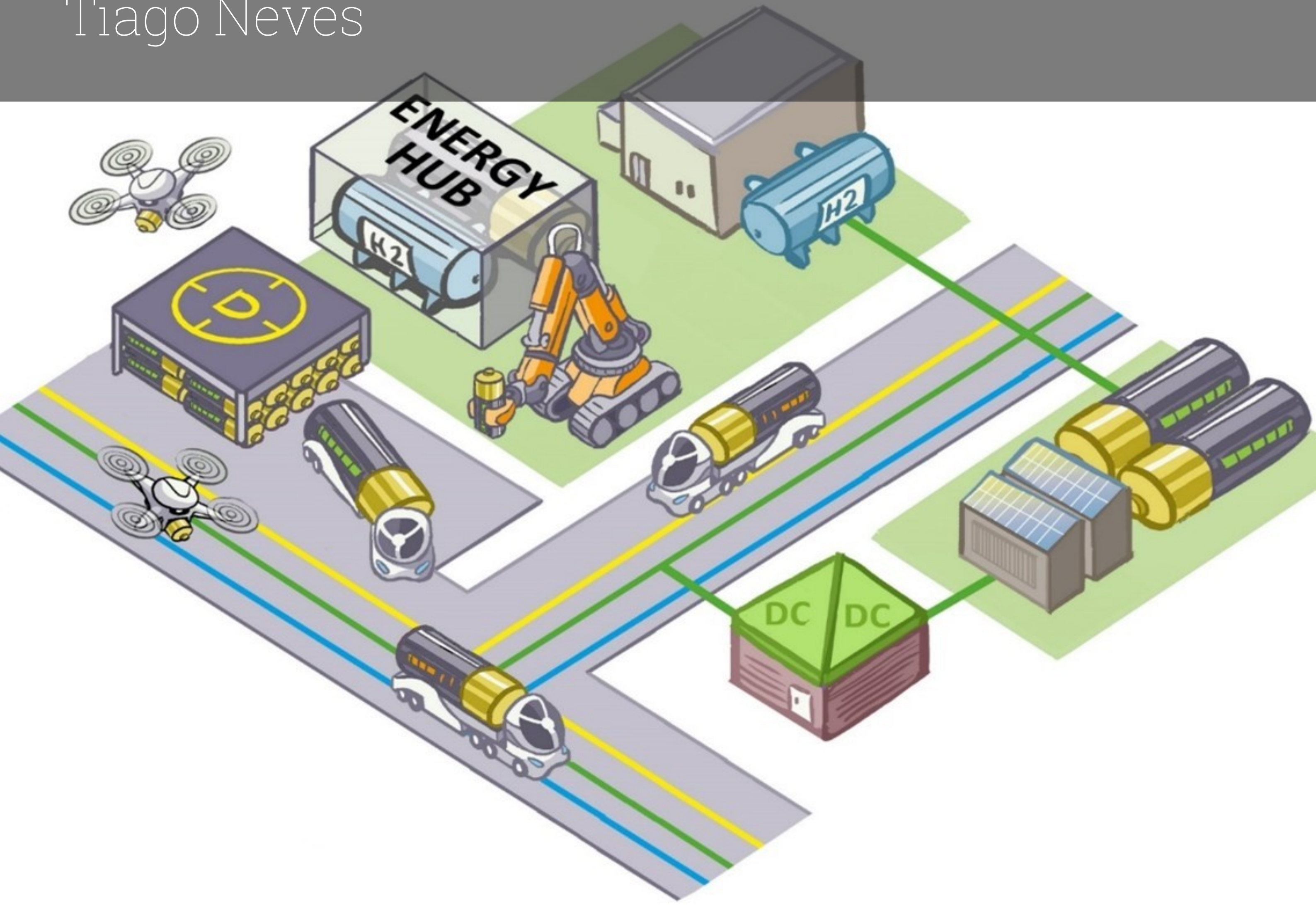
The Role of Energy Hubs in Battery Storage Technologies Business Models

How can we create
the energy system of the future?

Master Thesis

Tiago Neves



The Role of Energy Hubs in Battery Storage Technologies Business Models

How can we create the energy system of the future?

by

Tiago Neves

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at the Delft University of Technology,
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Executive summary

This study explores the intersection between battery storage technologies and energy hubs, with a particular focus on how the latter influences the development and implementation of business models for battery systems. With the acceleration of the energy transition and the growing electrification of energy supply, problems such as grid congestion have led to the growth in popularity of the concept of energy hubs and of battery storage technologies. Nonetheless, there is still a gap in understanding how these two concepts interact from a business perspective.

Despite the technical viability of batteries, their economic deployment remains constrained by high upfront costs, uncertain revenue streams, and regulatory ambiguity. Existing literature tends to address batteries and energy hubs as separate phenomena, leaving a gap in understanding how the integration of batteries within energy hubs alters their business models. This research addresses this gap by examining how battery storage business models are shaped in energy hubs.

The study employs a qualitative methodology, grounded in semi-structured interviews with twenty professionals representing various segments of the energy hub ecosystem, including aggregators, technology providers, grid operators, policymakers, investors, and energy suppliers. The thematic analysis of the interview data reveals that energy hubs influence battery storage technologies' business models in ways that create new drivers that both alleviate existing barriers and enable new forms of value creation. Key drivers for battery integration in energy hubs include the need for enhanced energy flexibility, mitigation of grid congestion, and strategic responses to energy market volatility. Conversely, persistent challenges such as capital intensity, uncertain regulatory frameworks, and technological constraints continue to shape the feasibility of different business strategies.

The findings identify a set of dominant business models that characterize the use of battery storage in energy hubs. These include configurations centered on energy storage services, market trading activities such as arbitrage and frequency regulation, and multi-service models that combine several revenue streams through value stacking. These business models generate a range of value for their customers, including cost reduction, increased energy capacity, facilitation of renewable energy integration, decarbonization of local energy systems, and security of supply.

Building on these insights, the thesis presents a conceptual framework that captures the relationship between drivers, barriers, business model configurations, and value creation in the context of battery storage technologies applied in energy hubs. This framework contributes to the academic understanding of business model innovation in the energy sector and offers practical guidance for stakeholders seeking to navigate the evolving landscape of decentralized energy systems. Ultimately, the research demonstrates that energy hubs have the potential to unlock more robust, scalable, and economically viable business models for battery storage technologies, while still supporting sustainability concerns and contributing to a more reliable grid.

Acknowledgments

This study marks the last milestone of my master's degree. This would not have been possible without the support of the people who accompanied me throughout the challenging process of writing this thesis.

I would like to express my sincere gratitude to Hanieh Khodaei and Linda Kamp for their invaluable support and guidance throughout this journey. Your feedback and encouragement pushed me to deliver a piece of work I can truly be proud of.

I am also thankful to all the participants of this research. The insights and perspectives you shared were essential to the development of this study. Many of you I met during my academic journey, and encouraged me to pursue this topic. You form the backbone of this thesis.

To my friends. Thank you for being there when I needed and for always listening to my long monologues about how decentralized energy systems will be the future.

Finally, Mum, Dad, and Bea, thank you for everything. I hope that I can make you proud.

Tiago Neves
Delft, July 2025

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Nomenclature

Abbreviations

Abbreviation	Definition
B2B	Business-to-Business
B2C	Business-to-Consumer
BESS	Battery Energy Storage System
C2C	Consumer-to-Consumer
DSO	Distribution System Operator
EaaS	Energy-as-a-Service
EU	European Union
EV	Electric Vehicle
FCR	Frequency Containment Reserve
GTO	Group Transport Agreement
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
P2P	Peer-to-Peer
TSO	Transmission System Operator

1 Introduction

1.1. Background and context

In April 2025, Portugal and Spain experienced a nationwide blackout. This event reminded Europe of how relevant it is to have a safe and resilient energy system. The causes of this event are still unknown, but the fragility of the energy system has concerned citizens and left them in doubt about their security. The integration of renewable energy started being questioned due to the fact that, in moments of distress, the significant investments from the state were not working, and when citizens pressed their light switch, the lights did not turn on. With the current tensions in the world, a resilient energy system is required to make sure that a country stays safe against possible threats.

Since the signing of the Paris Agreement (United Nations, 2015), climate change has become one of the biggest global concerns. With that, the increased emphasis on making our society carbon-neutral grew. Currently, there is a clear move towards a greener society, reflected in the new agreements signed by the members of the European Union, such as the Green Deal (European Commission, 2019) and the Clean Industrial Deal (European Commission, 2025). These deals increased the pressure on member states to decarbonize by imposing rules and creating ambitious goals to ensure that Europe moves in the right direction, and that global temperature rises stays under 1.5°C according to pre-industrial standards.

The increasing focus on decarbonization led to a tremendous increase in the electrification of our society, the rising adoption of electric vehicles and other solutions that replace old fossil fuels (gas, oil and coal) with electricity has been notorious in the last 5 years, as seen in Figure 1.1 when using the growth of sales of electric vehicles (EVs) as a benchmark. This increase in demand is currently being matched with unstable and intermittent renewable energy production, leading to this type of energy production to rise to 44% of the European energy mix (Brown, 2024). The closure of coal plants; for example, in northern Germany where RWE had already shut down more than five coal power plants by 2024 (RWE, 2024); and of gas plants and fields, such as the recent shutdown of the Groningen gas fields in the Netherlands (Reuters, 2024); has made the situation even more critical by reducing local energy production and increasing reliance on energy imports and renewable sources. Progress is currently hindered by challenges that have arisen, notably grid congestion.

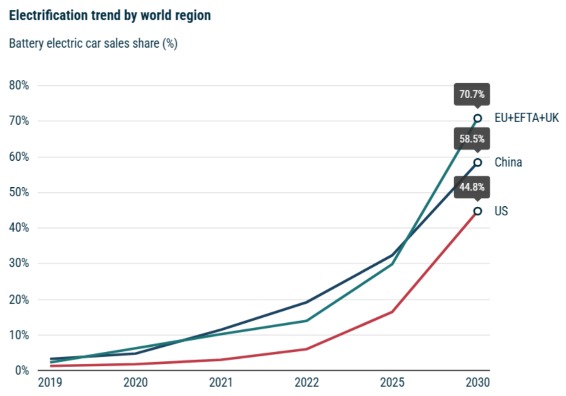

Figure 1.1: Electric car sales growth worldwide

With the growing demand for power from the energy system, grid congestion has become a significant problem. The grid is not capable of handling the distribution of energy during production and demand peaks, becoming overwhelmed. Which leads to an unbalance between the supply and demand, ultimately making the grid unable to respond to consumer needs. This leads to a plethora of problems and significant losses for stakeholders involved, ranging from energy consumers not having enough energy for their needs to producers having to reduce their output. For example, the Netherlands is facing severe repercussions due to grid congestion. Figure 1.2 showcases how congested the Dutch energy system is; this image was captured from the *netbeheernederland* website on April 2025. According to the International Energy Agency, 2025, the inability of the Dutch energy system to respond to the demand led to an economic loss of approximately 300 million euros in 2023, equivalent to more than 25% of the country's GDP.

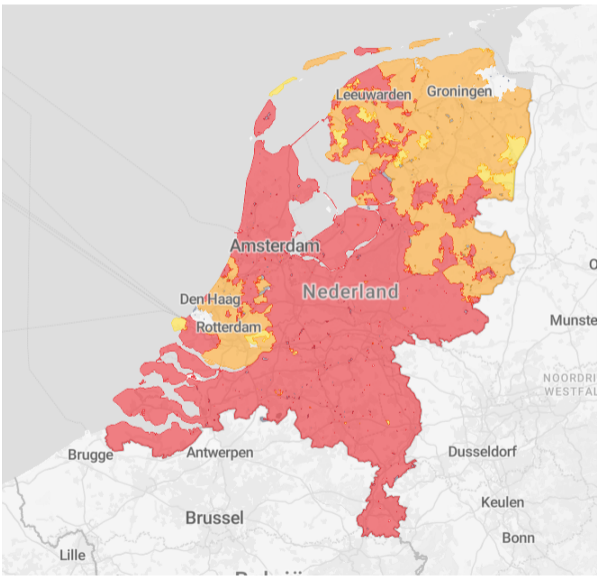

Figure 1.2: Grid congestion map of the Netherlands, April 2025

These issues increased the need for an updated and flexible energy system. With that in mind, new solutions such as energy hubs were created. An energy hub consists of a decentralized energy system that manages the energy production, storage, and distribution of multiple energy sources within a specific area (Papadimitriou et al., 2023). This kind of solution allows energy consumption to be more efficient and optimized, so as to ensure that the consumers can shield themselves from energy shortages (Mokaramian et al., 2025). These hubs can take multiple shapes and forms, and their designation is still contested in the field. Energy storage is a key piece of the puzzle for these hubs to be operationalized. There are numerous ways of storing energy, with their pros and cons; in this research, however, the focus will be on battery storage technologies.

Currently, batteries are one of the most common ways of assuring flexibility in energy hubs. Even though these systems are rather popular, batteries still have dubious business models, and struggle to make a profit (Hu et al., 2022). There are multiple factors contributing to this challenge, including high upfront costs, long payback periods, and safety concerns (Luo et al., 2015). Nowadays, battery storage systems take at least 10 years to become profitable (Fong et al., 2019), making them a risky investment. Additionally, due to highly volatile energy prices, relying upon a single source of revenue is not sufficient, pushing battery owners to search for new business models to accommodate this factor. Furthermore, regulatory constraints create difficulties in penetrating the market (Gissey et al., 2017), which delays the deployment and integration of battery storage technologies. These challenges hinder the adoption of battery storage technologies. The goal of this research is to understand if energy hubs can help overcome these challenges and create more efficient business models for battery storage technologies.

1.2. Problem statement and research objectives

According to X. Li et al., 2019, there is a push by big companies to further pursue battery storage as a flexible solution for their energy consumption, due to some of their reduction in profits being largely attributed to high energy prices and lack of energy availability. According to Fong et al., 2017 and X. Li et al., 2019, multi-service business models – models where the battery is used for more than one purpose – for battery storage technologies are currently the best option in terms of return on investment (ROI). These kinds of business models are extremely difficult to operate due to the need for intense and coordinated stakeholder cooperation, even though there are multiple sources of value available and ready to be explored. In this case, energy hubs, known for establishing a strong connection across their participants, may prove to be a catalyst. Due to their heavy reliance on collaboration and the important integration of these battery systems in their conception, energy hubs are clear contenders as an application for battery storage technologies that can lead to more efficient business models.

To deepen the problem at hand, the creation of energy hubs and the implementation of battery storage creates value that is not inherently monetary in different fields. X. Li et al., 2019 emphasizes the fact that batteries have benefits in terms of sustainability and contributing to a more stable and reliable energy system. Currently, that is not seen as a priority, but tends to grow in importance. With the rising pressure from the European Union for a greener economy, this becomes something that should be taken into consideration while addressing "creating value". Therefore, changing the way that business models are constructed and evaluated is important. Furthermore, with the introduction of price instruments like the carbon tax (Gandhi & Cuervo, 1998), the value of decarbonizing increases significantly.

In summary, batteries have been a widely known and available technology for a long time, but there is still no clear path in terms of applying them to provide flexibility and grid services. Also, in the past, the business models to create value from batteries were all based on the fact that there is only one owner of the battery, which contrasts with the energy hub application. These business models face numerous challenges, making them inefficient in creating value for the consumer and the environment. With the introduction of energy hubs, new options are available in terms of ownership models and overcoming the challenges of traditional business models. This study aims to understand how battery business models are changed by the implementation of energy hubs, taking into consideration all the nuances raised by it.

1.3. Research question and sub-questions

The business models of batteries in energy hubs are still unclear. Although the industry is clearly adopting more batteries and creating more energy hubs, there is still a clear gap when it comes to defining how the business models of batteries in the energy hub context are shaped. This research will focus on defining these business models and understanding the role of the battery within energy hubs. The following research question summarizes the goal of this research:

How do the business models of battery storage technologies work in energy hubs?

To answer this question clearly, the following research questions were developed. Each of these questions aims to answer one of the aspects driving business models.

1. *What are the drivers and barriers of the business models of battery storage technologies in energy hubs?*

For this question, the objective is to understand what are the key factors contributing to the adoption and choice of business models of battery technologies for energy hubs and what type of constraints exist for their application. These questions aim to delve into the reasons that define the adoption of these business models.

2. *What are the business models of battery storage technologies in energy hubs?*

   Battery storage technologies have multiple business models. This technology is known for its diverse applications; therefore, it is relevant to narrow down which applications are key for the operationalization of energy hubs. This question aims to summarize them and to provide a good understanding of what business models battery storage technologies are used in energy hubs.

3. *How do the business models of battery storage technologies create value when applied to energy hubs?*

   The objective of this question is to clarify the value proposition of battery storage technologies when applied to energy hubs. The goal is to achieve a comprehensive understanding of how battery technologies can be of value to the customers of the energy hub.

1.4. Limitations and structure

In order to construct a more relevant research, this study will mainly focus on industrial applications of energy hubs, where larger batteries are implemented. Although other types of energy hubs will be mentioned, this focus will aid in defining the participants of the research (further explained in chapter 4), and reduce the scope of the literature review, ensuring that more concrete results are achieved. Also, the sample acquired consists of professionals working in the Netherlands, which limits the generalizability of the findings.

Intending to make results as clear as possible, this study starts by giving background on the research topic, exploring the concept of energy hubs in more detail by providing context on their origin and typology, and exploring state-of-the-art battery storage technologies, as well as the main challenges identified in their business models. Following this chapter, a literature review is presented. Due to the nature of the topic, this section will cover what are the business models for battery storage technologies, and how energy hubs and battery storage technologies relate. Following the literature review, the methodology for this research will be presented, where the data collection and analysis methods will be explained in detail. This research will employ a qualitative research approach, based on data collected from semi-structured interviews with industry experts, culminating in a thematic analysis. The results will then be explained and discussed in the following section, where the 4 aggregate dimensions: drivers, barriers, business models, and value creation will be explained in detail. After, a framework based on these findings will be explained. In the end, the conclusion of this research will be provided, along with a reflection on the contribution to research and the real world. In the end, recommendations for further research will be given.

2 Background and Context

In the field of batteries and energy hubs, there are plenty of definitions that are not clear. This chapter aims to summarize some of the prior knowledge and information that will serve as background for the research. The goal of this chapter is to provide sufficient background information such that the research has a clear scope and there is a significant basis of information to build knowledge on top of. The main focus of this chapter will be to contextualize energy hubs and battery storage technologies and to explain this new application of technology.

To further understand how concepts relate, this chapter will address fields such as electrification, energy hubs, and the core types of batteries in a way that will facilitate the understanding of the findings. Further in this report, these concepts will recur; therefore, it is important to establish a baseline on which the study can be built.

2.1. The main problem: Electrification

The amount of electricity consumed is growing significantly – at 4% annually, on average (International Energy Agency, 2024). With the increased electrification of multiple industries such as transportation, heating, and manufacturing, the demand for electricity has surged, creating struggles that were not taken into consideration before. For the sake of this research, context will be provided regarding what these struggles are to better frame their relevance and contribution.

As of early 2025, about 10,000 large electricity users and 7,500 new generation projects were waiting to connect to the Dutch grid due to congestion constraints (ABN AMRO, 2024). This scenario is echoed in many European countries: WindEurope reports hundreds of wind farms across EU states face permit delays of up to 9 years for grid connection, with 500 GW of projects stuck in the queue (WindEurope, 2024). This is leading to an increasing loss of returns and overall loss of potential economic growth. Furthermore, it delays the integration of renewable energy and eventually stalls the energy transition. Most European countries are aware of these issues and are attempting to take action; however, high upfront costs and technical challenges complicate grid renovation and the creation of a more sustainable and reliable system (Reuters, 2025).

Grid congestion has diverse implications. The impact on the business of Transmission system operators (TSOs) is massive; cases like the one of TenneT, in the Netherlands, that spent almost 400 million euros on congestion management in 2022 (TenneT, 2024), or the German grid operator that had costs upwards of 4 billion euros in 2022, prove how tremendous this impact can be for the economy (International Energy Agency, 2023a). Ultimately, this cost will eventually be borne by the consumer.

These problems require new solutions that can improve flexibility and provide increased value for consumers. That is where energy hubs and battery storage technologies appear.

2.2. What is an energy hub?

Energy Hub is a buzzword from the industry to define multiple different energy systems, but where does this concept originate? And what is the meaning behind it?

This concept was introduced by Andersson et al., 2007 as part of a framework for multi-vector energy systems. The energy hub was described by them as:

"A unit where multiple energy carriers can be converted, conditioned, and stored. It represents an interface between different energy infrastructures and/or loads. Energy hubs consume power at their input ports connected to, e.g., electricity and natural gas infrastructures, and provide certain required energy services such as electricity, heating, cooling, compressed air, etc., at the output ports. Within the hub, energy is converted and conditioned using, e.g., combined heat and power technology, transformers, power electronic devices, compressors, heat exchangers, and other equipment. Real facilities that can be considered as energy hubs are, for example, industrial plants (steel works, paper mills), larger buildings (airports, hospitals, and shopping malls), rural and urban districts, and island energy systems (trains, ships, and aircrafts).".

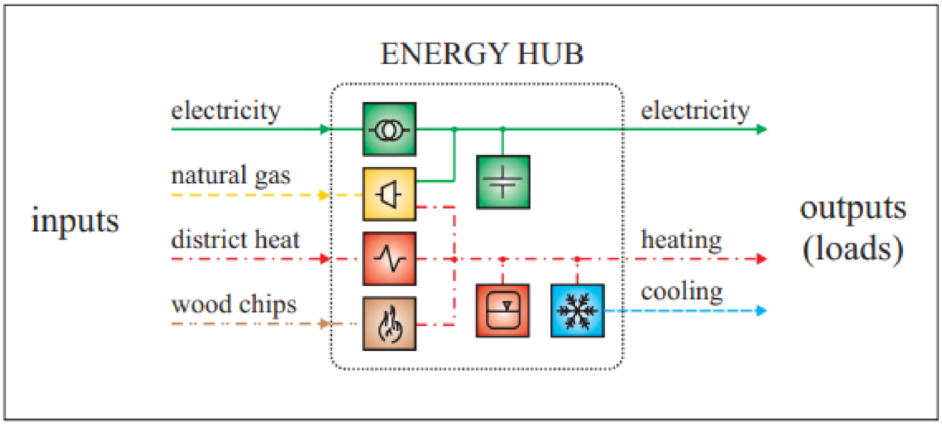

Figure 2.1: Example of an energy hub that contains a transformer, micro turbine, heat exchanger, furnace, absorption cooler, battery, and hot water storage.

In Figure 2.1, the first example of an energy hub is illustrated. In this example, multiple different technologies are present, including a battery. In this research, storage is already one of the key points of operating the energy hub, mainly due to the need for a flexibility point (charge and discharge) for the correct and efficient integration of renewable energy sources (Andersson et al., 2007).

Since then, the energy hub concept has evolved significantly. With the introduction of new promising technologies in the energy system, the concept had to adapt. Hydrogen production and storage are slowly becoming very important in energy hubs as their popularity increases and use-cases appear (Massaro et al., 2024). Integration with electrical mobility also became more common, raising the possibility of the use of the batteries of these vehicles for grid purposes when they are not being used (Hecht et al., 2023). Nonetheless, all of these applications are still recent and in the testing stage; the traditional type of energy hub is therefore still the most common application observed.

In spite of this, the most common descriptions in literature all reference the following topics (Mohammadi et al., 2017):

- **Energy Production:** The most straightforward system of an energy hub. It entails the production of energy required by consumers. This system can take multiple shapes, but is usually based on some form of renewable energy source, with solar and wind as the most common.
- **Energy Management System:** A digital platform that manages the collaboration between all other systems. This system determines how much and when energy is delivered to each partner, ensuring all demands are met (O'Dwyer et al., 2020). This system is also responsible for managing the connection of the energy hub to the grid, enabling some energy trading business models. This system also tracks the impact of the energy hub on the players involved, from energy used to emissions resulting from such usage.
- **Energy Distribution:** Usually performed by the grid operator (Stedin and Alliander in the Netherlands, for example); ensures that produced energy reaches the final consumer. One of the most difficult parts

of creating energy hubs, due to the difficulties of coordinating stakeholders and connecting to the public grid. In some cases, an independent grid is created to connect the hub (Bastianel et al., 2025).

- **Energy Storage System:** The focus of this research. Batteries are used to ensure that the fluctuations in supply and demand can be covered and that the surplus from energy production is not wasted or places an extra burden on the grid (Mohammadi-Ivatloo & Jabari, 2018). These batteries can take various shapes and forms, but they are usually one of the most expensive parts of the whole system.

To summarize, an energy hub is a multi-vector energy node that optimizes and integrates different forms of energy infrastructure, such as energy production and storage. It works as an energy router that transforms and transports energy as needed in a decentralized manner. Energy hubs provide a more flexible, reliable, and efficient energy system.

2.3. Energy hubs orchestration

There is currently a substantial amount of research on how to operationalize these kinds of hubs. Most of the research focuses on the technical difficulties that surround building such solutions (Maroufmashat et al., 2019), leaving a significant gap for further exploration of the business side of the application of energy hubs. Although energy hubs are a recent concept, created to mitigate the struggles created by the severely overwhelmed energy system in place, they are growing in popularity significantly (Mohammadi et al., 2017).

With the growing adoption of this application, there is also an increasing interest in how to make it economically efficient, not only sustainable. Therefore, business models for these applications have been getting increased attention in the literature. These business models are usually complex and incorporate different revenue streams and stakeholders, requiring astonishing levels of coordination and cooperation. Below, the most prominent models are explained.

According to Sousa et al., 2019, there are three main models for energy hubs, taking into consideration energy markets and peer-to-peer (P2P) schemes of energy trading. These models are:

- **Consumer to consumer (C2C):** The players involved in the energy hub can trade energy among each other; they can trade electricity produced locally independently and make the hub independent from the traditional energy system.
- **Business to consumer (B2C):** The most traditional way of selling energy, where a player retails its product directly to the consumers. Models like Energy-as-a-service (EaaS) are typical revenue models from this kind of energy hub model (Mohammadi-Ivatloo & Jabari, 2018).
- **Business to business (B2B):** In this case, different commercial entities exchange energy between each other, and profit from each other's different demands, and different energy consumption schedules. The Port of Rotterdam is a good example of this, by integrating renewable energy production and distribution for the industry players hosted there (Geidl et al., 2007).

2.4. Types of energy hubs

Depending on its scale, ownership, and characteristics, energy hubs can assume different shapes and forms. Royal Haskoning has defined four main types of energy hubs; these will be treated in this research and are summarized as follows (Royal HaskoningDHV, 2024).

- **Industrial estate hubs:** These hubs are located in industrial parks where there are multiple large energy consumers. They are designed taking into consideration the significant demands of these players. They usually accommodate local production of energy or leverage waste energy from the industrial installation. In these hubs, the various stakeholders work together in order to be more energy efficient. The demand is usually coordinated in a sense that there is always a player benefiting from the waste energy from other stakeholders. These systems help alleviate stress from the public grid and create a more reliable source of energy for the industry. These hubs are common in power-hungry industries, such as high-tech business parks, ports, and industry clusters (Pfenninger et al., 2014).
- **Large single-user hubs:** The goal of this kind of energy hub is to balance and optimize the energy consumption of a big player in the industry. This type of energy hub is commonly used by factories, data centers, and hospitals. These power-hungry facilities usually benefit thoroughly from having a mechanism of trading with energy prices, and a flexibility mechanism for local energy production

(Merei et al., 2016). These places also need a secure mechanism that can ensure a constant availability of energy. With that in mind, having a hub that can decentralize the production of storage is a good way of ensuring the safety of supply.

- **Built environment hubs:** These hubs coordinate residential and commercial buildings in a certain area. By coupling the supply and demand of these buildings, the system can provide a more efficient system and diminish the costs of hardware, while opening a gap for the use of higher-performance technologies. It is also a way of providing a major benefit to the grid from that area, while still integrating renewable sources of energy. A hub like this might look like the connection of multiple solar panels in multiple buildings, a communal battery, and even possibly a district heating system. These hubs are often mentioned as "energy communities", Figure 2.2 highlights these hubs around Europe.

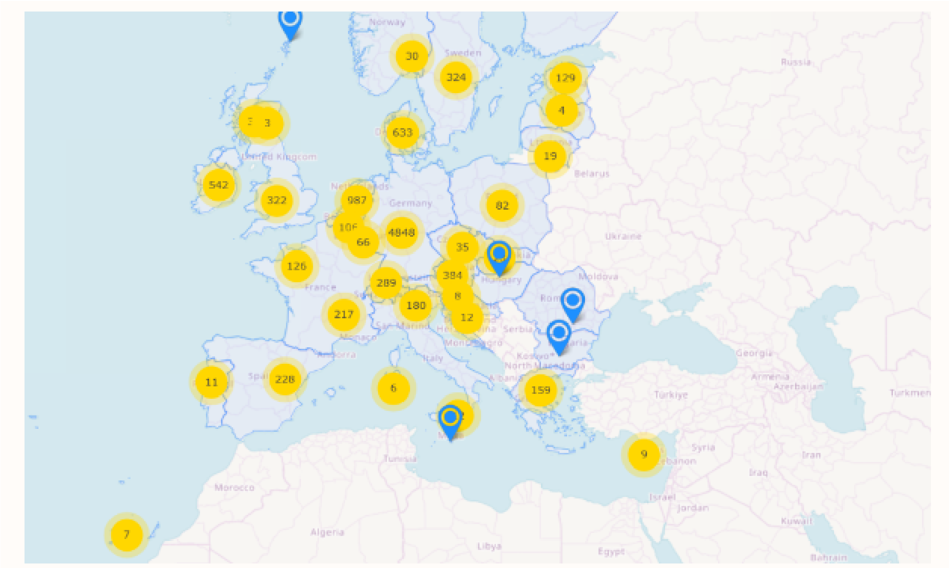

Figure 2.2: Energy communities in Europe

- **Hubs for sustainable mobility:** These hubs mainly focus on the infrastructure needed for green mobility. In these kinds of hubs, the central focus is enabling fast charging, hydrogen storage and production, and energy availability. These hubs usually have a BESS to make sure that there is enough power to suppress the peaks caused by fast charging (Petit & Vafeas, 2022). The main point of constructing these hubs is to make sure that the peaks of energy caused by the infrastructure needed for EVs do not impact the grid, while ensuring the availability of power and charging stations for electric mobility.

2.5. Battery storage technologies in energy hubs

Batteries have been around for a rather long time now; therefore, numerous experiments were made, and numerous types of batteries emerged from them. Currently, there are multiple types of batteries, with different chemistries and applications. This section will cover the most commonly used types for energy hubs and the most promising types of batteries in development that might change the panorama. This is important to understand the current state of the battery storage technologies industry, and how it connects with energy hubs.

2.5.1. State-of-the-art battery

Lithium-Ion is the most used type of battery in the world, and also the main type of battery used in an energy hub (International Energy Agency, 2023b). Lithium-ion batteries are characterized by their high performance metrics when compared to the rest of the industry. They have a high round-trip efficiency (9̃0%), high energy density, and high power density (Schimpe et al., 2018). Due to their usage in multiple industries, their prices are lowering fast, enabling new applications and wider distribution of this technology (BloombergNEF, 2023). Energy hubs employ what is traditionally called a stationary battery energy storage system (BESS) made out of lithium (Zakeri & Syri, 2015). For community hubs, a smaller scale battery is applied, with capacity in the order of 0,5-5 MWh is commonly found on these hubs (Clément et al., 2021). In industrial hubs, a bigger battery is applied, the capacity is usually in the tens of MWh, due to their demand for a higher capacity (Vasconcelos et al., 2023).

2.5.2. New technologies

As it was stated before, although Lithium-Ion is the most common type of battery to be applied in this context, there are upcoming technologies that provide some advantages in fields where Lithium-Ion technologies are not that strong (Kebede et al., 2022). Furthermore, the availability of lithium concerns the battery industry, driving the move to other technologies that can provide the same value and be more sustainable (Lebrouhi et al., 2022).

Flow batteries are the main promising solution used for longer-term storage. This type of battery allows storage up to 10 hours and a virtually infinite number of cycles. Although they are heavier and have less power density than Lithium-Ion, the advantages highlighted before can prove useful for renewable energy production buffering, and other use cases that require a lot of cycles to be made (Alotto et al., 2014).

Other types of batteries might also see niche uses, such as Sodium-sulfur batteries. There is also a huge push from the industry in creating Sodium-Ion batteries, which could be a replacement for Lithium-ion, overcoming the supply issue with lithium, but although the movement is fast, a commercially available technology is still far away (Pandey et al., 2025).

2.6. Business challenges of battery storage technologies

To better understand how the business models of batteries can take shape under energy hubs, it is important to understand what are the current challenges of battery storage technologies' business models. This section aims to summarize some of those challenges that were found when applying batteries in general, with the objective of comparing them with the drivers and barriers identified during the interview process.

- **High upfront costs:** Battery storage technologies require a significant initial investment (Hossain et al., 2020). Although prices of batteries are dropping, it is still very expensive to acquire a battery (Hu et al., 2021). Furthermore, investment is very difficult to get. The technology is still rather recent; therefore, most of the possible investors are very skeptical about applying their capital (EUROBAT Association, 2016). These investors require long-term contracts that can provide certainties in terms of outcomes, jeopardizing business models based on market trading, that suffer from high uncertainty (Hu et al., 2021).
- **Market uncertainty:** A lot of battery projects rely on market trading, and these markets can be unpredictable. For example, the frequency market relies heavily on frequency unbalance events, and with the application of more batteries and other flexibility assets, those events become less and less common, undermining the business case of trading in this market (Hu et al., 2021). This uncertainty makes it complicated to create a business model that can be reliable for 10-15 years, and, as it was already stated, to attract investment (EUROBAT Association, 2016).
- **Lifetime and degradation:** Chemical batteries, such as Lithium-Ion, suffer significant degradation with usage and time (Hossain et al., 2020). Usually, a battery can stay in peak performance for about 10-15 years, which is significantly less than the rest of the infrastructure that it connects with. Because of them, replacement and refurbishment costs have to be taken into consideration when planning the business model for said battery (Hu et al., 2021). Furthermore, in a value stacking context, where there might be a push to use the battery more aggressively in order to maximize profit, the consequences in terms of degradation can severely diminish the lifetime of the asset.
- **Regulatory and administrative challenges:** Batteries still face a lot of regulatory hurdles. Due to their nature, most of the regulatory frameworks in place struggle to define batteries. These batteries can provide and take electricity from the grid, and are one of the few technologies that are able to do both, making it harder to define what is their role in the system. This often culminates in the possibility of double charging of tariffs, with batteries being charged both for charging and discharging (EUROBAT Association, 2016).

3 Literature Review

In this section, the theoretical foundation for this research is established. A structured approach to the literature was taken, but it is noticeable a lack of literature regarding the integration of batteries in energy hubs from a business perspective. There is already very thorough research made in terms of the technical implications of energy hubs and of battery storage technologies, even considering how recent this application is, which highlights the possible gap for research regarding the organizational perspective.

This section aims to summarize the literature available and explain what is the gap that led to this research. In order to do this, the chapter is organized in a way that there is a clear flow in terms of how this application and technology connect, the business models studied for both, and finally, how they intersect. Finally, the information is summarized and synthesized, leading to the research gap identified.

3.1. Battery storage technologies applied to energy hubs

Batteries are a common part of modern energy hubs (Mohammadi-Ivatloo & Jabari, 2018). This application of decentralized energy systems requires a huge amount of flexibility and independence; therefore, a BESS is a common technology to be found in the heart of an energy hub. By including batteries in this setting, energy hubs are capable of dealing with peaks in demand, the volatility of renewable energy production, and the current state of distress of the grid. As seen before, these batteries can differ in scale, configuration, and strategy depending on the application, ranging from small neighborhood applications to huge multiple megawatt industrial applications. In this section, the main reasons for the integration of these batteries in energy hubs will be studied.

Peak shaving

Peak shaving is one of the critical functions of batteries in energy hubs. The goal of this function is to reduce the amount of energy taken from the grid in hours of peak demand, energy that is usually more expensive, by using energy that is locally stored. By discharging at peak demand moments, batteries can help flatten the demand curve and make the energy system more predictable and less reliant on centralized generation (Lund et al., 2015). In certain cases, this can also help foster self-consumption and local renewable energy production, enhancing the economic viability of both (Soares et al., 2023).

A notable example is the "Smart Storage Unit" implemented as part of the InterFlex project in the Netherlands. In Lelystad, at a substation, a 1MW/1MWh battery was implemented with the grid to do peak shaving and load balancing. According to the DSO operating this substation, the activities of the battery lead to an improvement in demand stability, and diminished the need for grid reinforcements (Consortium, 2019).

This function is also found in smaller-scale energy hubs. In the local energy hub of the Schoonship neighborhood in Amsterdam, every house is connected to a battery that smoothens the demand and contributes to renewable energy integration. Through the energy management system applied the inhabitants can enjoy cheaper energy due to the area's lower grid tariffs and the integration of self-production (Keirstead et al., 2012).

Batteries in energy hubs can contribute to peak shaving, contributing to economic optimization and reducing infrastructure stress on the grid.

Grid services

Storage can help with overall energy availability and shielding against possible grid congestion moments, ensuring grid stability and flexibility. Batteries can react in milliseconds, making them the ideal technology for frequency regulation and voltage control in areas with high renewable integration (Petit & Vafeas, 2022; Soares et al., 2023). In certain areas, energy hubs that have a BESS can act as an active grid node, smoothing the energy fluctuations on the grid. This kind of demand response is relevant to trade in energy markets (J. Li et al., 2019), and for making sure that the greenest type of energy is always obtained.

Projects like the FLEXITRANSTORE, an EU-funded initiative that took place in multiple European countries, with the goal of enhancing grid flexibility, placed large-sized batteries, around 1MW/2MWh batteries, at the intersection point between TSOs and DSOs, enabling the creation of an energy hub in this critical point of connection. These batteries became critical to manage the frequency, increased energy flows, and were able to better manage the integration of renewable sources and availability of energy (FLEXITRANSTORE Consortium, 2022). This project led to a 94.8% utilization of the battery for frequency response, yielding about 2000/month revenue (BRIDGE Initiative, 2023), corroborating the fact that batteries play a major role in grid stabilization and flexibility when integrated in the right place within an energy hub.

There are also cases where smaller-scale batteries were installed for similar purposes. In the Rijsenhout Neighborhood, a neighborhood battery was installed to store the surplus of solar energy produced by the houses. More than 35 households are connected to this 128kWh-capacity battery system promoted by Alliander. This battery, paired with an energy management system, helped manage the energy consumption of the neighborhood to make sure that the energy produced is always used. This significantly lowered the burden on the grid in that area. This system contributed to a saving of 25.000 just in grid reinforcement and stability costs, which is already a significant amount if the reduced energy prices from local production and consumption are not taken into consideration. This example helped set the tone for future similar applications in the Netherlands, showcasing the positive impact of the integration of energy hubs with BESS (NL4WorldBank, 2017).

Such cases highlight how embedded storage turns an energy hub into a source of grid services, effectively a flexibility provider that can stabilize the local grid and reduce strain on upstream infrastructure.

Renewable energy production integration

To better integrate renewable sources of energy, energy hubs must be ready to deal with the differences in demand peaks that can be observed in the typical green ways of energy production, like wind and solar. These energy sources usually only produce energy at certain moments of the day, meaning that it is most relevant to store some of this energy to use later. Sometimes this energy production goes above the requirements, needing storage to make sure that there are no losses. This process of dealing with demand peaks is commonly known as peak shaving (Baumgarte et al., 2020). The battery is used to store and release energy, balancing high and low demand periods. Ensuring the companies do not have to pay more when requiring more capacity outside of their agreements with the DSOs.

This was already tested in countries like Sweden, where a community energy hub using a Ferroamp system that allows for peak shaving. This system critically reduced local peak demand by charging and discharging automatically according to the status of the grid. This system led Ferroamp to develop their own products to manage an energy hub, connecting the grid, energy production, and the battery, ensuring the most effective energy management way (Ferroamp, 2021).

For example, the North Sea Port Vlissingen-Oost, where a battery was placed to ensure that the surplus of energy from renewable sources can be stored and used later (SemperPower, 2023). This project was one of the biggest battery storage projects in the Netherlands, with 30 MW of power and a capacity of 68 MWh. Located in a central part of the energy hub of the Port, Essent currently uses this system to offset the volatility of its wind production and ensure a stable supply of energy for its clients. With the help of this storage, this Port can produce almost 400 MW of energy annually, which could feed more than 200,000 households (North Sea Port, 2024).

3.2. Business models

To better understand what are the business models behind the application of battery storage technologies, it is important to understand what business models are and establish a common ground based on the literature.

In the context of energy hubs, there are numerous externalities that have to be analyzed and considered when looking at the business models of battery storage technologies. The way that business models interact with energy hubs is also explained.

3.2.1. What is a business model?

According to the literature, a business model describes how a certain firm creates, delivers, and captures value by the means of their activities, resources, partnerships, and customer relationships (Osterwalder & Pigneur, 2010; Teece, 2010). In other words, business models define who the customer is, what value is offered to the customer, and how this value is offered to said customer. Zott and Amit, 2010 emphasizes business model's systemic nature, explaining that the concept of business models transcends the firms boundaries and stating that value is created in collaboration with partners. This highlights the importance of the network as a key factor when talking about the value creation of a business model.

The centrality of value is often mentioned in business models literature. Focusing on innovation, Chesbrough and Rosenbloom, 2002 argues that connecting technological potential with the economic value is the key to a successful business model. In his view, for a technology to be successful, it requires a sound business model that can translate the groundbreaking nature of the finding into economic and commercial value. Without a business model that lays down the strategy for providing value, it is unlikely that a technology will perform up to the predicted standard.

Nowadays, business models are also treated as something dynamic. Previously, business models were looked at from the perspective of a static description of how firms operate and create value. With the development of the world, the literature now highlights business models as a flexible tool that innovates to cater to market developments and uncertainties.

In summary, these definitions converge into a value-centric view of business models (Chesbrough & Rosenbloom, 2002; Teece, 2010). For these researchers, business models explain how a certain business creates value for its customers and stakeholders. It is also clear that the concept of creating value extends further than from a single firm perspective. By creating a network of partners and suppliers, value is also to be considered from an ecosystem perspective, taking into consideration the co-creation of value (Zott & Amit, 2010). Business models can be seen as the blueprint for how an innovation or idea materializes into the creation of value, taking into consideration all the nuances around it.

3.2.2. Connection with energy hub and battery storage technologies business models

Currently, it is hard to define the business models of batteries in the different settings where they are applied. Batteries can provide value in different verticals, which increases the complexity of defining their business models. More so, it is also common for batteries to engage in more than one usage to create different types of value, which is called "value-stacking" (Teng & Strbac, 2016). This setting makes business models even harder to evaluate. Also, these different use cases fall over different regulatory frameworks and engage a different web of stakeholders, increasing even further the application and analysis of it.

Furthermore, it is noticeable that the role of battery business models is in this. Private firms' goal is to maximize profits, which means that there is an intrinsic interest in lowering the prices of energy. That is driven by the business model of the battery storage technology applied. If these business models are finely tuned, providing significant value to stakeholders, it is easier for the technology to be diffused. It will lead to more success cases, driving even more adoption and contributing to developments in the field. This impact is already being noted in the battery field from the development of EVs. The growth in sales and importance of this technology, due to a strong business model that creates a lot of value for customers, battery technologies development has skyrocketed, and is leading to a lot of improvements in the current technology.

3.3. Battery storage technologies business models

There are multiple ways that a battery can create value. Storing energy allows the user to have more flexibility in its usage, therefore being able to make the most out of energy when they truly need it. With that in mind, numerous different business models have been studied on how batteries can create the most value. When assessing business models for battery storage, there are numerous factors that must be taken into consideration. Currently, the most relevant ones revolve around the ownership model and the revenue model, mainly due to the multiple possible users of the system and the high price of it.

Business models for battery storage

Battery storage technologies are assets that can be used to provide value in multiple ways. Multiple business models build on these capabilities and create, deliver, and capture value in different ways. In the literature, there is already some research done in terms of what the main business models are when applying batteries outside of energy hubs. Therefore, it is important to understand what the current business models are and to connect them to the business models for battery storage technologies in energy hubs. Below, there is an explanation about the key business models of batteries and the value that they create for customers.

According to Li et al. (2019), battery storage business models can take different types or forms. Currently, the most common ones are:

- **Behind-the-meter solutions:** This solution is usually found in the consumer side of the spectrum. Business or private consumers acquire batteries to meet their energy demands and increase cost savings. This system usually happens in two main ways, either it is used for peak shaving purposes, where the battery steps in in moments of high peak of consumption to promote savings to the customer, or for management of self consumption, by controlling and managing energy produced locally (e.g. solar panels on the roof) deploying said energy in the moments were grid prices are the highest ensuring the best consumption profile possible and ensuring savings in terms of energy consumption (Coccato et al., 2025; Merei et al., 2016). Hoppmann et al., 2014 found that with declining battery costs, households in Germany could use batteries to boost PV self-consumption and potentially achieve payback under certain tariff structures. In community structures, this business model is also very common, in apartment complexes, for example, the presence of a battery with solar panels can lead to major savings for all of its inhabitants (Coccato et al., 2025; Sousa et al., 2019). Furthermore, in geographies like Europe, where taxes and electricity prices are a huge share of the costs of energy, a solution like this provides more and more savings to consumers (Hall & Roelich, 2016).
- **Energy arbitrage:** A trading strategy where the battery is charged during off-peak hours when the energy is cheaper, and then the energy is sold back to the grid for higher prices during high-demand hours. In Europe, due to the growing integration of renewable energy sources and grid instability, the profits from energy arbitrage are growing significantly. A well-placed battery with a good management system can leverage the "buy low, sell high" strategy to have easy profits (Baumgarte et al., 2020).
- **Frequency Regulation and Ancillary Services:** Providing fast-response grid support is one of the most relevant and profitable business models for batteries currently. Batteries react extremely quickly and precisely; therefore, they are the ideal component to be able to smooth out grid problems. Batteries can easily mitigate frequency deviations and participate in frequency containment reserve (FCR) markets that are currently extremely profitable (Petit & Vafeas, 2022; Teng & Strbac, 2016). In the EU, companies have earned very profitable contracts regarding the FCR market, making this case even more profitable than energy arbitrage, although very similar, this model focuses more on decongesting the grid than on smart energy usage. Overall, this business model centers on the battery as a reliability asset for the grid, paid for stabilizing services (Soares et al., 2023).
- **Storage-as-a-Service and Aggregation Models:** Instead of treating the battery as an asset that can be bought by a certain consumer, in this model, what is commercialized is the storage capacity for energy. In this business model, a third-party company owns and operates the hardware, and only provides the storage capacity to the customer (Coccato et al., 2025). Usually, they lease part of the capacity for different players, having them pay only smaller service fees and not having to do the full investment in a new battery. This model is especially interesting for allowing different stakeholders to use the battery in their own terms and for their own benefit, allowing other models already mentioned, such as the peak shaving and energy arbitrage (Lazzeroni et al., 2023; Sousa et al., 2019; Zhou et al., 2019).

In the table below, you can find a summary of the business models identified in the literature, alongside their most important features.

Table 3.1: Overview of battery storage technologies business models

Business Model	Value Proposition	Customer Segment	Revenue Mechanism	Key Partners / Actors
Behind-the-Meter (BTM)	Reduce energy costs via peak shaving and increased self-consumption	Households, SMEs, local communities	Energy bill savings through tariff avoidance	PV providers, energy service companies, DSOs
Energy Arbitrage	Profit from price differentials by buying low and selling high	Energy traders, aggregators, industrial users	Market price spread margins	Market operators, grid operators, EMS providers
Frequency Regulation / Ancillary Services	Provide fast-response grid services (e.g., frequency containment, voltage control)	TSOs, DSOs, system operators	Capacity payments, participation in ancillary services markets	Aggregators, battery operators, balancing authorities
Storage-as-a-Service / Aggregation	Enable access to battery services with no upfront cost through leasing or shared models	Industrial sites, municipalities, multi-tenant buildings	Service fees, leasing contracts, capacity-based billing	Third-party storage providers, aggregators, platform operators

It is still important to understand that these business models are often intertwined. A battery can usually act in many different fields at the same time, making it an even more interesting asset. The research made in this field points out a clear trend in this multi-use approach that helps improve the return and justify the difficult business cases usually presented. The stacking of different revenue streams aids in overcoming the initial investment, creating more confidence in investing in these kinds of technologies (Baumgarte et al., 2020). Nonetheless, this approach is still presented with two major bottlenecks. From a European perspective, the regulatory frameworks are not ready for a battery to operate in different markets, having some of those markets denying the participation of certain players due to their presence in other energy markets (Soares et al., 2023), which critically diminishes the returns that you can capture. Furthermore, technology-wise, the battery cannot perform two actions at the same time. So there is still a technological limit to a certain extent. Scientists and engineers are currently working on developing strategies to mitigate this problem, by, for example, having a battery management system that can change the market that the battery operates in an hourly basis, intelligently managing this can help with improving results and making sure that the battery is always working in the most profitable market.

3.3.1. Value creation on battery storage technologies business models

After understanding what are the main business models in place for battery storage technologies, it is important to understand in what verticals value is created, to later compare it with the fields where value is created in energy hubs. In this section, an overview of the main fields found in the literature where battery storage technologies can provide value is given to clarify what these value creation verticals are.

- **Reduction of electricity costs:** By providing activities like peak shaving and by optimizing the time of use, batteries are able to reduce the spending on energy costs. By reducing the exposure to demand changes, batteries are able to shield the consumer against energy price volatility and high grid tariffs (Kooshknow, 2022).
- **Integration of renewable energy:** As it was already stated, renewable energy production has an intermittent schedule, which contrasts with the demand profiles found in customers. Therefore, when applying a battery, this can be mitigated by storing the energy produced and releasing it when it is

most needed. This helps stabilize the energy system, whilst improving the business case for renewable energy production locally (Coccato et al., 2025; Soares et al., 2023).

- **Provision of backup power supply:** In case of shortages of energy, batteries can be an important asset to mitigate this problem. Numerous battery storage systems also have the function of working as a backup power system, which can actuate when there are outages (Brogan et al., 2020).
- **Generation of revenue streams:** By enabling the possibility of market trading, it means that batteries can also become a means of creating revenue. Operators of batteries can also use this to make a profit, instead of just cutting costs or enabling the introduction of other technology (Argiolas et al., 2022; Brogan et al., 2020).
- **Enhancement of grid stability and power quality:** Due to grid congestion and other grid instability issues, batteries are also a valuable asset in terms of enhancing the grid. Through frequency regulating services and voltage control, batteries can make sure that the grid is more resilient and can take some of the pressure placed on top of this infrastructure (Petit & Vafeas, 2022; Soares et al., 2023).

3.4. Literature gap

The existing literature offers a robust foundation for understanding both energy hubs and battery storage technologies, often analyzing their technical and operational aspects in depth. Energy hubs are conceptualized as multi-vector energy systems that optimize energy production and storage, acting as an interface between different energy infrastructures (Geidl et al., 2007; Mohammadi et al., 2017). They integrate components such as energy production (frequently renewable sources like solar and wind), a comprehensive Energy Management System that coordinates energy delivery and trading, and Energy Distribution mechanisms (Mohammadi et al., 2017). Energy Storage Systems, particularly batteries, are recognized as a key piece for operationalizing energy hubs, providing flexibility by managing demand peaks, volatile renewable energy production, and grid distress (Mohammadi-Ivatloo & Jabari, 2018). Energy hubs are ultimately designed to optimize energy consumption, shield consumers from shortages, and contribute to a more flexible, reliable, and efficient energy system. Their operational models vary from C2C and B2C to B2B exchanges (Sousa et al., 2019). Depending on their scale and characteristics, energy hubs can manifest as industrial estate hubs, large single-user hubs, built environment hubs (energy communities), or hubs for sustainable mobility (Royal HaskoningDHV, 2024).

Battery storage technologies, notably Lithium-Ion batteries, are currently the predominant choice in energy hubs due to their high-performance metrics (around 90% round-trip efficiency) and rapidly decreasing costs (International Energy Agency, 2023b). Capacities typically range from 0.5-5 MWh for community applications to tens of MWh for large industrial uses (Clément et al., 2021; Vasconcelos et al., 2023). Nonetheless, the deployment of batteries faces several challenges. These include high upfront costs, uncertain revenue streams, regulatory ambiguity (e.g., potential for double charging tariffs), market unpredictability (such as diminishing frequency unbalance events), and concerns regarding battery lifetime and degradation (Hossain et al., 2020; Hu et al., 2021). For standalone battery storage technologies, established business models include Behind-the-Meter solutions for cost reduction and self-consumption, energy arbitrage to profit from price differentials, frequency regulation and ancillary services for grid support, and Storage-as-a-Service and aggregation models that offer storage capacity without upfront investment (X. Li et al., 2019). Multi-service business models, which combine multiple revenue streams, are considered optimal for return on investment but demand significant stakeholder cooperation and navigate complex regulatory environments (Baumgarte et al., 2020). The value creation from batteries typically leads to reduction of electricity costs, integration of renewable energy, provision of backup power supply, generation of revenue streams, and enhancement of grid stability (Brogan et al., 2020; Coccato et al., 2025; Kooshknow, 2022; Petit & Vafeas, 2022; Soares et al., 2023). However, academic analysis often overlooks the non-monetary benefits, such as contributions to sustainability and grid stability, when evaluating these business models.

While the technical and operational dimensions of both battery storage technologies and energy hubs have been extensively investigated, a significant gap persists in the academic understanding of their integrated business models, value propositions, and economic viability when these technologies are combined within decentralized energy systems (Maroufmashat et al., 2019).

According to X. Li et al., 2019, current business models of battery storage do not take into consideration their value creation outside of the monetary value, opening the possibility of batteries having a perceived value below their actual value. Research still struggles to frame the impact of external factors, such as the increased use of green energy and the decongestion of the grid in the business model of the technology, which might be a point to explore in the future with the collaboration of energy hubs. This opens the possibility for further research and further development of the current business models in place.

Regarding energy hubs, the same is verified; the business model exploration is minimal compared to the technical exploration, showcasing that there is a clear path to follow to make this kind of application of technology even more attractive. Quantifying the impact on grid congestion and the increase in consumption of green energy sources will most likely contribute to deepening the viability of energy hubs' business models, and positively contribute to other business models attached, such as batteries.

Both battery storage technologies and energy hubs have been thoroughly studied from a technical and operational perspective, but there is still a significant lack of information regarding their business model, their value proposition, and economic viability when combined. During the analysis of the literature, the findings regarding the impact of energy hubs on battery storage were practically non-existent, confirming the assumption that there is a gap in terms of research in this field.

4
Methodology

In this chapter, the methodology behind this study will be explained. An outline of the backbone of the research design, the data collection, sample strategy, interview process, and data analysis will be explained, in the context of finding out how business models of battery storage technologies work in energy hubs.

4.1. Research design

The objective of this research is to find out how business models of battery technologies are shaped when applied to energy hubs; for that to be possible, information from key players in the industry has to be accessed. According to the literature, currently, to operationalize an energy hub, the cooperation of multiple entities is needed, and to create stable business models for battery storage, usually a multi-service approach is used (X. Li et al., 2019), which requires the involvement of multiple entities too.

To adhere to these specifications, a qualitative approach is the most adequate for this research. By employing semi-structured interviews with key professionals within the energy hub ecosystem, this study aims to validate and expand on current literature about battery storage business models and position them in the context of energy hubs. The information gathered in this interview process will then be analyzed following the thematic analysis methodology by Gioia et al., 2013. From the thematic analysis, a framework will be constructed that can summarize the context of battery storage business models in energy hubs.

4.2. Sample strategy

To achieve a satisfactory result in this research, difficult-to-access information had to be tapped to define trends in battery storage technologies usage. This information will be key to coming up with a well-supported framework that can explain battery storage technologies' business models in energy hubs. The approach chosen to ensure success was to conduct semi-structured interviews with industry experts, who are directly involved in the creation and application of energy, and have a deep understanding of the state-of-the-art business models applied to battery storage technologies in this setting.

To build the best possible sample, this research will follow a non-probability judgmental sample approach, where interviewees will be picked by the researcher according to relevance to the study (Patton, 2015). This type of approach, often used in qualitative research to gain in-depth information rather than statistical generalization (Creswell & Creswell, 2018), will ensure that there is a wide range of interviewees, who can cover the web of stakeholders in an energy hub. To make sure that every field is covered, the following map was constructed to give a holistic view of the stakeholders involved, ensuring that the results obtained can be as meaningful as possible.

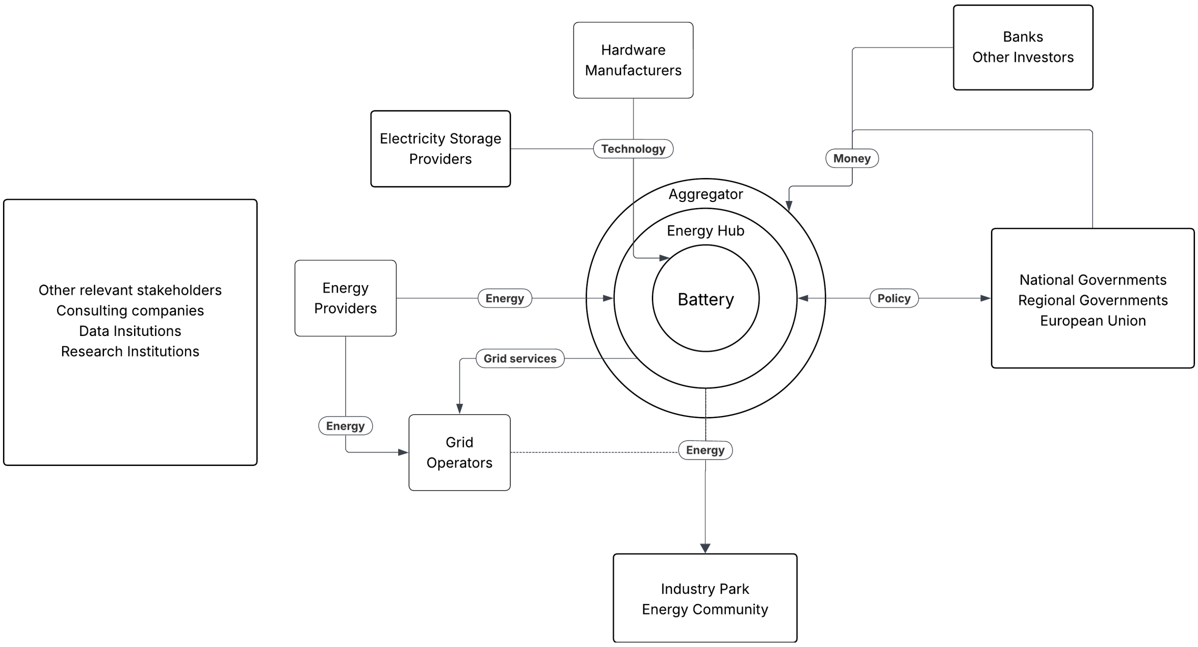

Figure 4.1: Energy hub with battery storage technology stakeholder map

Figure 4.1 summarizes the stakeholders involved in the creation of an energy hub. In the center of this map, there is a circle that highlights the core of this research. In this circle, we can observe three different layers, from the inside to the outside: "Battery", "Energy Hub", and "Aggregator". This builds up from the literature analyzed, where the battery storage technology is applied inside the energy hub, which is managed by an aggregator company or institution that takes care of the logistics of operation of the energy hub. The aggregators are core professionals for this research due to their privileged spot, where they interact with every stakeholder and usually, in collaboration with the customer, come up with the business model for the battery storage technology.

Furthermore, there are five core factors connected to energy hubs in the center: "Technology", "Money", "Policy", "Energy", and "Grid services". These factors are key to defining the relevant stakeholders that need to be interviewed to come up with in-depth results. The importance, and what information can be acquired from the stakeholders from each factor, is highlighted below:

- **Technology:** The characteristics of batteries strongly relate to the possible business models that they can support. Electricity storage providers are key to understanding how the characteristics of the battery storage technologies impact the business models chosen. Also, other hardware providers that complete the technical needs of energy hubs play a crucial role in integrating battery storage technologies with renewable energy production and other technologies; therefore, this can lead to relevant findings.
- **Money:** Governments, banks, and other private investors are key to the implementation of battery storage technologies in energy hubs by enabling access to capital. From these stakeholders, it is expected to get a structured view on the reasons why investment in these applications can be beneficial, leading to important conclusions on how to enhance the profitability of these technologies. Furthermore, investors can give key insights regarding the risks of these business models and the reasons why they might choose to invest in some projects and not in others.
- **Policy:** Regarding policy, the main stakeholders involved are governments. The connection to the national grid always raises constraints; therefore, the government has clear rules on what can or cannot be done in this field. This regulation has a clear impact on the business models of battery storage technologies in energy hubs. It is of extreme importance to have the perspective of this stakeholder to define these business models and the context around them.
- **Energy:** Energy is the core commodity traded within the system. It is important for the research to have the perspective of the energy providers in terms of how energy hubs integrate with their systems,

and how battery storage can create value for them. Also, industry parks and energy communities, the most common customers of these business models, are important to take into consideration, even though, in this context, their impact is just establishing the need for battery storage technologies and energy hubs.

- **Grid services:** The grid plays a very important role when talking about energy hubs. The collaborative nature of this application leads to the need for a stable grid to transport energy among partners. Also, the mitigation of grid congestion and the positive value that energy hubs and battery storage technologies create for the grid cannot be disregarded. Talking to grid operators is key to defining the business models of battery storage technologies in energy hubs.

To ensure the validity of the findings, the interviewees were picked regarding their role in the map of Figure 4.1. Below, Table 4.1 provides an overview of the professionals interviewed for this research. To clearly depict the ecosystem in the research, at least one interviewee was picked for each type of stakeholder identified. 20 professionals from the field were interviewed for this study. In said table, it is also possible to find a code associated with each interview for a better understanding of the results.

Type of company	**Description**	**Role of the interviewees**
Aggregator	Companies that act as the orchestrator of the energy hub or as external consultants to facilitate their creation	Energy hub consultant (AG1, AG2, AG3), Product specialist (AG4), Project manager (AG5), Program manager (AG6)
Hardware Provider	Company that provides technical hardware to the creation of energy hubs, including batteries	Vice president business and project development (HP1), Head of business development (HP2)
DSO	The local grid operator	Challenge officer (DSO1), Product owner energy hubs (DSO2)
Policy Maker	The national government	Senior policy advisor (PM1)
Bank	Financial institution that provides capital	Lead energy transition finance (BK1)
Energy Provider	Company that provides energy solutions for their customers, including batteries and energy hubs	Consultant (EP1)
Research Institution	Institutions that perform research on energy systems, and lead the public opinion with impactful publications and consultancy	Project manager (RI1), Program director (RI2), Strategic advisor (RI3), Business director (RI4), Principal business and commerce (RI5)
Asset Management	Investment manager for customers that want to invest in assets such as batteries	Director energy and sustainability (AM1)
Battery Storage Provider	Provider of battery storage solutions	CTO (BSP1)

Table 4.1: Overview of the interviewed companies

4.3. Data collection

The following section explains how the interview scripts were created, and what was the process used to achieve a dataset ready to be analyzed.

Three interview scripts were created based on the type of stakeholders found in the ecosystem. Below, there is an explanation of what these categories are, and in between brackets, at the end of each category, the stakeholders who were interviewed with the respective script.

- **Entrepreneurs and Business professionals:** professionals that are not directly related to the engineering part of energy hubs, but that are usually the champions in the application of new technologies. This group will be the most relevant in this research, due to their connection to the business models of battery storage technologies in energy hubs. This group of stakeholders is usually the one creating and evaluating the business models; therefore, the most well versed ones to answer questions regarding the state-of-the-art business models and future trends of the industry. (Aggregators, DSO, Energy providers, Research institutions, Asset management)
- **Technical professionals:** professionals who work in the technical part of creating and enabling energy hubs and/or with the technical challenges of implementing batteries (for example, engineers). The most relevant stakeholders to ask questions regarding the technical feasibility of the projects at hand, those who have a deep understanding of how the technical specifications of a project can influence its business models. (Hardware providers, Battery storage provider)
- **Enablers:** this group joins all of the stakeholders that have an indirect impact on energy hubs and on battery storage technologies, with special attention to investors, politicians, and policy makers. Although this group of individuals is not directly correlated to the creation of energy hubs, they play a crucial role in influencing the direction of battery storage technologies' business models in energy hubs. They set the policy standard for the future of these systems and provide the necessary investment to make them a reality. This leaves them in a position of power that it is important to take into consideration when coming up with assessing business models. (Policy Maker, Bank)

In order to make sure that the research achieves the suggested goal, the interview approach is based on the research questions in place:

- What are the drivers and barriers of the business models of battery storage technologies in energy hubs? (Sub-question 1)
- What are the business models of battery storage technologies in energy hubs? (Sub-question 2)
- How do the business models of battery storage technologies provide value when applied to energy hubs? (Sub-question 3)

By following this structure and combining it with the findings from the literature, a question bank was created to aggregate all the possible relevant questions that could be asked during the interview process. This question bank was divided according to the research question to better align with the research topic. These questions can be found in Appendix A. Later, these questions were used to come up with the three different, targeted scripts according to the stakeholder division provided before. The three scripts, available in Appendix B, were created based on the specifications of every stakeholder group, guaranteeing that the most relevant information was obtained during the interviews. The questions used are all from the previously formulated question bank, which allows the interviewees to remain aligned with the core of the research.

All the interviews were held during April and June 2025, online, using Microsoft Teams. The transcription was obtained directly from the software and cleaned for irrelevant passages, mistakes in transcription, and hesitation markers, in order to increase fluidity and help with the analysis. The interview process was approved by the TU Delft Human Research Ethics Committee (HREC), and the informed consent form distributed to all participants of the research can be found on Appendix C.

4.4. Data analysis

To study the business models that battery storage technologies can have in energy hubs, there is a need for a methodology that can fit within the multi-actor, complex system of energy hubs. Thematic analysis was chosen based on the good fit that this kind of analysis has with complex multi-actor systems (Eisenhardt & Graebner, 2007; Gehman et al., 2018). Furthermore, to clarify the process of the research, the analysis follows the process highlighted by Gioia et al., 2013 for qualitative data analysis.

The first stage of the research consisted of open coding the whole sample. This manual review process was taken to ensure that a first moment of familiarization with the sample happens, with the goal of having an idea about what the main topics addressed during the interview process are. From this initial coding, the first-order themes were then derived, in a way that they could give a solid overview of the entire sample. This section was crucial to outline what were the key excerpts of the interviews that could contribute to this study.

From these preliminary first-order categories, the second-order themes were created. These themes aggregated topics that mentioned similar fields, and could be grouped to drive deeper meaning from the answers of the participants. This process involved defining patterns and conceptual similarities between concepts, in order to establish a logic that can connect them in a larger section. Also, during this stage, the first-order themes were evaluated and often rephrased in order to better explain the excerpts that they were summarizing and better align with the research purpose. There was also a push for standardizing the codebook, in order for codes that mention the same phenomena to be mentioned in similar ways, enhancing their identifiably and facilitating their organization into a second-order theme.

To ensure the validity of the findings, the second-order categories identified were cross-referenced with the literature available about battery storage technologies, business models, and energy hubs. This step ensured that the findings are in accordance with what scholars have previously researched and enables the data to be filtered for any possible outliers or misunderstandings.

Finally, the second-order themes were grouped in aggregate dimensions, the highest level of abstractions, that can answer the sub-questions that structure this research. These aggregate dimensions are the key for creating the framework that concludes the research, and help with providing and high-level, comprehensive view of how business models of battery storage technologies work in energy hubs.

In the following chapter, the code tree will be presented and discussed based on the empirical findings of this data analysis process.

5

Results and Discussion

In this chapter, the results obtained from the analysis of the interviews will be presented and discussed. The following sections will be organized in the same order as the sub-questions defined at the beginning of the research. The analysis in place revealed four aggregate dimensions that interact with the sub-questions as follows:

- **Drivers** and **Barriers** - What are the drivers and barriers of the business models of battery storage technologies in energy hubs? (Sub-question 1)
- **Business models** - What are the business models of battery storage technologies in energy hubs? (Sub-question 2)
- **Value creation** - How do the business models of battery storage technologies create value when applied to energy hubs? (Sub-question 3)

These aggregate dimensions cover the most prominent topics discussed during the interviews. Based on the findings of this chapter, a framework that summarizes the business models of battery storage technologies was constructed. Although this framework is only introduced in the following chapter, during this chapter, it is already noticeable the connection between sections and how aggregate dimensions interact with each other based on the second-order themes identified.

Every section of this chapter is presented in the same structured approach. First, an introduction to the aggregate dimension will be done based on the findings, accompanied by the code tree that summarizes the findings from the code book, and the logic behind the second-order themes and the aggregate dimensions discovered. The second-order themes identified are then analyzed based on the empirical findings from the interviews and the literature available. These themes will be ordered based on the frequency with which they are mentioned in the code book, therefore based on their importance for the interviewees. These frequencies are available in Appendix D for further clarity. During this chapter, the codes given to the interviewees will be used to identify quotes for further context, and there will also be in-text references, using "[]", that identify the stakeholders that back certain statements. By also cross-referencing the findings with academic work, it is possible to understand if the results align with the current research from scholars, defining where the gaps are that should be filled and the conclusions of this research. This chapter aims to deepen the understanding of how business models of battery storage technologies are shaped in energy hubs.

5.1. Drivers

To understand the business models of battery storage technologies in energy hubs, it is important to define the main drivers for those business models. This section aims to summarize the findings of this research on what concerns the drivers for battery storage technologies' business models in energy hubs. The interviews revealed several important factors, such as collaboration, the demand for energy, and the need for clean energy sources.

In Figure 5.1, there is a summary of the findings of this section. The first column shows some examples of first-order categories regarding the drivers found. Those are then grouped in second-order themes, which will be analyzed in this section and connected to the literature. The last column of the diagram shows the aggregate dimension that is derived from the second-order themes.

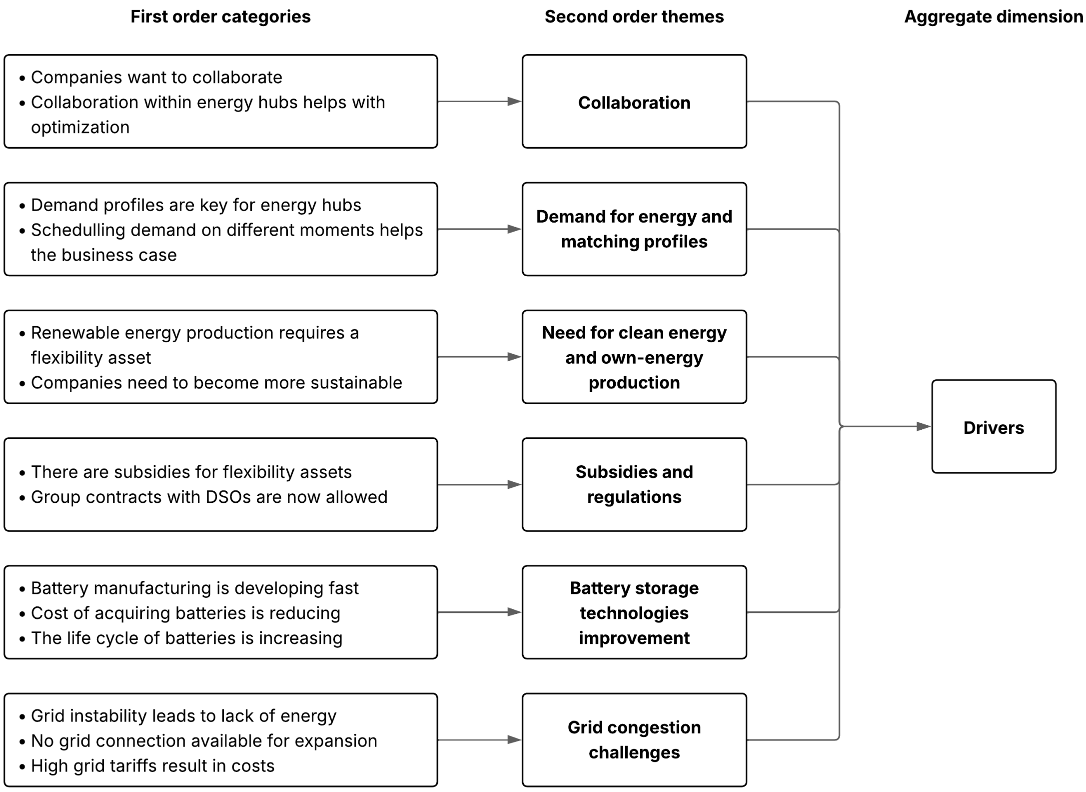

Figure 5.1: Data structure of the aggregate dimension "Drivers"

Collaboration

Collaboration was found in the research to be one of the critical parts of organizing energy hubs. The interviewees agreed with this to a certain degree and mentioned collaboration often as one of the key drivers for the implementation of batteries. For example, one of the interviewees stated:

> "*It can also be then a more interesting thing, and like an asset to invest in together, like as an energy hub, right? Not that one company buys a battery and then loans it or sells it out to other companies, but you buy it all together. That would make sense to me, and then you can really use it all together.*" (Energy hub consultant, Aggregator [AG1])

From the increase in availability of energy to co-owning assets, collaboration was presented as one of the core aspects to drive the business models of batteries in energy hubs, and one of the most important aspects in terms of how these business models are constructed. By being the vertical where energy hubs can provide the most impact, establishing these collaboration networks becomes key in creating a strong business model. According to the interviewees, collaboration brings significant added value by enabling optimized energy consumption [HP1] and battery cost sharing [AG3]. Collaboration was also the most mentioned driver, which positions it as a key driver in applying batteries in energy hubs and the formulation of their business models.

The literature highlights the importance of collaboration in energy hubs often, but it does not develop on what is the role of collaboration. That aligns with the answers from the stakeholders interviewed in this research. Nonetheless, the importance given by interviewees to this topic contrasts with the depth of the research about the outcomes of these collaborative networks. Often, collaboration is analyzed in the literature from the orchestration of an energy hub perspective, highlighting socio-economic topics that have to be taken into consideration when building a collaborative energy system (Lazzeroni et al., 2023; Mengelkamp et al., 2018). Also, some literature already references the need for collaboration to be taken into consideration when building business models in energy systems (Hall & Roelich, 2016), but it does not directly reference how this aligns with battery storage technologies' business models in energy hubs.

Demand for energy and matching profiles

Demand is one of the core drivers for battery storage technologies applied in energy hubs. According to the participants, the demand profiles of the companies involved in an energy hub are extremely important to make it happen and be profitable [RI2, RI3, BSP1]. For example, the following quote highlights the importance of demand profiles:

> "*You could still have a business case, but then it of course very much depends on the energy demand of the specific companies and industries that you have on that site. What is their profile?*" (Strategic advisor, Research Institution [RI3])

The ability to schedule the demand and use a battery to peak shave when demand is too high has been deemed one of the most important usages of the battery [AG2, DSO2]; therefore, having a demand profile that enables this kind of function is absolutely key in order to create a strong business model. In order to make the battery as efficient as possible, it is important that the energy needs of the participants in the hub match.

> "*The whole design of their energy system, both in terms of production and of their demand, and whether the demand of the different companies, different parties consuming energy, overlap or whether they are more or less complementary.*" (Strategic advisor, Research Institution [RI3])

Having a matching demand profile within an energy hub contributes to the creation of a sound business model for battery storage technologies and can drive the adoption of these technologies significantly.

Need for clean energy and own-energy production

Several interviewees mentioned the willingness of companies to electrify and become more sustainable as one of the key reasons for wanting to partake in an energy hub, and have a battery [AG3, HP2, DSO2, PM1]. One of the interviewees stated:

> "*What you see is that a lot of end users are increasing their electricity demand because they are phasing out fossil types of energy. That transition that is going on will actually uphold future developments for these companies, which will have quite a detrimental economic impact. So, if the company can't grow, then the competition in the market will be worse. Or they might even not be able to put in a new building.*" (Director energy and sustainability, Asset Management [AM1])

In this quote, an asset manager highlights the importance of adopting renewable sources of technologies and their challenges in terms of demand management. It further explains the consequences of it, as in the impairment of growth and the loss of competitiveness in their respective market. Quotes like this one clearly position the need for a solution to deal with the intermittency of renewable energy production, which often is one of the roles of battery storage technologies, as an important driver for their business models. This type of need drives the creation of business models that can cover this gap.

Due to the nature of renewable energy production, batteries are often used to provide flexibility and cover for the high and low production moments (Coccato et al., 2025; Soares et al., 2023). This has been thoroughly highlighted in the literature as one of the main drivers for the adoption of battery storage technologies. Storing energy in a battery and releasing it at a more profitable moment makes the ability to produce renewable energy significantly more powerful. This clearly aligns with the answers obtained during the interview process. The following quote confirms the importance of the need for clean energy and the self-production of renewable energy as a key driver for the business models of battery storage technologies.

> *Basically if we have intermittent renewables, batteries are an essential pillar of the infrastructure.* (CTO, Battery storage provider [BSP1])

Subsidies and Regulations

Governments (national and regional) were indicated as one of the core and most relevant stakeholders in the process of creating an energy hub and placing a battery, enhancing their role in the business models of these technologies [AG5, RI5, PM1]. For various reasons, such as promoting the growth of the economy [PM1] or even national energy system security [PM1], the government's role in managing the creation of energy hubs and the implementation of batteries was mentioned often by the participants. In this case it was pointed out that currently the governments are moving towards regulation that can structure the application of energy hubs and batteries, enabling contracts such as group capacity agreements [HP1], that enables the sharing of capacity among energy hub participants, which was valued by the interviewees, that mentioned it in quotes such as:

> "*But the thing is, you get this limit and everyone has this limit and back in the days, if you go over it, well, who cares? It wasn't a problem, but nowadays it is a problem. Everyone should stay underneath it. So everyone has their own individual limit. Now, with this group transport, we say no, not anymore, these individual limits, we stack them up.*" (Energy hub consultant, Aggregator [AG3])

In this regard, the group transport contract, GTO contract in the Netherlands, was one of the most touched topics [AG3, EP1], due to its role as the enabler of the creation of energy hubs, and therefore its extreme importance to drive the business models of batteries under these applications. Without mechanisms like the GTO contract energy hubs can become obsolete, further increasing their importance as a driver for the business models of batteries in the energy hub setting.

> "*They [government] will support this because they need more storage. If you look at the subsidy schemes in Europe and also the Netherlands, they are more and more opening up to give subsidies for the batteries, and they have already been doing so for a while.*" (Principal business and commerce, Research Institution, [RI5])

Furthermore, subsidies like the Flex-E and some other Europe-wide initiatives were addressed [RI2, AM1, EP1]. These show commitment from the government in these initiatives and facilitate the creation of profitable business models in the short term, pushing for a possible long-term profitable business model.

In the literature, governments are highlighted as a key stakeholder in the creation of energy hubs and on the regulation for adoption of battery storage technologies (International Renewable Energy Agency (IRENA), 2020). That aligns with the answers received throughout the interview process. Nonetheless, although it is clear the positioning of European governments in terms of renewing the energy system and enabling platform technologies for renewable energy production, from this interview process we can retrieve valuable examples of the move in that direction, such as the GTO contract and the Flex-E subsidy. Further proving the commitment of these institutions and positioning them as a driver for the business models of battery storage technologies in energy hubs.

Battery storage technologies improvement

Battery storage technologies are the core of this research, and throughout the interview process, the development of batteries was pointed out as one of the core drivers for their adoption. These technologies are becoming cheaper and more powerful, which contributes to their adoption and to the creation of more robust business models that can become more profitable in the long run [RI4, HP2, BSP1].

> "*And that spills over into the real economy on a tremendous scale because now we know so well how to make batteries at such a low cost that the function and role changes completely drastically and accelerates tremendously at the moment. And I think this is the development of which energy hubs can take profit of.*" (Program director, Research Institution [RI2])

In the literature, it is stated that battery storage technologies' business models struggle due to battery lifetime and degradation (Hu et al., 2021). This aligns with the responses obtained. Furthermore, the fact that interviewees are referencing that battery storage technologies are improving in quality means that these challenges might be overcome in the near future [AG5]. This optimistic perspective is a driver for the business models of battery storage technologies, enabling more use cases and eventually more profit.

Grid congestion challenges

Grid congestion problems [AG4], tariffs [HP1], and lack of connection available [BK1] have been highlighted by the interviewees as some of the reasons for the need for a solution. They reference these points as one of the main drivers for the implementation of batteries and creation of energy hubs [RI2, BSP1], due to the severe push from companies for more and affordable energy, and from other bigger players such as grid operators and governments, as a way of making the energy system more resilient. The need for a more reliable grid drives the implementation of flexibility assets, and in the case of energy hubs, battery storage technologies are one of the main methods of achieving this flexibility. This will flatten the demand curve of energy and further contribute to grid stability.

> "*So, everybody who says those energy hubs are a great idea, looks from a grid point of view.*" (Head of business development, Hardware Provider [HP2])

Congestion reduces the availability of energy, which concerns companies about the impacts that it might have in the long run if these events become more and more frequent. This contributes to making grid congestion one of the main drivers when building the business models of battery storage technologies. By shaping the business model, taking grid congestion into consideration, it is possible to guarantee that the battery will be available to provide backup power in curtailment events. In the literature, this driver is commonly referenced. The potential of batteries to deal with congestion problems is already established knowledge, and it is known for them to have a positive impact in this regard (Petit & Vafeas, 2022; Soares et al., 2023).

Discussion and Theoretical Context

The empirical findings in this section confirm several drivers already established in the literature. For instance, the need for more renewable energy generation and grid congestion-related constraints are commonly cited as primary motives for battery storage technologies adoption (Petit & Vafeas, 2022; Soares et al., 2023). Similarly, technological advancements that reduce cost and improve performance directly address limitations outlined in prior research on battery lifespan and economic feasibility (Coccato et al., 2025).

Nonetheless, two of the most important findings, according to the frequency of mentions, were found to be underdeveloped in the literature. Firstly, collaboration is framed by interviewees as not just a means of coordination but as a mechanism that enables value generation through shared ownership, flexible operation, and joint investment in battery storage technologies. While some literature touches on this from a socio-technical perspective (Lazzeroni et al., 2023), its specific impact on battery storage technology business model design in energy hubs remains underdeveloped. Second, the importance of matching demand profiles across stakeholders emerges as a critical enabler of energy hub performance. While often implicitly assumed in research, its role in improving the efficiency of energy hubs and driving battery storage technologies' business models is not explored.

Additional drivers, such as clean energy targets and growing electricity demand from electrification, are broadly consistent with EU energy transition policies and reinforce known rationales for battery use. Finally, government intervention through regulations (e.g., GTO contracts) and financial incentives (e.g., Flex-E subsidies) is seen by the interviewees as decisive for de-risking investments and making business models viable, in accordance with the literature (International Renewable Energy Agency (IRENA), 2020).

Furthermore, these drivers can be complex to understand. They exert influence on business models in different ways. Impacts can be felt regarding battery storage technologies, energy hubs, or the business models themselves. With that in mind, the following diagram was constructed, laying the groundwork for the framework that will be developed in the next chapter.

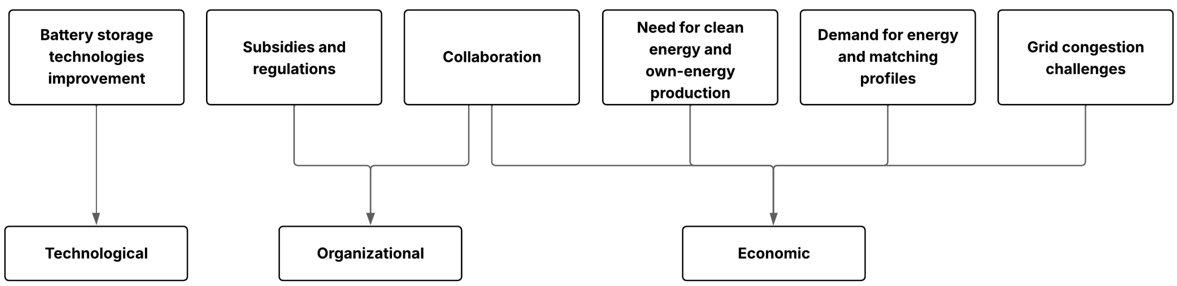

Figure 5.2: Drivers divided by vertical

In Figure 5.2, there are 3 verticals: Technological, Organizational, and Economic. They refer, respectively, to the dimensions aforementioned: battery storage technologies, energy hubs, and business models. With this division, it is expected to be easier to understand the influence of drivers in the business models adopted. Regarding "Technological" drivers, the only one identified is "Battery storage technologies improvement". Furthermore, "subsidies and regulations" and "Collaboration" are both "Organizational" drivers, by shaping the way energy hubs are created and organized. "Collaboration", due to its influence, was also noted as an Economic driver. As the rest of the "Economic" drivers, we can observe "Need for clean energy and own-energy consumption", "Demand for energy and matching profiles", and "Grid congestion challenges" due to their heavy influence on the profitability of a business model

It is also relevant to understand the importance of each one of the drivers found, considering the frequency with which they were mentioned in the code book. "Collaboration" was mentioned 52 times, making it the most important driver to take into consideration. Furthermore, "Demand for energy and matching profiles" and the "Need for clean energy and own-energy production" were the following most mentioned drivers, with 47 and 42 mentions, respectively. Then, "Subsidies and regulations" were mentioned 38 times, and finally, "Battery storage technologies improvement" (28) and "Grid congestion challenges" (26) were the least mentioned. From this information, we can assume that there are drivers that are more significant to interviewees, ultimately having more impact on the business model adopted. Figure D.1 in the Appendix D synthesizes this information.

In summary, these factors contribute directly to the decision of the business model that is to be applied when installing a battery storage technology in an energy hub. These drivers, also align with the value-centric business models research (Teece, 2010), by implying that the core factors that drive the adoption of certain business models for battery storage technologies are often tied to the future value that the technology can provide (for example the need for clean energy, leading to decarbonization).

5.2. Barriers

To understand the business models of battery storage technologies in energy hubs, it is not only important to explore the enabling factors but also to identify the main barriers that hinder their development and implementation. This section aims to summarize the key barriers uncovered during the research process that negatively impact the feasibility and scalability of these business models. While the interviews revealed significant potential for battery integration, they also pointed out several limitations, ranging from technical difficulties and governance issues to legal, market, and standardization constraints.

In Figure 5.3, a summary of the findings of this section is presented. The first column lists selected first-order categories that emerged from the interview data. These are then grouped into second-order themes that are further discussed in this section and connected to existing literature. The final column displays the aggregate dimension derived from each theme, reflecting the broader structural barriers faced by battery storage business models in energy hub contexts.

Technical and business challenges of energy hubs

Technically, energy hubs still need to develop to become a widely used application. There are still several unknowns regarding the technical difficulties of operating an energy hub, and some of these uncertainties are tied to the application of a battery. It was mentioned often that these technical challenges hinder the development of energy hubs as a scalable application [AG4, BSP1, RI2], which poses a clear challenge for the implementation of battery storage technologies and for their business models. This can be seen, for example, in the following quote:

> "*I think right now it's maybe even making it harder to capture value from a battery. Because it's such a complex task right now to create an energy hub.*" (Product owner energy hubs, DSO [DSO2])

Although the development of batteries is driving their adoption, the current state of the technology is still pointed out as one of the main barriers to the current business models [AG2, AG3]. The developments offer a positive scope to the future, but in the present, the participants of the research show some skepticism regarding technical considerations. Currently, battery life cycle is still too short [BSP1], there are too many energy losses [BSP1], and the cost is too high [DSO2], which makes the creation of a solid business model more difficult. The following quote highlights this problem:

> "*I am not sure about it yet. I think we're going to learn that in the coming months or years. Because right now, a battery is quite expensive. But the capacity is often quite low.*" (Product owner energy hubs, DSO [DSO2])

Other concepts, such as safety and space, were also mentioned as problematic when creating an energy hub [AG4, HP2, AM1]. Although less prominent during the interviews, they are still important to highlight,

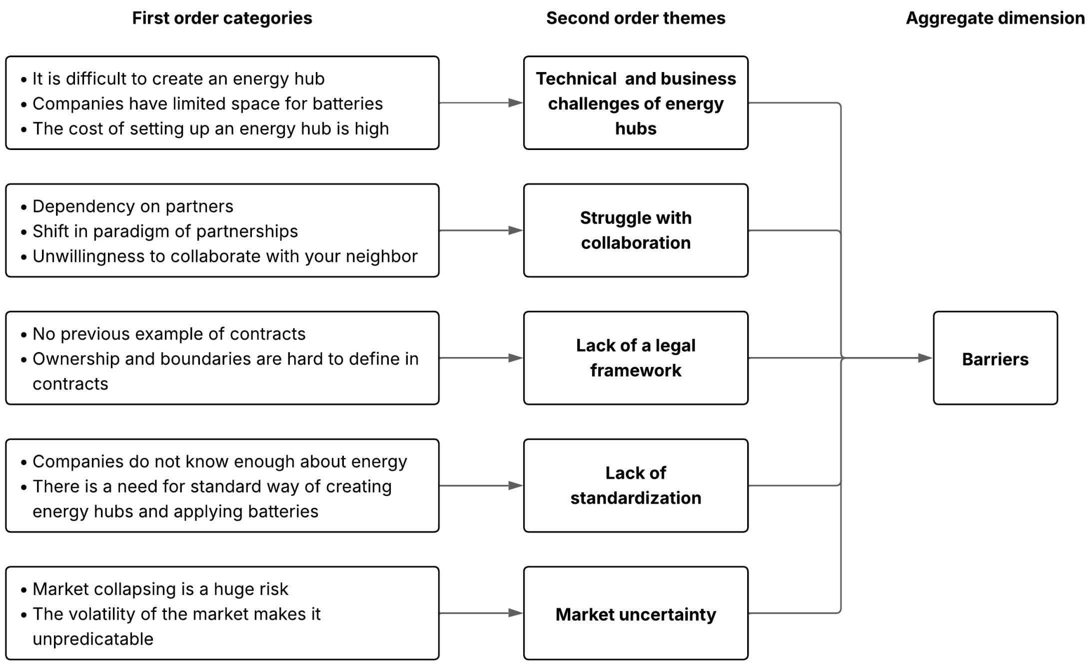

Figure 5.3: Data structure of the aggregate dimension "Barriers"

because they are still challenging factors to consider for the business models of battery storage technologies in energy hubs.

Also, literature covers these challenges. Lazzeroni et al., 2023 highlights in its research the socio-economic challenges of stakeholder collaboration in the creation of energy hubs, showcasing how it limits scalability and efficiency. From a technical standpoint, scholars also mention in their research mention in their research the struggles with battery storage technologies, costs, lifespan, and space and safety are commonly addressed when talking about the challenges of battery business models (Coccato et al., 2025).

Struggle with collaboration

Although collaboration is seen as one of the biggest benefits of organizing as an energy hub, it is also sometimes problematic. The interviewees pointed out collaboration as something that, depending on the situation, discourages players from adopting a battery in the context of energy hubs [AG1, DSO1, EP1]. It is stated during the interviews that companies are not used to collaborating, and usually do not look at their neighbor to collaborate in terms of energy consumption [HP2]. Throughout the interview process, it was made clear by the interviewees that there is still a long way to go to ensure that the collaboration when creating an energy hub still needs improvement, and it is still a challenge when applying batteries [DSO2, RI5]. The following quote highlights the struggle with the rotation of companies in a hub, for example:

> "*So in real life, all these things just take much longer. There are also stories like, you know, in let's say, within one or two years, some companies come and some companies go. So you need to get those aligned again. So just from a governance, from an organizational perspective, it's very difficult.*"
> (Energy hub consultant, Aggregator [AG3])

In the literature, it is stated that extreme coordination is needed to make sure that every stakeholder is satisfied with the outcomes of the project (Lazzeroni et al., 2023), making the projects more time-consuming and less attractive. Furthermore, companies are not used to collaborating in these sorts of fields, leading to some skepticism and trust issues on working with the company next door (Hall & Roelich, 2016). This aligns with the perspectives shown by the interviewees.

Lack of a legal framework

Cooperation also has to be standardized, and the number one tool for this is contracts. But according to the participants of this research, there is still a lack of a legal framework that can define boundaries in collaboration [RI1, BSP1]. They pointed out that there is still a clear need for a way of overcoming the barrier of contracts, the need for a document that can answer questions such as: "Who owns the asset?", "How much energy can you consume? And when?" and "Can you expand your consumption?" were mentioned often [HP2, RI2]. The CTO of a battery storage provider said:

> "*From a technology point of view, we already have everything. So technology is not the main issue, really, at the moment it is about legal barriers and about having a kind of standard contract and these kinds of things to make it easy.*" (CTO, Battery Storage Provider [BSP1])

There are still significant legal barriers in place in terms of asset sharing and implementation of energy hubs that undermine the business models of batteries under these circumstances. There is also a gap in the literature regarding this topic; scholars have not conducted research about it, demonstrating a clear gap that has to be covered to allow for better battery storage technologies business models.

Lack of standardization

Standardization is the number one way of making an application scalable. With energy hubs being a recent method of applying certain technology, there is no standardized way of doing it yet, which makes technical integration and contractual procedures more time-consuming and resource-intensive [DSO2, BSP1]. Also, the variable characteristics and demands of the stakeholders involved in an energy hub are difficult to assess, which contributes to more difficulties in terms of creating a standard for the application of batteries [RI1, EP1]. A Project Manager from a DSO said:

> "*Integration is still a big issue because there is no real standardization of how batteries communicate with each other, with solar panels, or with energy management systems. So, I think if there is a rise in need for collaboration will also trigger or benefit the development of standards, standardization for batteries, or in a bigger picture, just communication between assets that play a role in energy hubs.*" (Product owner energy hubs, DSO [DSO2])

Interviewees have pointed out this topic to be one of the core areas that need solving to mass apply batteries in these setting and as one of the most influential challenges for their business models, they ask for a standardized way of applying energy hubs and batteries in order of creating a way of comparing out comes to better pinpoint the right business case [DSO1, RI4, PM1].

In contrast with most of the barriers presented, the lack of standardization appears as an outlier due to its lack of connection to the literature. Scholars only mention briefly the lack of standards for the interoperability of technologies and for the control architecture of the energy system (International Renewable Energy Agency (IRENA), 2020; Zhou et al., 2019), not approaching it from a contractual and business perspective.

Market uncertainty

One of the problems highlighted by the interviewees was the fact that the market is still severely unpredictable [EP1]. That brings concerns regarding the longevity of the technology, which damages the business model. The fact that congestion is not predictable and might be solved one day diminishes the possibility of some business cases that might be anchored in solving this problem [AG1]. The interviewees expressed concerns about the overall volatility of the energy field and the reliance on external factors. That can be seen in quotes like the following:

> "*The biggest risk right now, I think, is that the market collapsing, which is what you're already seeing a little bit. So if you buy a battery now with the idea, I'm going to earn money, I'm going to make back my investment in five, six years, and that market collapses in three years.*" (Energy hub consultant, Aggregator [AG1])

Also, it was pointed out that the implementation of more batteries can undermine the business case of the technology. The diminishing returns seen for the application of more storage technologies contribute to the skepticism in investing in these technologies and committing to the business models [RI1, DSO1, PM1]. Furthermore, the implementation of some other technologies also impacts the business case of batteries. For example, the following quote explains the impact of applying nuclear energy to the grid.

> "*If you have these SMRs, small modular reactors, then I think the business case for these energy hubs with battery is not really required. Maybe a small battery for backup for the automation control system.*" (VP business and project development, Hardware Provider [HP1])

Furthermore, other sources and types of energy, such as Nuclear and Heat, do not have the same reliance on batteries as electricity. There is some movement in this regard, and the interviewees pointed out that other methods of storage could be a threat to the business models of batteries [HP1].

Discussion and Theoretical Context

This study identifies five key barriers to the implementation of battery storage technologies' business models in energy hubs: technical and business challenges of energy hubs, struggle with collaboration, lack of a legal framework, and market uncertainty. These findings show that while the technological potential of battery storage technologies in energy hubs is recognized, there are still barriers to their business models that significantly limit their adoption and scalability.

Technical and organizational complexity remains a major challenge, as energy hubs require high coordination, integration of diverse technologies, and management of intermittent demand patterns. These concerns are also mentioned in the literature on energy hub design and battery business models (Coccato et al., 2025; Lazzeroni et al., 2023). Similarly, collaboration-related issues such as stakeholder turnover and lack of trust are well documented in the literature on innovation ecosystems (Hall & Roelich, 2016), reinforcing the observed difficulties in governance and stakeholder alignment. These issues were highlighted by the interviewees as core barriers to the development of strong business models for battery storage technologies.

However, two barriers emerge as underexplored in academic literature: the lack of standardization and a legal framework. While practitioners consistently identify the absence of a shared contract framework as a major bottleneck, existing studies only touch briefly on these issues (International Renewable Energy Agency (IRENA), 2020; Zhou et al., 2019). This reveals an important gap for future research, especially in terms of defining legal ownership, energy sharing boundaries, and interoperable standards for battery storage technologies on energy hubs. This has a significant impact on how the business models are shaped and perceived in this setting.

Lastly, market uncertainty was frequently cited as a barrier to investment. The volatility of energy prices, the ever-changing regulatory environment, and the technological risks contribute to skepticism. While literature recognizes these risks conceptually (Baumgarte et al., 2020), there is limited focus on how these issues impact the choice and application of battery storage technologies' business models in energy hubs.

Barriers to the adoption of business models involving battery storage technologies in energy hubs are multifaceted. These barriers have different impacts in different parts of the system, culminating in a complex web of concepts. To better conceptualize these issues, the barriers identified were divided into the same three verticals used for drivers, and shown in the diagram below.

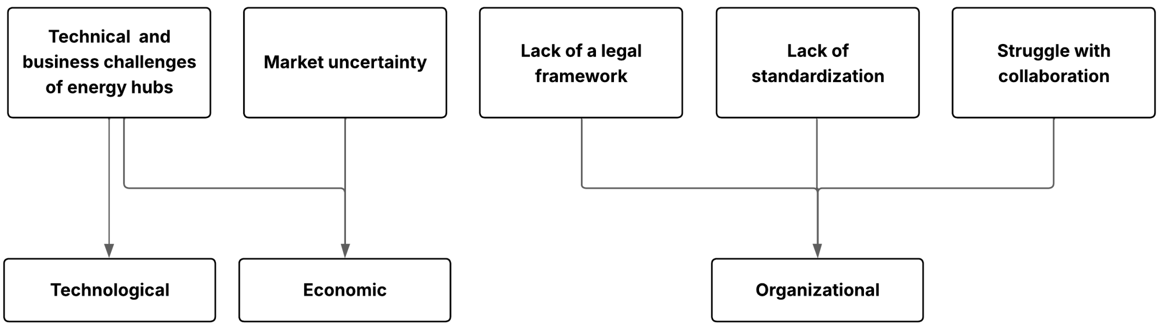

Figure 5.4: Barriers divided by vertical

In Figure 5.4, barriers are grouped into three main verticals: Technological, Economic, and Organizational. The "Technological" vertical refers to issues inherent to the functioning and deployment of energy technologies, with "Technical and business challenges of energy hubs" representing the main identified obstacle. This barrier also partially overlaps with the "Economic" vertical, where "Market uncertainty" also plays a role, highlighting the main economic barriers.

On the other hand, "Organizational" barriers include the "Lack of a legal framework", "Lack of standardization", and "Struggle with collaboration", all of which hinder coordination between stakeholders and complicate the integration of battery storage systems. This vertical, therefore, emphasizes the need for institutional support and alignment among actors for the implementation of new business models.

It is also relevant to understand the significance of the barriers identified, based on the frequency with which they were mentioned during the coding process. The most frequently mentioned barrier was "Technical and business challenges of energy hubs," with 38 references, highlighting its central role in limiting the implementation and scalability of such systems. This was followed by "Struggle with collaboration" with 20 mentions, pointing to the difficulties in aligning diverse stakeholders. "Difficulties in contracting" and "Lack of standardization" were both cited 17 times, reflecting common institutional and procedural hurdles. Lastly, "Market uncertainty" was mentioned 15 times, indicating its relevance, though comparatively less prominent. These frequencies suggest that technical and organizational complexities are perceived as more critical challenges than market-related concerns. This analysis is visually represented in Figure Figure D.2 in the Appendix D.

5.3. Business models

To understand the integration of battery storage technologies in energy hubs, it is essential to explore the business models that enable their viability. This section presents the key business models identified through the interviews conducted in this research and connects them to existing academic literature. The goal is to analyze how batteries can be deployed within the energy hub context and how different value propositions and market mechanisms shape these business models. The interviews revealed several recurring business model configurations, including storage-based models, energy trading, frequency regulation, and multi-service applications. These models reflect both traditional battery applications and emerging trends such as servitization and flexibility markets.

In Figure 5.5, the findings of this section are summarized. The first column presents selected first-order categories identified during the interview process. These were grouped into second-order themes that will be discussed in this section and interpreted through the lens of relevant academic literature.

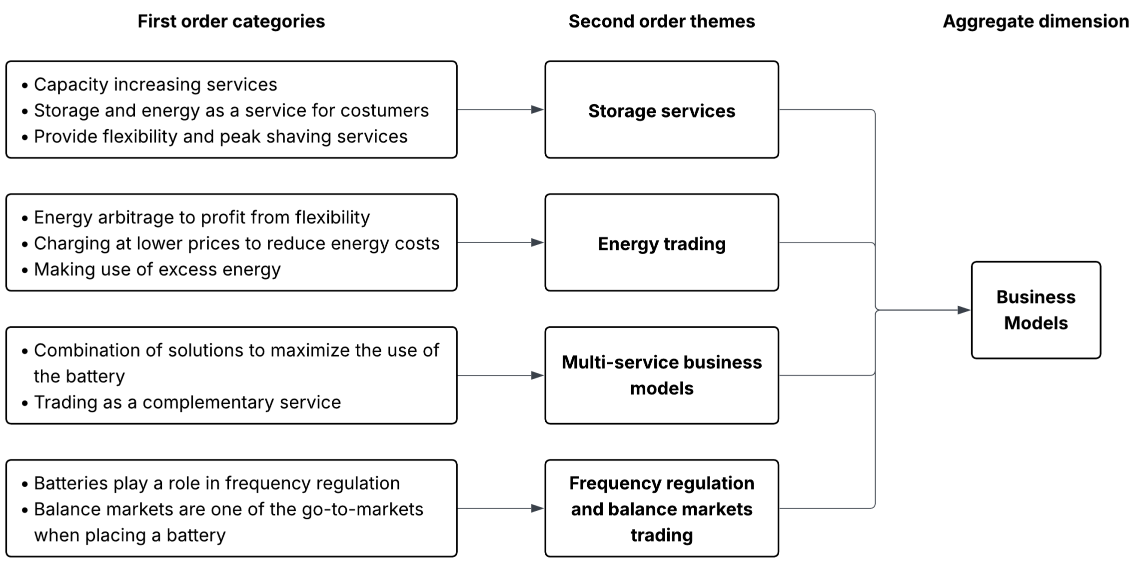

Figure 5.5: Data structure of the aggregate dimension "Business models"

Storage services

Batteries are an asset that has the capability of storing electricity. The ability to store electricity and release it at a later moment is something currently highly valued by customers. According to the interviews, the most important business models of batteries still revolve around storing energy and releasing it at the right time [AG4, AM1, RI3]. This can be seen in the following quotes:

> "*Well, the ability to store power for a number of hours is of course a huge advantage in a system where you have these high price peaks every now and then.*" (Strategic advisor, Research Institution

[RI3])

"*You need the battery as a means of storage.*" (Director energy and sustainability, Asset Management [AM1])

This aligns closely with the literature that identifies energy management as central to the value proposition of battery business models (Baumgarte et al., 2020; X. Li et al., 2019). These models create value by charging during low-cost periods and discharging during high-demand periods, effectively reducing electricity costs and increasing grid efficiency.

Furthermore, Interviewees highlighted the servitization of battery storage technologies' business models. Models such as energy-as-a-service [AG2, AM1], storage-as-a-service [AM1, DSO2, PM1], and even charging as a service [AM1] were mentioned as new, innovative ways of operating batteries and applying them to energy hubs. This kind of business model helps diminish the cost and dodges the constraints of acquiring a physical asset. This aligns with the "Storage-as-a-service and Aggregation models" discussed in the literature (Hoppmann et al., 2014; Teng & Strbac, 2016). An example can be seen in the following quote:

"*So you can use batteries even more flexible. So you can say for example, hey tomorrow at this place we expect congestion and there will be a company say hey I've got a battery for you for tomorrow or you can rent it for 3 days when you need it and after that I will take it back and I can use it on another place.*" (Product owner energy hubs, DSO [DSO2])

Energy trading

The interviewees from this research highlighted energy trading as one of the most common usages of a battery [RI2]. Combating price fluctuations can help raise the profitability of applying a battery tremendously and can help companies drive down the cost of their energy consumption significantly [RI3, RI5, DSO1]. Due to the volatility of energy prices, business models based on just trading around this difference emerged. Companies now not only charge their batteries at low prices, but they also sell energy back to the grid when the prices are favorable. This was mentioned thoroughly as a method of creating profit from the battery, not only promoting cost reduction [RI1, PM1, HP1]. For example, the following quote highlights that:

"*If you can save a lot by taking in power at low prices and trading it back to your local market at the higher prices, you can create a very good business case.*" (Program director, Research Institution [RI2])

This aligns with the literature on energy arbitrage, which describes this trading strategy as one of the central business models for battery storage technologies (Baumgarte et al., 2020; X. Li et al., 2019). In the Dutch context, where price volatility is exacerbated by the integration of renewable energy sources and grid constraints, this model becomes particularly lucrative.

Multi-service business models

The main way of maximizing value out of a battery is by guaranteeing that it is always being used. In that way, multi-service business models are very common to be applied according to the participants of this research [AG1, AG2, HP2, AM1]. Only providing storage and peak shaving services might not be enough to create a strong business case, but when these kinds of activities get paired with trading in energy markets or frequency regulation, it might become easier to justify the need for a battery [BK1]. Most of the use cases of battery storage technologies are intermittent and do not require a constant operation of the asset; therefore, it opens the possibility of matching use cases based on the most lucrative model at different moments [AG1].

"*If an energy hub is solely focused on peak shaving, most of the time you are not using the battery as efficiently as it should. You can, however, by combining uses, of course. But first, if you are talking about energy hubs that are fully focused on peak shaving, then the battery is only being used in certain moments of the year. Hence, we have to work towards giving it a multi-usage when it's being implemented in energy hubs, not only focused on peak shaving.*" (Energy hub consultant, Aggregator [AG2])

This reflects the concept of value-stacking, which has been identified in the literature as a promising business model for battery storage technologies (Baumgarte et al., 2020; Teng & Strbac, 2016). By switching between use cases based on market conditions or system needs, batteries can provide value in multiple ways and become more efficient.

Frequency regulation and balance markets trading

The interviewees also highlighted the possibility of trading in other kinds of markets, apart from the energy markets [RI5, HP2]. Frequency regulation is critical to the good functioning of the grid, and there is a profit to be made in this field. The possibility of using the battery to trade in FCR markets is seen as highly beneficial and a good way of having an extra source of income [AG2, AG4]. The importance of these markets is highlighted by the following quote:

> "*Some electrical equipment is extremely sensitive to frequency fluctuations or fault ride through or any other of the stuff. Maybe the battery can play a role there. That could really add to the business case without saying the battery itself per se generates money.*" (Head of business development, Hardware Provider [HP2])

This reflects existing academic findings, which position frequency regulation as one of the most valuable applications of battery storage today (Baumgarte et al., 2020; Soares et al., 2023). Batteries are capable of delivering millisecond-level response, which is essential for frequency containment, voltage control, and other ancillary services (X. Li et al., 2019).

Also, balance markets operate similarly. There is a need for more assets balancing supply and demand due to severe grid congestion problems created by intermittent sources of energy. By owning your flexibility asset, in this case the battery, you can improve your business case by making use of these markets where you make your capacity available to cater for grid constraints [AG1, DSO2, PM1]. One interviewee noted:

> "*Right now, the real way to make money, as far as I am aware, is steering in the imbalanced markets using those price signals to make a lot of money.*" (Energy hub consultant, Aggregator [AG3])

Discussion and Theoretical Context

The empirical findings of this research align with the business models for batteries previously found in the literature (X. Li et al., 2019). The findings reinforce the importance of storage as a means of reducing energy costs, and cover the introduction of new business models related to the servitization of batteries. It also covers market trading, from the energy perspective and from the frequency perspective. Furthermore, the concept of multi-service business models is also mentioned, which is also a common topic in the literature, often mentioned as value stacking (Teng & Strbac, 2016).

In what concerns the frequency of mentions, "Storage services" was the most frequently referenced, with 38 mentions, suggesting it is considered the most established or immediately applicable business model among stakeholders. Following this, "Energy arbitrage and trading" (24) and "Multi-service business models" (23) appeared with similar frequency, highlighting the relevance of combining different value streams or leveraging market dynamics to enhance profitability. Lastly, "Frequency regulation and balance markets trading" was mentioned 21 times, indicating that while important, it is seen as slightly less central compared to the other models. These frequencies reveal the prioritization of certain business models and reflect where stakeholders see the most value or feasibility in the context of battery deployment in energy hubs. This distribution is visually presented in Figure D.3 in the Appendix D.

These findings suggest that the business models used for battery storage technologies in energy hubs are similar to those used by standalone batteries. The core difference identified during the interview process refers to the importance given to each one of the topics and how they relate to the priorities of participants in energy hubs. According to the interviewees, battery storage technologies' business models in energy hubs contrast with standalone batteries due to the fact that they are not focused on profit. That highlights the role of drivers and barriers and the value created, in framing the relevance of the business models identified.

5.4. Value creation

To fully understand the role of battery storage technologies in energy hubs, it is crucial to examine the types of value these systems generate for participating stakeholders. While business models define the structure for capturing value, it is the specific benefits created that contribute to evaluating the choice of business models.

This section presents the core dimensions of value creation identified in this research, as derived from the interview process. The insights highlight both direct and indirect forms of value, ranging from increased energy capacity and reduced costs to broader goals such as enabling business growth, supporting decarbonization, and enhancing security of supply. These values reflect the motivations and expectations of energy hub participants and align to varying degrees with current academic literature on battery storage systems.

In Figure 5.6, a summary of the findings is provided. Together, these findings illustrate how battery storage technologies in energy hubs generate meaningful value for firms, the energy system, and society.

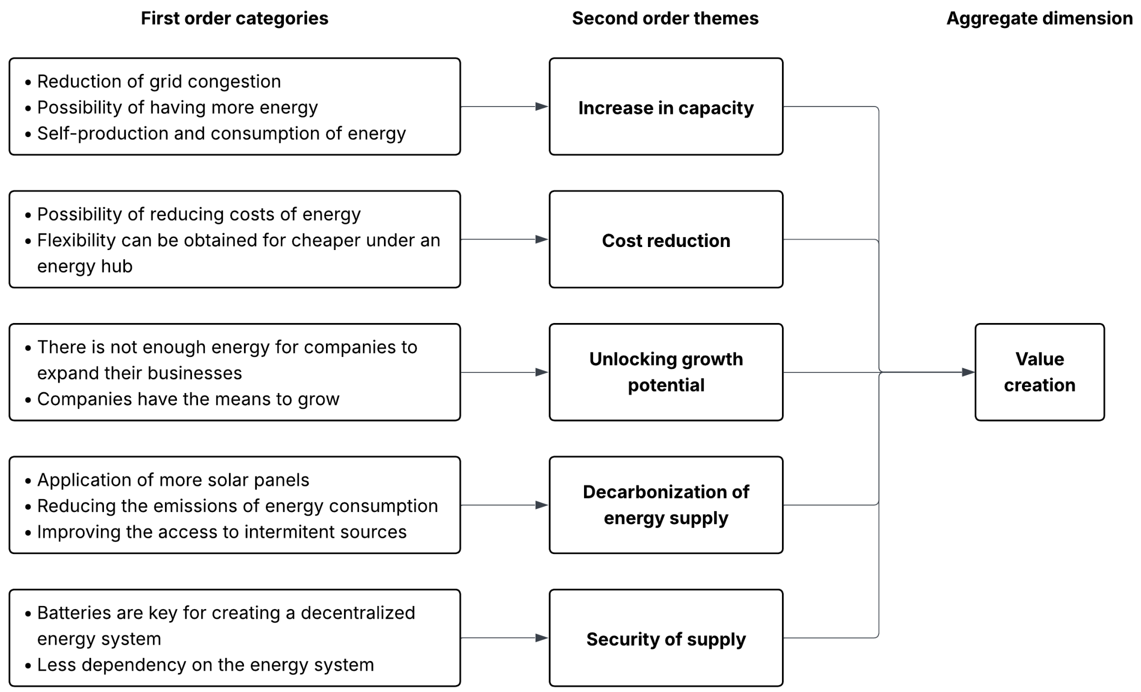

Figure 5.6: Data structure of the aggregate dimension "Value creation"

Increase in capacity

The main value mentioned by participants was capacity. Companies' day-to-day activities are being hindered by the lack of energy available on the grid, which has a significant economic impact [AG2, RI1, PM1, EP1]. Events of congestion are increasingly more frequent, and companies show their concerns regarding business continuity and energy availability. Interviewees stressed during the interviews that the goal of companies in partaking in energy hubs is often only to ensure the availability of energy [AG3, AG4, DSO2, BSP1, BK1], through the implementation of a battery that extends capacity or efficient demand scheduling. The following quote highlights the need for a battery to increase capacity:

> "*The reason to buy a battery in an energy hub is to increase capacity.*" (Project manager, Research Institution [RI1])

Energy, in the context of energy hubs, is a means to an end that has to be available for companies to continue their activities. With batteries in energy hubs, this extra capacity needed to cover the peak consumption events is granted, ensuring that companies do not need to tailor their activities to energy availability and can run their business with more flexibility.

This finding aligns with the literature that highlights peak shaving and grid congestion mitigation as core functions of battery storage systems. As mentioned by Lund et al. (2015) and Soares et al. (2023), batteries are increasingly used to provide localized flexibility in constrained networks, allowing businesses to maintain operations during peak load periods or grid limitations.

Cost reduction

Another relevant factor mentioned was the reduction of costs. Sharing batteries allows stakeholders to save a significant amount on CAPEX and OPEX [AG3, PM1], and that is a value that is widely searched for due to the expensive prices of batteries (Hoppmann et al., 2014). The need for these assets is already established, and it is in the interest of the company that they can be acquired as cheaply as possible to ensure that the margins of their businesses stay as high as possible [HP1, AM1]. For example, the following quote highlights how it is relevant to cut battery-related costs:

> "*Cost or business case will definitely be benefited by energy hubs because you will be able to use it more efficiently in a shared way, so you can share the cost, or you get higher revenues from your battery if you own one yourself.*" (Product owner energy hubs, DSO [DSO2])

For companies participating in energy hubs, energy works as a commodity that impacts business continuity and margins. With that in consideration, reducing the costs of this commodity comes as something extremely important, making it a determining factor [AG1, RI4]. The majority of the participants of energy hubs have a different core business than energy, meaning that for them, energy is just a cost that has to be covered, disregarding possible revenue streams from energy. Which is mentioned in quotes like the following:

> "*Now if you are not only selling to the grid, but you're only also using the power, then the business case really is all about reducing the cost of your own power.*" (Program director, Research Institution [RI2])

Findings also mention the reduction of reliance on the grid as contributing thoroughly to diminishing the costs of batteries, due to the shielding against volatility and grid tariffs. That aligns with the literature that highlights these factors are critical for lower energy prices (Kooshknow, 2022).

Unlocking growth potential

Companies are being constrained by energy when they try to grow their activities [AG4], and battery storage technologies can provide value in this regard. Currently, there are no available resources for expansion, although several businesses have the money and willingness to do it [AG1, AG4, AG6]. Energy hubs with batteries enable this expansion by providing extra future capacity and enabling the realization of projects that are currently not possible. Quotes like the following highlight this:

> "*I think money is not even the biggest threshold right now because when people are faced with "I cannot let my production grow for 10%" or "I have to invest in a battery of 200,000," that's an easier business case because they don't have to have like a return on investment in per kilowatt hour, but it's a question of "I can grow" or "I cannot grow".*" (Project specialist, Aggregator [AG4])

Even though it is hard to put a price tag and quantify how much growth is valued, it is important to take into consideration that the majority of the businesses involved in energy hubs and using these batteries are not in the energy business; they perceive energy as a commodity and use it as so [DSO2, BSP1]. If there is a need for further investment to acquire more energy, this is just seen as a cost without any other implications. Therefore, the analysis made is just in terms of cost-benefit, and according to the interviewees, the benefits outweigh the costs [AG5, EP1], as it is possible to see in the following quote:

> "*The value of not expanding your business or not growing has exceeded the cost of a battery.*" (Energy hub consultant, Aggregator [AG1])

This insight connects closely with the literature. According to Soares et al. (2023) and Coccato et al. (2025), battery storage technologies enhance not only cost savings and grid support but also provide a platform for business continuity and expansion, especially in congestion-prone regions.

Decarbonization of energy supply

Building on the need for sustainable energy, and taking into consideration the ambitious decarbonization goals of the EU and the national governments, one of the main impacts of applying batteries is the fact that it allows for more renewable integration. With that being said, it was highlighted by the interviewees that the importance of electrification and how the value of batteries as an enabler of electrification is extremely valued [HP2, AG5, RI5].

> "*They have got solar panels on the roof, but when the sun stops shining, you could put a battery in place, charge the battery when the sun is shining, and have an hour or two depending on the depth of the battery of additional power which would enable them to reduce the electricity demand from the grid. That's an objective in itself.*" (Head of business development, Hardware Provider [HP2])

The aforementioned intermittent nature of renewable energy production can be mitigated with a battery. Currently, the value of applying your own solar panels as efficiently as possible and lowering your emissions is valued significantly [RI3, RI4, DSO2, EP1].

Security of supply

Decentralized systems bring robustness to the energy system, and energy hubs enable these kinds of energy systems. Although this value is not felt directly by the stakeholders profiting from the battery, it was mentioned often the fact that energy hubs allow for the further development of a decentralized energy system [AG4, AG5, PM1]. With the growing tensions around the world, the security of the energy supply is growing in importance. The following quote highlights it:

> "*Especially what you see now happening with wars in Ukraine, you need to bomb three big power plants, and you're done. So getting decentralized is, of course, a good strategy as a whole for countries in Europe, or other countries. So batteries will become more and more important.*" (Project specialist, Aggregator [AG4])

Connecting with real-world problems, such as the situation in Portugal and Spain, with an energy system that has the capacity for localized self-sufficiency, it is possible to have a more robust energy system. Furthermore, the self-sufficiency of an energy hub with a battery can also contribute to mitigating possible problems with energy availability due to grid congestion [RI4, BSP1, BK1].

This finding also aligns with the literature regarding decentralized energy systems. Although underexplored as the concept of security, there is already literature that highlights the need for a decentralized energy system that can be more resilient (Lund et al., 2015; Soares et al., 2023). This also aligns with the literature discussing broader value creation from battery storage technologies to society (Teng & Strbac, 2016).

Discussion and Theoretical Context

This study identifies five key value creation dimensions for battery storage technologies in energy hubs: increase in capacity, cost reduction, unlocking growth potential, decarbonization of energy supply, and security of supply. Some of these values, such as an increase in capacity and decarbonization of energy supply, clearly align with the literature, reinforcing the empirical validation character of this chapter. According to interviewees, increasing the capacity available while maintaining low-cost energy is still the most relevant value created by the business models of battery storage technologies in energy hubs.

Importantly, the findings highlight unlocking growth and security of supply as two values that are highly relevant in the energy hub context, but remain underdeveloped in the current literature. Battery storage technologies can be key for overcoming hassles where the lack of energy available is the problem. In the context of company growth, energy is currently one of the main bottlenecks. Interviewees highlighted that by joining an energy hub with a battery storage technology applied, companies can expect enough capacity to keep expanding their business, eliminating that constraint. Furthermore, the decentralized nature of energy hubs, which is heavily tied to the presence of the battery, can contribute directly to the creation of a more robust energy system, where there is less grid dependence for energy supply. Both these topics are severely underaddressed in the literature and could profit from further research.

It is also valuable to assess which value propositions are considered most relevant by the interviewees, based on the frequency of their occurrence in the data. The most frequently cited value proposition was "Increase in capacity" with 43 mentions, emphasizing its significance in enabling higher energy demand or system expansion. Closely following, "Cost reduction" (41) and "Enabling company growth" (39) highlight the economic and strategic benefits that battery systems and energy hubs are expected to deliver. "Decarbonization of energy supply" was mentioned 27 times, indicating the environmental value is important but not as predominant. Lastly, "Security of supply" had the lowest frequency, with 15 mentions, suggesting it is perceived as a secondary concern. This distribution is visualized in Figure Figure D.4 in the Appendix D and indicates that economic and capacity-oriented value creation is seen as more impactful than risk mitigation alone.

Furthermore, these results highlight the importance of values in defining business models, clearly aligning with previous research (Teece, 2010). Interviewees highlighted multiple times the need for a well-developed value proposition in business models, which can translate to significant value creation that fits within these values identified.

6

A Framework For Business Models of Battery Storage Technologies in Energy Hubs

A framework was created to provide a better understanding of how business models of battery storage technologies take shape when they are applied in the energy hub setting. The framework aims to summarize the four main dimensions found: drivers, barriers, business models, and value creation, and connect them based on the evidence gathered.

It was often mentioned during the interviews held that energy hubs differ in size and organizational aspects based on multiple factors. Grid congestion is not felt the same in every place, production of renewable energy is also heavily tied to geography (Petit & Vafeas, 2022), and different demand profiles might require different technical settings and contractual scenarios (X. Li et al., 2019). With that in mind, the framework aims to better summarize how these factors are taken into consideration in terms of the creation of these hubs and the implementation of batteries.

The participants of this research referenced the need for a standardized, easy-to-comprehend method to understand the business models of battery storage technologies in energy hubs. It was commonly highlighted by the interviewees the need for a standard way of defining business models of batteries inside an energy hub, to facilitate comparability, as it can be seen in the following quote, interviewees still perceive the business models for applying a battery in an energy hub as hard to understand:

> *I think there is not really a problem with adopting battery technologies. As long as the use case and the finances are logical for companies, they will do it. The problem is that it is quite hard to see the benefits of batteries. In energy hubs, companies will only really pursue batteries if they have a problem or they want to expand, and cannot expand. Instead of, for example, solar, where there is a quite clear cost-benefit analysis, you can do. You can say that over five years, you have produced X amount of energy, and we expect that you have made a profit. For batteries, that's quite difficult. You need to have a case. I want to expand my production. I cannot use more grid capacity, essentially. So I need to have a battery to make it happen.* (Project manager, Research Institution [RI1])

Also, there is a clear gap in the literature on what regards the definition of business models of battery storage technologies inside energy hubs and on the nuances related to it. Scholars only described phenomena related to the application of standalone batteries and energy hubs separated from each other, without integrating them. Furthermore, business models are not static; therefore, there is a clear need for a framework that pictures the phenomena accurately in order to understand how these business models are changing through time and application (Hall & Roelich, 2016). By building on previous research and the data gathered during this project, this framework helps clarifying what business models are being applied with batteries in energy hubs, why are these business models chosen, and what kind of values are created by these business models, establishing a structured methodology for assessing the business model adopted for battery storage technologies in energy hubs.

6.1. Framework design and structure

As stated, the framework is developed by combining the literature and the interviews conducted. The experts who participated in this research pointed out a clear path for the business models under energy hubs. This path delineates a clear road from the drivers for battery storage technologies business models in energy hubs to the moment of value creation, at the end of the framework. Providing a structured approach that can picture this phenomenon.

Visually, the framework follows a linear approach, from top to bottom, that intends to describe the staged process found of picturing business models of battery storage technologies in energy hubs. Also, there are four boxes with titles in bold that highlight the aggregate dimensions that resulted from the thematic analysis based on the research questions in place.

In this section, an in-depth explanation of the rationales behind arriving at this framework will be presented by walking through the multiple areas of the structure of the framework and contextualizing them with empirical findings.

Drivers and Barriers

According to the interviewees, the drivers found are the foundation of the business models, therefore, the starting point of this framework. This group of factors defines what are the key values that should be taken into consideration when creating a business model for battery storage technologies in energy hubs. It is to be expected that, depending on what the drivers are for the realization of the project that the specifications of the energy hub and the battery applied differ. For example, one of the participants highlights the need for assessing the drivers, and the possibility of multiple drivers existing on different occasions, and different business models to be relevant:

> *At first, I started saying, Is there net congestion or not? If there is, then there is a driver in its own right? To buy a battery, because otherwise they run into serious problems. If they do not have net congestion in that area, it takes away one of the drivers. It may still be a good idea, beneficial to install a battery. But then, if you go one step down, it probably starts making a difference to what extent they produce their own renewable power energy.* (Strategic advisor, Research Institution [RI3])

This reiterates the importance of drivers in setting the tone for the business models for battery storage technologies applied in energy hubs. These drivers are the core foundation of these business models and act as motives for the choice between different models.

After considering the main drivers for the application of battery storage technologies in business models in energy hubs, it is also important to consider the core barriers for these business models. Although there were some significant developments in the field, there are still some clear barriers to the implementation of these business models, which define the choice of what is the best-fit business model for the battery storage technology applied to the energy hub.

For a business case to be successful, it has to take into consideration its limitations and the possible barriers to value that can be found. That makes barriers of extreme importance when trying to understand the rationales behind the choice of the business models. Barriers such as the struggle with collaboration can jeopardize demand scheduling, making the business model in terms of capacity more difficult and maybe requiring a bigger battery and more emphasis on trading. On the other hand, technical challenges can thoroughly influence the amount of trading that can be done through problems such as the battery size and charge and discharge rates not being compliant with the need.

To further improve the understanding of the framework, the three verticals identified during the chapter 5, "Technological", "Economic", and "Organizational", were used. In the framework, it is possible to see the connections between the drivers and barriers identified and the respective verticals that they connect to. The division in place contributes to creating more clarity on how the drivers and barriers interact with each other, helping to understand where the biggest problems to be faced are. With this, a more comprehensive understanding of the impact of the drivers and barriers can be seen.

Business models

After considering the drivers and barriers present, the business model has to be formulated. Multiple business models were identified throughout the research, mainly due to drivers and barriers differing from project to project.

A critical moment highlighted by the interviewees in the definition of the business model of battery storage technologies in energy hubs relates to the function that this business model has. Throughout the interview process, the extreme flexibility of battery storage technologies was highlighted, noting that these technologies can work in different ways and create value in different fields within a day. This requires that there is careful planning in terms of what services can be done by the battery storage technology to provide the most value to the energy hub customers. Quotes like the following give an example of this concern during the research:

> *So what's the objective in the end of putting a battery? To create a hub and put batteries in place, there could be multiple objectives that I could see, and maybe some of them occur simultaneously.* (Head of business development, Hardware provider [HP2])

This is highlighted in the framework as a decision node, that defines if the energy hubs needs more than one service, and connects it in case of "no" to the business models found during the interview process, or in case of "yes" to a multi-service business model approach, also frequently mentioned during the research. This multi-service business model approach is often a combination of the three other business models, culminating in a more complex web of services delivered to the customer.

Value creation

After crafting the business model, the value is analyzed to understand if it is in tune with the expectations and necessities of the involved parties. According to the participants of this research, it is crucial to assess the value creation to understand if the business case is strong.

In the framework, Value creation appears as the last section. It stems from the application of the business models and summarizes the values that these business models can provide to the customer. It is the endpoint of the framework, but also the goal of the application of a battery storage technology to an energy hub. These values are the ones felt by the customer, and the ones that dictate if the business model applied is in tune with the expectations.

6.2. The framework

Based on the structure and design covered, the framework available in Figure 6.1 aims to describe battery storage technologies' business models in energy hubs.

6.2.1. Contribution of the framework

The framework provides a structured approach to evaluate the business models of battery storage technologies in energy hubs. With this framework, there is a clear scope on the formation and value creation of the models, which can help to better define what the factors are that influence these models inside energy hubs.

From this framework, it is possible to assess that there are more barriers regarding the "Organizational" vertical than the other ones identified, revealing that there might be a problem with the way that energy hubs are set up. But also, by crossing this information with the frequencies obtained, "Collaboration" is also one of the most important drivers, which can lead to the possibility of overcoming these barriers.

Furthermore, there is a notable presence (4) of "Economic" drivers, meaning that, according to the interviewees, consumers value economic viability highly. Nonetheless, some barriers were also identified for this economic viability that can undermine the business case. "Technical and business challenges of energy hubs" and "Market uncertainty" have to be overcome to ensure a strong business model.

In conclusion, this framework answers the request of the interviewees on coming up with a structured approach to evaluate the business models of battery storage technologies in the context of energy hubs, creating an empirically validated approach that can picture the result of the ecosystem, and under-pin the core factors in a value-centric business model approach that influence the construction of the business case of battery storage technologies in an energy hub setting.

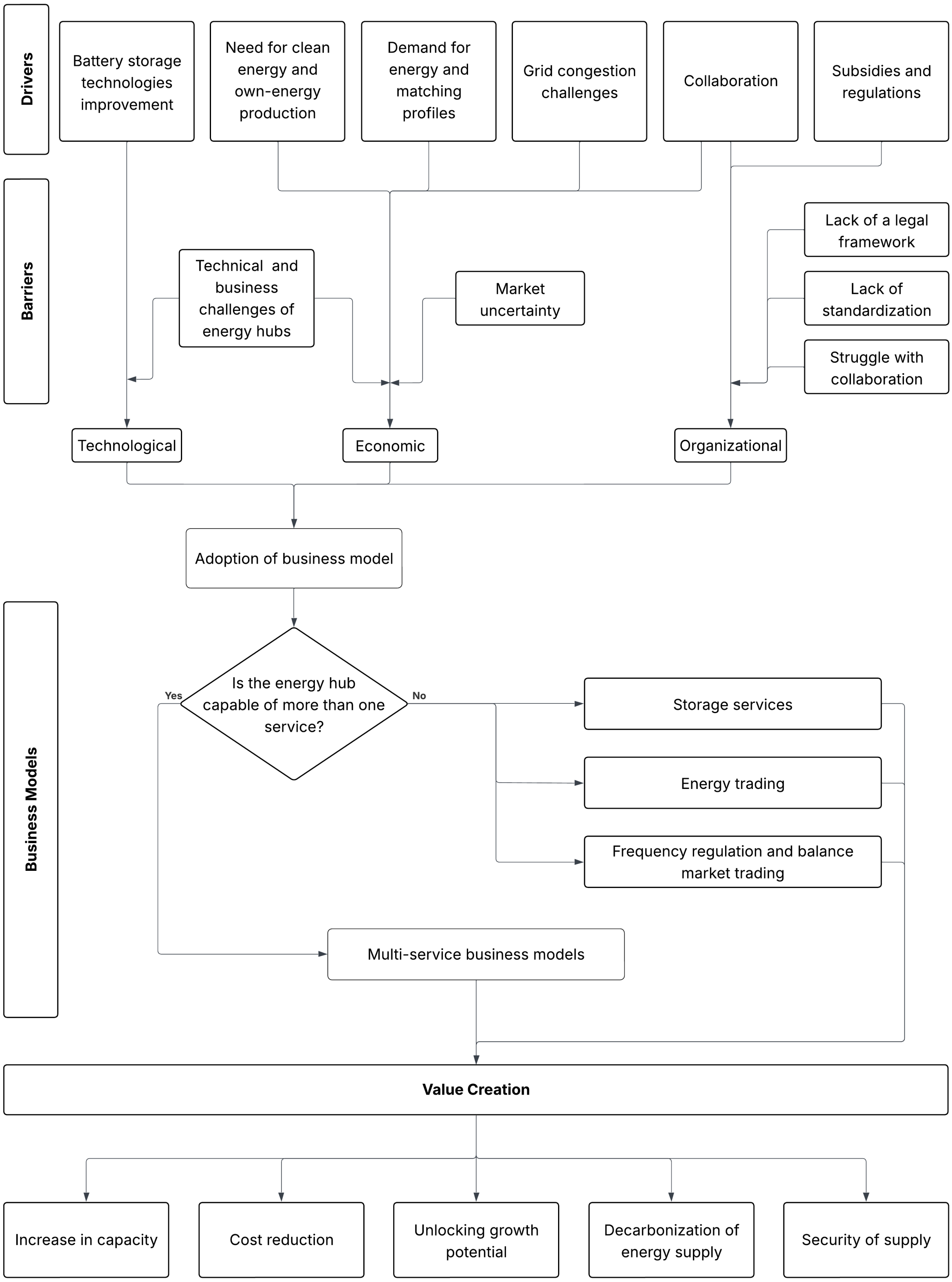

Figure 6.1: Battery storage technologies business models in Energy Hubs - Framework

7 Conclusion

The goal of this study is to define how business models of battery storage technologies are shaped in energy hubs. The research aims to point out some of the core factors that influence these business models, such as drivers and barriers, the business models applied in different hubs, and the value created by these.

Using a thematic analysis of expert interviews, this study culminates in a descriptive framework of the operationalization of business models of battery storage technologies in energy hubs. This framework incorporates the answers to the sub-questions in place, a structures them in a way that they are capable of answering the main research question of this research.

Sub-question 1: What are the drivers and barriers of the business models of battery storage technologies in energy hubs?

The thematic analysis of this research revealed a clear group of drivers and barriers for the business models of energy hubs. They are summarized in this section as an answer to the first sub-question of this research.

Drivers of the business models of battery storage technologies in energy hubs

Below is a summary of the drivers identified for the business models of battery storage technologies in energy hubs:

- **Collaboration:** Collaboration emerged as a key enabler for battery storage technologies business models in energy hubs. Interviewees emphasized that shared ownership and cooperation in the operation of batteries among companies drive business models by optimizing the use of battery storage technologies and reducing costs. Collaboration is presented as one of the core verticals of energy hubs in the literature (Geidl et al., 2007), and in this study, its role in driving the business models of battery storage technologies was empirically verified. While existing literature acknowledges the importance of collaboration in energy hubs, it lacks depth in exploring how these collaborative structures concretely shape business models in the context of energy hubs.
- **Demand for energy and matching profiles:** The compatibility of energy demand profiles among hub participants is a central factor in shaping viable business models for battery storage technologies in energy hubs. Energy hubs are most effective when companies have complementary or staggered energy needs, which influences the impact and formation of battery storage business models. Interviewees stressed that without such alignment, the economic case for batteries weakens considerably. Therefore, demand matching not only supports technical optimization but also becomes a foundational condition for financial viability in energy hub models. Furthermore, interviewees also mentioned the need for more energy to be available for companies, and the extreme interest from companies in expanding their capacity, providing a potential business case for the application of batteries.
- **Need for clean energy and own-energy production:** The transition away from fossil fuels is accelerating battery storage technologies adoption in energy hubs. Companies seeking to decarbonize their energy supply are turning to self-production of renewable energy, but face challenges due to the intermittent nature of this type of energy production (Lund et al., 2015; Petit & Vafeas, 2022). The

interviewees often mentioned that battery storage technologies have the capacity of suppressing the intermittency and increasing efficiency in the usage of renewable energy; therefore, this can drive the creation of a business case for battery storage technologies in energy hubs.

- **Subsidies and regulations:** Policy instruments such as subsidies and regulations play a pivotal role in battery storage technologies' business model development. Government support was seen by interviewees as critical not just for financial viability but also for facilitating structural mechanisms like shared capacity agreements (e.g., the Dutch GTO contract). With governments as one of the key stakeholders for the development of energy hubs, the policy frameworks and the capital that they make available for this type of initiatives has a critical impact on driving the business models of battery storage technologies.
- **Battery storage technologies improvement:** Technological advancements were cited as significant drivers of business models of battery storage technologies in energy hubs. As batteries become more reliable and cost-effective, new use cases become feasible, enhancing the potential for new application and stronger business models. The optimistic perspective that challenges of battery storage technologies will be overcome in a near future helps drive battery storage technologies business models in energy hubs, by allowing to analyze new applications an improving the efficiency of the current ones.
- **Grid congestion challenges:** Grid congestion is a pressing issue that battery storage technologies can directly address. By acting as a grid flexibility asset, battery storage technologies can mitigate the lack of energy caused by congestion events by helping to stabilize the grid. Interviewees and literature agree that this is one of the most urgent and compelling reasons for integrating batteries into energy hubs (Soares et al., 2023). The ability of batteries to offer resilience and flexibility makes grid congestion challenges a driver for business models of battery storage technologies in energy hubs.

Barriers of the business models of battery storage technologies in energy hubs

- **Technical and business challenges of energy hubs:** Energy hubs face several technical issues that hinder the integration of battery storage technologies. Interviewees highlighted that there are still plenty of issues in creating energy hubs, focusing on the complexity of the integration of the technologies needed and issues in managing the different interests of customers technically. These uncertainties make it difficult to develop strong business models for battery storage technologies and poses as a barrier to applying these models. Although technical progress is ongoing, the state-of-the-art battery storage technologies still struggle in terms of performance, safety, and spatial constraints, which, according to the interviewees, is detrimental to their business models. These challenges are confirmed by literature, especially regarding socio-economic coordination and technological limitations (Coccato et al., 2025).
- **Struggle with collaboration:** While collaboration is essential for energy hubs, it also represents a substantial barrier. Many companies lack experience in joint energy initiatives and show hesitance towards cooperating with neighboring firms. Misaligned interests complicate coordination and reduce the attractiveness of collaborative business models for battery storage technologies, which are the foundation of energy hubs. The literature reinforces these concerns, emphasizing the level of coordination required to align all the interests of stakeholders within cooperative energy systems such as energy hubs (Hall & Roelich, 2016; Lazzeroni et al., 2023).
- **Lack of standardization:** The absence of standard protocols for battery storage technology integration in energy hubs significantly slows scalability, creating a barrier for the business models of these technologies. Interviewees noted the lack of interoperability between systems as a critical bottleneck that results in increased difficulties for the application of battery storage technologies. Without clear technical and procedural standards, each project becomes a singular, custom situation, increasing costs and risks. This topic is still underexplored in the literature, revealing an important field to be further explored.
- **Lack of a legal framework:** The interviewees also stressed the lack of a clear legal framework as a barrier for the application of battery storage business models in energy hubs. Aligning with the findings in terms of struggles with collaboration, it was often mentioned the need for a framework that can help institutions to enforce the agreed usage of the assets on an energy hub. The fact that such a type of document does not exist hinders the application of battery storage technologies' business

models in energy hubs due to legal boundaries that diminish the trust of customers. This topic is also underexplored by scholars, presenting itself as an interesting further research topic.

- **Market uncertainty:** The uncertainties related to energy markets introduce a significant barrier for battery storage technologies' business models in energy hubs. Stakeholders expressed concerns over the unpredictability of congestion events and the potential for market saturation. Diminishing returns from over-deployment of batteries and the emergence of alternative technologies further threaten the long-term viability of battery investments. These uncertainties undermine the confidence of stakeholders in engaging in energy hubs and can jeopardize the usefulness of some of the business models for battery storage technologies currently in place.

Sub-question 2: What are the business models of battery storage technologies in energy hubs?

In this section, the business models identified during the thematic analysis are explained, answering the second sub-question of this research

- **Storage services:** According to interviewees, storage remains the focus of battery storage technologies' business models in energy hubs. Interviewees emphasized that the core value lies in storing energy during low-price periods and using it in moments where the prices from the grid are high. This aligns with literature that positions energy management as the key battery storage technology function (Baumgarte et al., 2020; X. Li et al., 2019). Furthermore, emerging servitization models, such as storage-as-a-service, were identified as innovative strategies to deploy batteries without requiring asset ownership, lowering adoption barriers. These models are growing in popularity and becoming standard for energy hubs where customers lack the financial means to acquire the asset.
- **Energy trading:** Energy trading was highlighted as a primary application of battery storage technologies, particularly within volatile markets such as the Netherlands. By capitalizing on price fluctuations, companies can buy low, store energy, and sell high, generating significant profit. The literature refers to this mechanism as energy arbitrage, a widely studied and validated business case for battery storage (Baumgarte et al., 2020; X. Li et al., 2019). Although this model is widely explored and profitable, it was highlighted that it is not a prioritized model by energy hubs, where energy trading is not the core business of the stakeholders involved in the hub; these applications surge as a possibility to reduce the costs of energy hubs.
- **Multi-service business models:** Multi-service models maximize battery storage technologies' utilization by combining multiple use cases, creating a new paradigm for the business models of these technologies in energy hubs. Interviewees stressed that relying solely on one application results in an underused asset, which could be generating more value if it participates in other applications. This aligns with academic research referring to "value-stacking" as a core concept to enhance battery storage technologies business models (Baumgarte et al., 2020; Teng & Strbac, 2016).
- **Frequency regulation and balance markets trading:** Trading in ancillary service markets, such as FCR markets and imbalance markets, offers another profitable application for the business models of battery storage technologies in energy hubs. The ability of battery storage technologies to deliver a fast response to grid distress signals can be extremely profitable, even in the concept of energy hubs. Literature also mentions this, highlighting frequency regulation and ancillary services as lucrative and technically suitable battery storage technologies applications (Baumgarte et al., 2020; X. Li et al., 2019; Soares et al., 2023).

Sub-question 3: How do the business models of battery storage technologies create value when applied to energy hubs?

To answer the third sub-question of this research, the highlighted values discovered during the thematic analysis are summarized below.

- **Increase in capacity:** The most emphasized form of value from battery storage technologies in energy hubs is the increase in capacity. Companies face operational constraints due to limited grid availability and congestion; therefore, they are constantly looking for solutions that can increase their capacity and reduce energy-related costs. Battery storage technologies allow firms to continue their activities without the risk of energy shortages, which, coupled with the integration within an energy hub, can be even more valuable. This finding aligns with literature mentioning congestion management and flexibility as a commonly procured value for battery storage technologies business models (Lund et al., 2015; Soares et al., 2023).

- **Cost reduction:** The integration in an energy hub setting allows for a significant cost reduction on the application of battery storage technologies, according to interviewees. The ability to share the ownership of the battery storage technology allows companies to reduce their expenditure on this asset. Cost reduction is also enhanced through diminished exposure to grid tariffs and improved energy efficiency, also fostered by the collaborative nature of energy hubs and the application of a battery storage technology. This is particularly important for firms where energy is a significant cost factor.
- **Unlocking growth potential:** During the interview process, it was stressed often the impact of limited grid capacity on company growth. Energy has emerged as a bottleneck for company growth; therefore, battery storage technologies and energy hubs are growing in popularity as solutions that eliminate this constraint by providing more energy. Furthermore, this topic is very underdeveloped in literature, showcasing another significant gap for further meaningful research. It was often mentioned by interviewees that the need for a quantifiable way of measuring this value is to make business models based on growth even more attractive.
- **Decarbonization of energy supply:** Battery storage technologies are key in enabling the integration of renewable energy sources, which are intermittent by nature. By storing solar or wind energy for later, more efficient use, companies can reduce their energy-related costs while reducing their carbon footprint and maintaining compliance with sustainability rules and goals. Interviewees viewed battery storage technologies as a key enabler of electrification and sustainability in energy hubs. This is in line with the broader academic consensus on battery storage technologies as facilitators of the energy transition (Lund et al., 2015).
- **Security of supply:** The development of decentralized energy hubs supported by battery storage technologies contributes to a more robust and resilient energy system. While this value may not be immediately quantifiable for individual companies, it is widely recognized as a strategic benefit of these applications. It was often pointed out by interviewees that there is a significant interest from companies and governments to create a decentralized, robust grid that can lower the costs of energy and remain secure against possible threats.

Main research question: How do the business models of battery storage technologies work in energy hubs?

The goal of this research was to find how fo business models of battery storage technologies work in energy hubs. To achieve meaningful conclusions structured framework was constructed to depict how these business models take shape in the energy hub context. Energy hubs create a unique multiple stakeholder context for battery storage technologies business models, this context leads to multiple different nuances that influence how these business models are structured. This research highlights how these business models are shaped in the energy hub setting, covering fields from their conception to their outcome.

In the energy hubs context, the business models for battery storage technologies are chosen based on drivers and barriers. The six drivers identified are key for defining what the core values that the participants of energy hubs are looking for when applying battery storage technologies, and are intrinsically correlated with the business model that will be chosen. For example, the study highlights multiple cases where the members of energy hubs are looking for electrifying and incorporating more renewable energy production, this directly relates to a driver found in the research, "Need for clean energy and own-energy production", that will then lead to the choice of a business model that can accommodate that, such as "Storage services". Furthermore, this relationship between drivers and business models in energy hubs is moderated by barriers to their implementation. The choice of the business model for battery storage technologies in the setting of an energy hub is often impaired by barriers such as "Technical and business challenges of energy hubs", "Struggle with collaboration", "Lack of standardization", and "Lack of a legal framework".

This research also identified four core business models for battery storage technologies in energy hubs: "Storage services", "Energy trading", "Multi-service business models", and "Frequency regulation and balance markets trading". "Storage services" have been identified to be in the core of the business models of battery storage technologies, while some core innovations on how to apply these services, such as energy-as-a-service models, were often mentioned during the research. Also, market trading models, represented by "Energy trading" and "Frequency regulation and balance markets trading", are common models to be applied in energy hubs in the energy arbitrage and grid services verticals, respectively, creating the possibility of generating profits from the battery storage technology. Lastly, "Multi-service business models" incorporate combinations of the prior business models, focusing on value-stacking and optimizing the use of the battery storage technology.

Finally, the thematic analysis led to five core values created by business models of battery storage technologies in energy: "Increase in capacity", "Cost reduction", "Unlocking growth potential", "Decarbonization of energy supply", and "Security of supply". Increase in capacity was identified as the most relevant value, particularly in congested regions where access to additional grid capacity is limited. Cost reduction was typically linked to peak shaving, optimized energy use, and participation in trading markets. Unlocking growth potential refers to the ability of batteries to enable business expansion by overcoming grid constraints, a critical factor for industrial and commercial stakeholders. Decarbonization of energy supply reflects the batteries' role in enabling greater use of intermittent renewable sources by storing excess generation. Lastly, Security of supply was emphasized as a strategic driver, ensuring continuity of operations and energy availability in mission-critical environments. These values underline that battery business models in energy hubs extend far beyond financial returns, offering strategic, environmental, and operational benefits that are essential for the energy transition.

By incorporating all these findings, a structured framework was constructed. This framework offers a schematic approach to comprehend the business models of battery storage technologies in the energy hub setting. The framework suggests a linear process where drivers and barriers establish the ground for the decision on the business models for battery storage technologies that are more relevant to apply in energy hubs. Business models which then lead to the final part of the framework, the value created for the customer.

7.1. Scientific contribution

This study contributes to filling the gap in the literature on battery storage technologies, specifically relating to their application in energy hubs. As it was previously mentioned, battery storage technologies have been analyzed as a standalone technology, disregarding the connection with other stakeholders, technologies, and applications. Recently, with the introduction of decentralized cooperative systems such as energy hubs, a growing demand for a study that defines how these technologies can be valuable in this application has emerged. This study aims to fill that gap by providing a framework that can be used to describe how these business models for battery storage technologies are shaped in energy hubs.

This research builds upon existing literature to empirically validate the process by which business models of battery storage technologies are built in energy hubs. This process highlights the start from drivers moving into business models, while moderated by barriers, and eventually culminating in the creation of value. This perspective offers a structured way of assessing the rationales behind business models of battery storage technologies in energy hubs and a standardized method to evaluate the business models in place regarding whether they make sense.

Furthermore, this research empirically validates some of the information already known from the literature by identifying the core drivers and barriers for the adoption of battery storage technologies' business models in energy hubs, the main business models applied, and also the values created by them, further emphasizing their importance. For example, the majority of the business models found used in energy hubs are already a common occurrence in standalone batteries (e.g., storage-as-a-service, energy arbitrage, or frequency regulation); nonetheless, there was no indication that they would also be used in the energy hub setting, and on how they could be valuable in this setting. More so, their relevance changes significantly for different applications; most commonly mentioned topics in the literature, such as energy arbitrage and trading, were mentioned as an extra value for this case, and not a priority, as the literature states.

This study also highlighted some unknowns in the literature that can lead to further research. Regarding the barriers found, the lack of standardization and the lack of a legal framework were a novelty when compared to the available literature. Neither of these barriers is addressed as relevant by scholars, but the experts from the industry who participated in this research highlight them as core barriers for the application of battery storage business models in energy hubs.

In summary, this research fills the gap for a framework that explains how battery storage business models are shaped in energy hubs, by providing a comprehensive, structured approach for the process behind the choice and evaluation of these models. By empirically verifying the results through qualitative research based on semi-structured interviews with industry professionals, this study ensures validity and relevance, while exposing fields that require further exploration in research.

7.2. Practical implications in the real world

Energy hubs are a recent concept that is still in development. Throughout the interview process, it was often stated that there is still a significant amount of uncertainty surrounding the application of energy hubs in the energy system. Interviewees highlighted the need for a carefully constructed framework that can define the business cases for the technologies applied to such concepts. This study aims to fill this gap for battery storage technologies.

The novelty of energy hubs is the foundation for the most important practical application of this research. There is a clear lack of research in this field from a business perspective; therefore, this research can serve as a backbone for a further definition and exploration of battery storage technologies' business models to energy hubs. Professionals can use this research as an empirically verified aggregation of information that can contribute significantly to the understanding of the application of batteries to energy hubs. Nonetheless, it is still important to note that there is a crucial need to apply more energy hubs in order to build a good base of case studies that can help better explore the potential of this application.

With this research, there is also a clarification of the procedure of having battery storage technology in an energy hub. With this research, there is a clarification of the needs for this technology inside a hub, and the barriers for its application, giving a clear picture for industry professionals from which they can base their plans and choices. Furthermore, it helps evaluate what the most valued values are and understand what customers want from different perspectives.

Furthermore, regarding the expensive nature of battery storage technologies and the versatility of their application, this study can help professionals better frame the business model that they plan to use for their battery storage technology in their energy hub. For example, an energy hub that struggles with capacity, using this framework, can easily understand that energy arbitrage might not be the best business model to partake in and opt for a storage-as-a-service model that can provide more capacity in moments of peak demand. Furthermore, if this energy hub has an extensive number of companies involved, they will most likely suffer in terms of collaboration and the legal framework. By looking at this study, the industry can already be aware of these constraints and consider them when evaluating the business model that they are choosing.

8 Further Research

Even though this study provides relevant information regarding business models for battery storage technologies within energy hubs, there is still a significant research gap in this field. As mentioned in this report, energy hubs are a novel application of battery storage technologies; therefore, there are still plenty of areas where scholars can provide additional value. Moreover, certain topics mentioned during the interview process were not covered in this research, although they are important to take into account in a broader scope. In this section, suggestions for further research based on the hitherto presented findings will be provided.

Barriers of the battery storage technologies in energy hubs

The barriers identified hinder the application of battery storage technologies in energy hubs. This presents a gap where research can be conducted on how to overcome these challenges. The current literature still focuses solely on the technical challenges of operating energy hubs, disregarding many business challenges related to the application of technologies.

With a focus on battery storage technologies business models, this research highlights the work still to be done in covering all the barriers hindering the application of these business models in energy hubs. Further exploration of these could have practical impacts on the improvement of overall functioning and profitability of these models, and on driving the application of battery storage technologies in energy hubs.

Two of these barriers will be highlighted below. Due to the lack of research in those two specific cases, the need for research about them is even more important.

Lack of standardization of energy hubs

Throughout the interview process, the lack of standardization surrounding the concept of energy hubs was mentioned often. Interviewees highlighted the need for a standard way of creating and evaluating an energy hub; they expressed concerns regarding the integration of different technologies within the hub and a method for assessing outcomes of hubs prior to their implementation. Furthermore, the literature does not often delve into this need for standardization; there is a clear gap for further research to be undertaken.

More studies in this regard would have an impact on the application of energy hubs across the world. With increased standardization, this concept has the potential to be scalable, diminishing the need for extensive research on the viability of the business models of all the technologies involved, such as batteries. Even those studies would contribute to a standardized way of orchestrating energy hubs, which could also reduce uncertainty in these business models.

Lack of a legal framework for collaboration in an energy hub

Although this topic is not directly related to technology, it has a significant impact on energy hub behavior and orchestration. It was frequently noted that current contractual frameworks fail to capture the operational characteristics of an energy hub. This creates skepticism in terms of asset ownership and benefit collection; companies are less inclined to collaborate in the absence of clearly defined boundaries governing permissible activities in the context of an energy hub.

Research in this field also has the potential to enable the large-scale application of energy hubs. However, for this research to be effective, numerous factors have to be considered, including the political frameworks different countries adopt, the interests of different parties, and technological constraints. The conduction of further research into this facet is needed to increase the robustness of energy hub applications and improve the business models for battery storage technologies.

Unlocking company growth

Currently, there is still a considerable gap in the investigation of the role of battery storage technologies and energy hubs in fostering company growth. It has been established that reduced energy availability and high energy prices pose as a barrier for company expansion, but exactly how company growth could increase as a result of increased energy availability is yet to be quantified. Further research in this field would be important to better measure the outcomes of applying a battery storage technology in an energy hub and correctly assessing its impact.

Furthermore, it was common for interviewees to state that there should be a clearer approach to measuring growth tied to an increase in energy supply. The industry does not have a standardized way of quantifying growth as a value proposition of business models, consequently undervaluing the impact that it can have as a rationale for choosing a business model. There is a clear need for a structured, quantifiable approach that enables company growth to be studied as a parameter affecting business models.

Investment

During the interview process, investment was a topic that was often mentioned. Although vaguely, interviewees highlighted that the availability of capital has an impact on battery storage business models in energy hubs. Nonetheless, the emphasis and frequency indicated that it was not sufficiently relevant to be included as part of this research. Nonetheless, it is worthy of further exploration, as it has the potential to impact the dissemination of the technology.

Therefore, the impact of investment in business models of battery storage technologies within energy hubs is a field where a significant research gap persists. There is relevance in exploring what the key mechanisms of acquiring capital are, the key investors and stakeholders involved in this process, and research into a method for driving private investment into this field. This research could lead to practical implications, such as an increase in private stakeholders' willingness to invest and an overall broadened understanding of this paradigm for energy hub aggregators and participants.

Integration with other types of technologies

Energy hubs are capable of integrating multiple technologies. Hydrogen and heat-related technologies are growing in popularity, which was often mentioned during the interview process. There is a significant lack of literature exploring how the interaction between these technologies and batteries is reflected in business models.

It is relevant to describe how the business models for these technologies can profit from each other in a structured manner. Research in this field could uncover potential for novel business models centered around the combination of multiple technologies to create more value. That could have a significant positive impact on the application of batteries and energy hubs on a larger scale, and enable a more solid business case for customers who plan to invest in these technologies incorporated in an energy hub.

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A

Question Bank

Main Research Question: How do the business models of battery storage technologies work in energy hubs?

- On a scale of 1 to 5, how central are batteries to the success of energy hub projects?
- What percentage of your projects ROI is tied to battery-related functions?
- How many years do you expect batteries to be economically viable within your current hub setup?

Sub-question 1: What are drivers and barriers of the adoption of battery storage technologies in energy hubs?

- What makes a battery setup within a hub more adaptable to future technologies or markets?
- How do hubs help mitigate risks related to energy prices or grid constraints?
- What are the biggest risks to the long-term viability of battery solutions in energy hubs?
- How do partnerships or ecosystem dynamics within an energy hub contribute to capturing value from battery technologies?
- Do current regulations support the use of batteries in energy hubs?
- Can the batteries be easily upgraded, repurposed, or expanded in an energy hub?
- Does asset sharing in hubs (e.g., shared inverters or controls) reduce battery-related costs?
- What do the usual business models from batteries need to become more efficient? How can Energy Hubs help with that?
- Can energy hubs mitigate the main challenges for the adoption of batteries?
- What kind of battery would be ideal for an (your) energy hub?
- How do energy hubs help optimize the use of batteries from a technical or operational standpoint?
- Can you give me examples of situations where Energy Hubs enabled the application of batteries? And for what purpose?

Sub-question 2: What are the business models of battery storage technologies in energy hubs?

- What are the most promising business models you've seen for battery storage within energy hubs?
- Does the co-location of energy assets (e.g., renewables, EV charging, heat) create or enhance revenue streams for batteries? How?
- Are there specific market mechanisms or services (e.g., frequency regulation, capacity markets) that become more accessible or profitable in an energy hub setting?
- Do energy hubs enable new use cases for batteries that wouldn't be viable otherwise (e.g., load shifting, peak shaving, grid services)?
- Do batteries in hubs participate in local flexibility markets or capacity markets?

- How does the energy hub structure lower operating costs for battery systems?
- What strategies can you use to ensure batteries stay economically viable over time?

Sub-question 3: How do battery storage technologies provide value when applied to energy hubs?

- How does the integration with other technologies (PV, EVs, heat) increase the usefulness of batteries?
- Do energy hubs make battery investments more cost-effective? How?
- Is the impact of energy hubs on topics such as grid congestion and the integration of renewable sources in the energy mix a driver to the application of battery storage technologies?
- Are there environmental or social benefits that are intentionally included in your value proposition (e.g., CO reduction, energy autonomy)?
- Does battery integration in the hub help improve energy reliability or autonomy?
- How do you perceive the impact of the implementation of energy hubs on the implementation of batteries? Are there more grid-sized batteries being implemented due to the creation of energy hubs?

B

Interview Scripts

Below there are the scripts uses to interview the participants that participated on the research. The scripts are divided based on the groups shown and explained before.

All the interviews started with a round of introductions when the research could better understand the background of the interviewee, followed by an explanation of the research given by the research and going over the following topics:

- Explanation of the thesis topic
- Relevance of the research
- Methodology and "Why?"
- Summary of the process of the interview
- Consent for the use of information

B.0.1. Entrepreneurs and business professionals

1. How do you perceive the impact of the implementation of energy hubs on the implementation of batteries?
   (a) Are there more batteries being implemented due to the creation of energy hubs?
2. Can energy hubs mitigate the main challenges for the adoption of batteries?
3. Do energy hubs make battery investments more cost-effective?
   (a) How?
4. How do energy hubs enable new use cases for batteries that wouldn't be viable otherwise (e.g., load shifting, peak shaving, grid services)?
5. What are the most promising business models you have seen for battery storage within energy hubs?
   (a) Are there specific market mechanisms or services (e.g., frequency regulation, capacity markets) that become more accessible or profitable in an energy hub setting?
6. What role do energy hubs play in reducing costs or improving ROI for battery storage investments?
7. How do partnerships or ecosystem dynamics within an energy hub contribute to capturing value from battery technologies?
   (a) Do they make costumers more willing to take the risk of investing in battery storage technologies?
8. Do current regulations support the use of batteries in energy hubs?
9. What makes a battery setup within a hub more adaptable to future technologies or markets?
10. On a scale of 1 to 5, how central are batteries to the success of energy hub projects?
    (a) Why?

B.0.2. Technical professionals

1. How do you perceive the impact of the implementation of energy hubs on the implementation of batteries?
   (a) Are there more batteries being implemented due to the creation of energy hubs?
2. What kind of battery would be ideal for an (your) energy hub?
   (a) Why? What characteristics do you look for in a battery?
3. How does the integration with other technologies (PV, EVs, heat) increase the usefulness of batteries?
4. Do energy hubs enable new use cases for batteries that wouldn't be viable otherwise (e.g., load shifting, peak shaving, grid services)?
5. Can energy hubs mitigate the main technical challenges for the adoption of batteries (e.g., costs, system integration)?
6. How do energy hubs help optimize the use of batteries from a technical or operational standpoint?
   (a) Does asset sharing in hubs (e.g., shared inverters or controls) reduce battery-related costs?
7. How does the energy hub structure lower operating costs for battery systems?
8. Do current regulations support the use of batteries in energy hubs?
9. What makes a battery setup within a hub more adaptable to future technologies or markets?
10. On a scale of 1 to 5, how central are batteries to the success of energy hub projects?
    (a) Why?

B.0.3. Enablers

- How do you perceive the impact of the implementation of energy hubs on the implementation of batteries?
  1. Are there more grid-sized batteries being implemented due to the creation of energy hubs?
- What is the importance of battery storage technologies in energy hubs?
- What are the main drivers for the government/investor wanting more batteries and energy hubs?
- Is the impact of energy hubs on topics such as grid congestion and the integration of renewable sources in the energy mix a driver to the application of battery storage technologies?
- What are the ideal use-cases for batteries in energy hubs?
  1. Do you look for any specific value from the application of battery storage technologies in energy hubs?
- How likely would you support/invest in an energy hub with a battery storage technology incorporated?
- What role do energy hubs play in reducing costs or improving ROI for battery storage investments?
- Do current regulations support the use of batteries in energy hubs?
- Does policy incentivize the implementation of batteries in energy hubs?
- On a scale of 1 to 5, how central are batteries to the success of energy hub projects?

C

Informed Consent

Below, the consent form distributed among the participants can be found.

Delft University of Technology
THE ROLE OF ENERGY HUBS IN BATTERY STORAGE BUSINESS MODELS
INFORMED CONSENT FORM

Dear participant,

You are invited to participate in a research study titled *"The Role of Energy Hubs in Battery Storage Business Models"*. This study is conducted by Tiago Neves, MSc student at Delft University of Technology (TU Delft), as part of a graduation project within the master programme *Management of Technology*, under supervision of Prof. Hanieh Khodaei (TU Delft) and Linda Kamp (TU Delft).

The aim of this study is to explore how the adoption of energy hubs, has decentralized energy systems to combat grid congestion and other struggles with energy availability and pricing, are changing the business models of battery storage technologies. This study has the objective of creating a framework that can define how value creation, capture and delivery of battery storage technologies is being changed by this new application.

The study consists of a semi-structured interview that will last approximately 60 minutes. Participation is voluntary, and you may refuse to answer any question or withdraw from the study at any time, without providing a reason. With your permission, the interview may be audio recorded for accurate transcription and analysis. This transcript will be sent to you for review.

All data collected will be stored securely (TU Delft OneDrive) and treated with strict confidentiality. Any identifying information will be removed. Anonymised findings may be included in the thesis and in related academic or professional publications. A summary of the interview may be shared with you for feedback before publication.

All personal data will be preserved until July 2027 at the latest. It may be reused for future research and education purposes in the domain of business models for renewable energy. You will be anonymous in any and all outputs.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
3. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: data anonymisation, aggregation into key findings of all interviews and secure data storage only accessible by the TU Delft research team.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
4. I understand that the anonymised summaries will be made available for the research partners and will be publicly available with the scientific publication.	☐	☐
5. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

Signature

____________________________	____________________________	_________
Name of participant [printed]	Signature	Date

D

Mention Frequency Codes

D.0.1. Drivers Code Frequencies

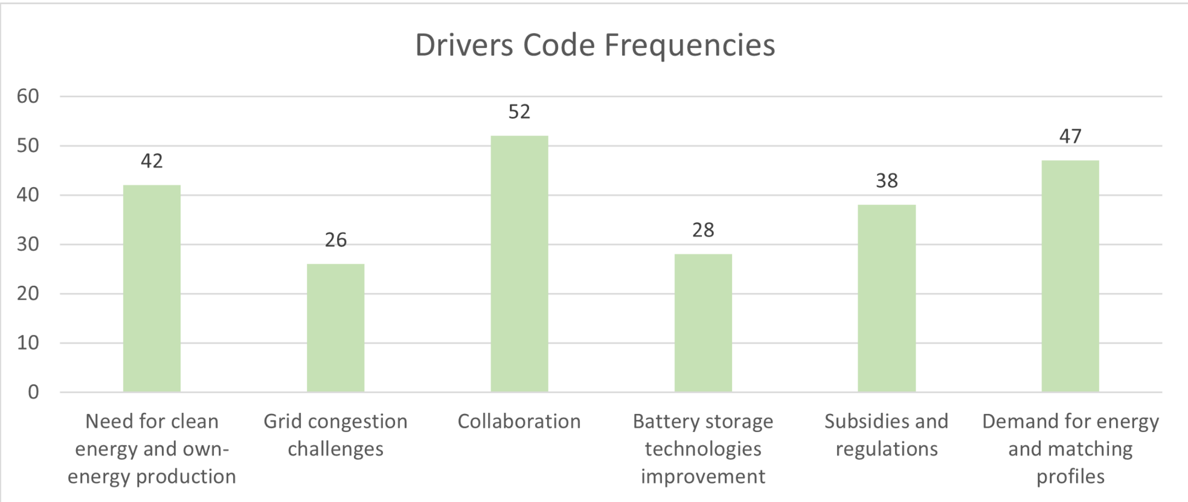

Figure D.1: Drivers Frequencies

D.0.2. Barriers Code Frequencies

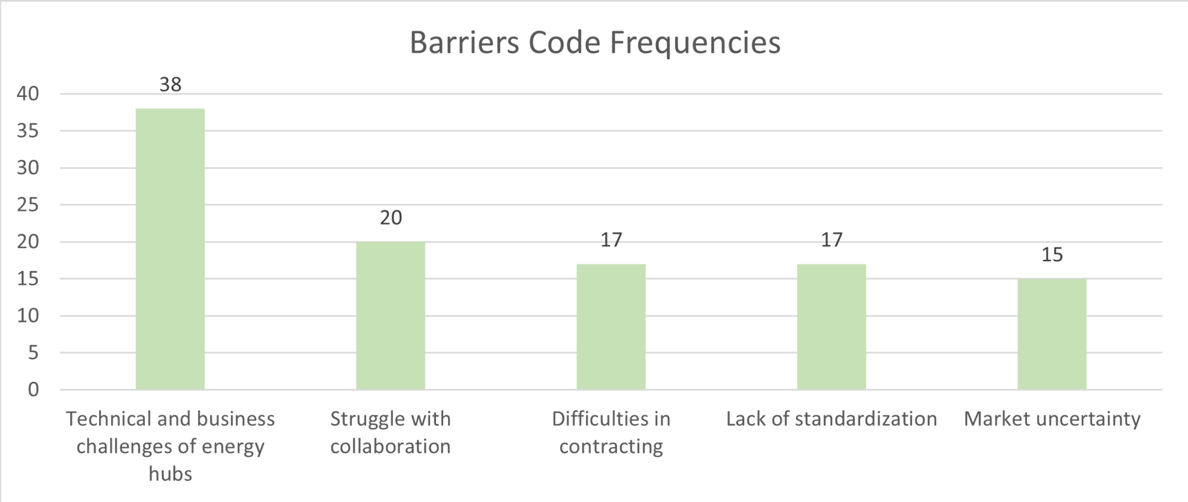

Figure D.2: Barriers Frequencies

D.0.3. Business models Code Frequencies

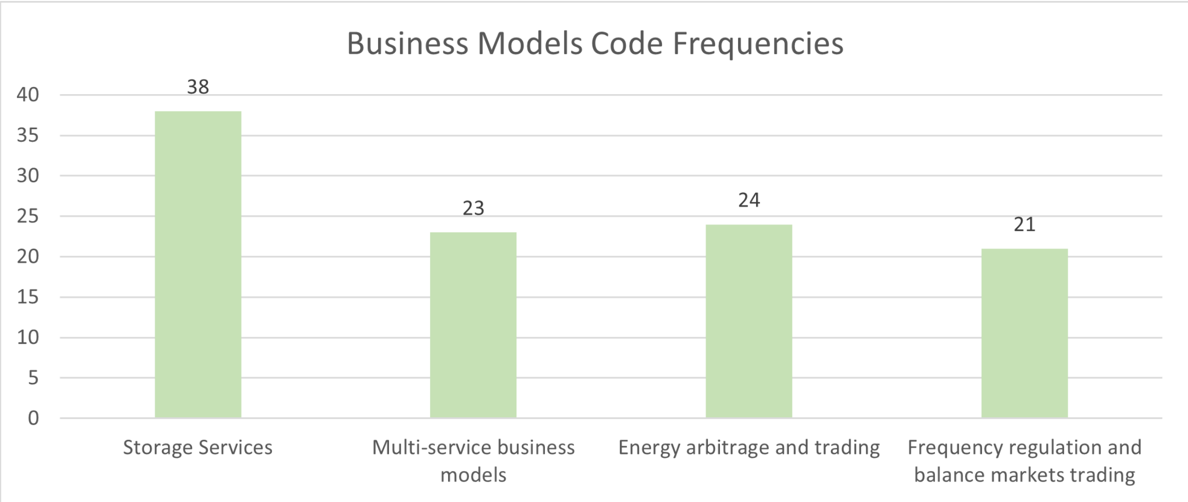

Figure D.3: Business models Frequencies

D.0.4. Value creation Code Frequencies

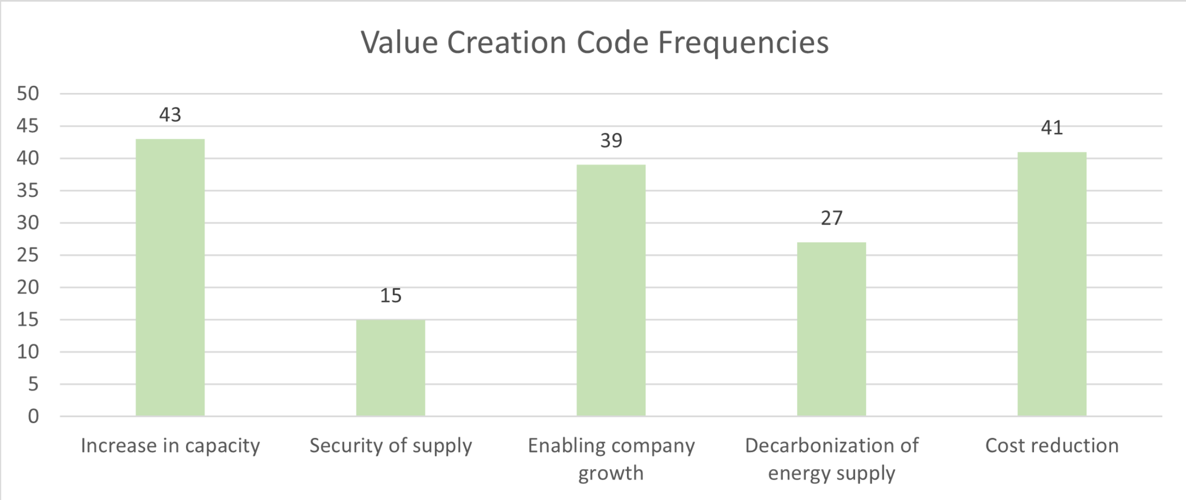

Figure D.4: Value creation Frequencies