



CHALMERS



The role of battery energy storage in industrial flexibility: Barriers to implementation & business model innovation at paper & pulp mills

Bachelor's Thesis at the Department of Technology Management and Economics

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**The role of battery energy storage in industrial
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Barriers to implementation & business model
innovation at paper & pulp mills**

**Batterilagringens roll för industriell flexibilitet:
Hinder för implementering och affärsmodellsinnovation
inom massa & pappersindustrin**

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Abstract

The Swedish electricity system is undergoing a transition characterized by increasing electrification, rising industrial electricity demand and a growing share of variable renewable electricity generation. These developments increase the need for flexibility resources that can support system balancing and reduce exposure to electricity market volatility. Battery energy storage systems (BESS) have therefore gained attention as a potential flexibility solution for energy-intensive industries. This thesis investigates the role of BESS in the Swedish paper and pulp industry and identifies the main barriers limiting implementation at paper and pulp mills.

The study combines semi-structured interviews with actors from the paper and pulp industry and the electricity system with a quantitative simulation and investment appraisal based on site specific data from two anonymized mills. The qualitative results show that BESS implementation is constrained by high investment costs, uncertain and market-dependent revenues, requirements for continuous production, existing flexibility solutions that reduce the perceived need for BESS, and regulatory uncertainty flexibility. The quantitative results indicate that electricity price arbitrage alone is financially insufficient while profitability depends mainly on revenues from ancillary services. In the base-case assessment, only one of the two studied sites reaches operating payback within the 24-month analysis period, and the investment outcome is highly sensitive to revenue levels and financial assumptions.

The thesis concludes that BESS can create value under specific site conditions, particularly where grid capacity, operational constraints and market access enable effective participation in ancillary service markets. However, under current conditions, BESS cannot be regarded as a generally viable flexibility solution for all paper and pulp mills. Whether BESS is viable depends on site-specific energy profiles, existing flexibility resources, investment costs and future electricity market development.

Keywords: BESS, Battery Energy Storage System, Paper and pulp industry, Pulp, Forest industry, Interview study, Flexibility, Industry, Ancillary service, Business model

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Malcolm Björsson, Hampus Hell, Karla Jerresand,
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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

P&PI	Paper and Pulp Industry
P&PM	Paper and Pulp Mill
BESS	Battery Energy Storage System
SvK	Svenska Kraftnät
aFRR	Automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
BSP	Balancing Service Provider
DoD	Depth of Discharge
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve - Disturbance
FCR-N	Frequency Containment Reserve - Normal operation
FRR	Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
PPA	Power Purchase Agreement
SoC	State of Charge
TSO	Transmission System Operator
EI	Swedens Energy Markets Inspectorate

1

Introduction

Climate change is a global threat primarily driven by anthropogenic emissions from fossil fuels. In response, global organizations such as the United Nations and the European Union have committed to achieving climate neutrality by 2050 [1, 2]. A key strategy for reaching these targets is the electrification of energy systems. According to the International Energy Agency, electrification plays a central role in decarbonizing the energy system and achieving net-zero goals [3].

In Sweden, this transition is particularly significant due to the country's energy-intensive industrial sector. Industrial electricity demand is projected to increase substantially, from approximately 48 TWh today to around 145 TWh by 2035 [4]. The industrial sector is a cornerstone of the Swedish economy and is responsible for nearly one-third of the nation's total greenhouse gas emissions. Achieving Sweden's climate goals, therefore, requires not only a transition away from fossil fuels but also rapid technological innovation and significant improvements in energy efficiency [5].

Within the industrial sector, the forest industry as a whole is a major economic driver, contributing approximately 2–3% to Sweden's total GDP and representing about 10% of the nation's total goods exports [6]. Within this framework, the paper and pulp industry (P&PI) plays a particularly important role. The P&PI sector also accounts for more than 50% of the total industrial energy use in Sweden with its energy-intensive production processes [7]. At the same time, the P&PI has been one of the industrial frontrunners. Since 2006, it has achieved a 60% reduction in carbon emissions, the most significant reduction compared to any other sub-sector [8]. This is largely due to long-term energy management efforts and increased use of biofuels instead of oil [9].

In parallel with the changes in energy use, the role of the industry in the electricity system has evolved. Historically, large parts of the Swedish P&PI owned and operated their own power generation, particularly through hydropower [9]. Although much of this capacity was decommissioned during the electricity market reforms of the 1980s and 1990s, the industrial interest in electricity production has increased once more in recent years. The P&PI has favorable conditions for renewable electricity generation and has invested in biofuel-based combined heat and power (CHP) plants as well as wind power on forest land. Today, companies within the forest industry produce up to 50% of the electricity they consume internally [10]. This combined role as both producer and consumer places the P&PI in a unique position

to contribute to system flexibility.

At the same time, the Swedish electricity system is currently undergoing a fundamental transformation, characterized by a shift from centralized, dispatchable power generation to a decentralized landscape dominated by variable renewable energy. The rapid expansion of wind and solar power has introduced intermittency into the national grid, resulting in increased price volatility and uncertainty regarding system stability. As the future indicates a continued expansion in both renewable capacity and industrial electricity demand, these fluctuations are expected to intensify. As a consequence, maintaining the required frequency balance between generation and consumption around 50 Hz has become increasingly complex [11]. The resulting instability has created an urgent need for expanded system flexibility [12]. In Sweden, this flexibility is largely procured through ancillary services markets operated by Svenska kraftnät (SvK), the Swedish transmission system operator. In recent years, particularly during 2023 [13] and 2024 [14], batteries and wind power have been the fastest-growing technologies in the Swedish ancillary service market.

To maintain the industry's trajectory towards net-zero in 2050, traditional sectors like the P&PI will need to integrate new technological solutions to handle this new energy reality. While various energy storage technologies, ranging from thermal and mechanical to chemical solutions, offer potential for managing grid variability, battery energy storage systems (BESS) have emerged as a particularly versatile choice for enhancing industrial flexibility. From a business perspective, BESS may provide several potential value streams for industrial actors. The system can be used at a paper and pulp mill (P&PM) site to reduce costs by discharging stored energy during periods of peak demand, thus lowering electricity costs, a known strategy called arbitrage. Through participation in ancillary services markets, BESS can also provide frequency regulation services to the national grid, thus creating an additional revenue stream for a P&PM [15]. Furthermore, battery systems can enhance energy resilience by providing rapid-response backup power to protect sensitive equipment from voltage drops or short-term outages [12].

Svenska Kraftnät has identified BESS as a critical tool for regulating volatile renewable production and providing essential frequency regulation services to maintain grid stability [15]. Large-scale industries, like P&PI, must play a central role in achieving climate neutrality. Despite being a frontrunner in the Swedish energy transition, there is a lack of comprehensive studies exploring how BESS can be integrated into the operational environment of a P&PM. This thesis aims to bridge that gap by investigating the technological and economic viability of BESS within this sector.

1.1 Purpose, problem definition and research questions

The purpose of this bachelor's thesis is to investigate the current situation of BESS in the Swedish paper and pulp industry, and to identify the main barriers limiting the implementation and business model innovation. By adopting a mixed-methods approach, including both quantitative and qualitative studies, the research aims to establish a comprehensive understanding of the subject. Further, the thesis focuses on understanding why BESS is not yet widely adopted, despite its potential role in increasing flexibility, and how technical, economic, and operational factors influence this development.

Despite that, BESS can be used to increase the flexibility of industries, it remains limited within the P&PI. While the technology is highlighted for improved energy management and participation in the ancillary market the interest from the P&PM is still low. Therefor, this study addresses the following research question:

What are the different barriers of implementing BESS in paper and pulp mills today?

2

Theory

This chapter provides the theoretical foundation for examining the implementation of BESS within the P&PI, including its associated potentials and barriers.

First, the paper and pulp industry is introduced to explain the operational context in which BESS would be implemented. The chapter then describes the Swedish electricity system, balancing markets and flexibility demand, since these create potential value streams for BESS. Finally, BESS technology, aggregation, investment appraisal, and simulation approaches are presented to support the later qualitative and quantitative analysis.

2.1 Background to the Pulp and Paper Industry

The P&PI has a long history in Sweden and is one of the most important sectors of the country's industry where 90% of all pulp and paper products being exported, which contributes considerably to the national GDP. [16, 6]. Pulp production is today primarily based on cellulose fibers from wood, making the industry closely connected to Sweden's forest resources [17].

Since the P&PI is energy-intensive and includes several different production processes [7], it is important to understand the basic structure of the industry when analyzing barriers and opportunities related to BESS implementation.

2.1.1 Importance of the Forest Industry in Sweden

Sweden has extensive forest resources with approximately 68% of the country's land area being covered by forest [18]. Due to this access to resources, the forest industry in Sweden has developed into one of the most important industrial sectors for the country, employing around 23% of the total workforce within the Swedish industry [16].

Sweden is the world's third-largest exporter of wood products, highlighting the importance of this industry to the country's economy. Alongside being important for the country, the forest in Sweden is also important for Europe, as 20% of the continent's forests are located in Sweden. Due to this, the Swedish forest industry is important for Europe from a pure economic perspective but also from a supply

perspective [16].

2.1.2 Overview of Pulp Production Processes

To produce pulp, different production methods can be used, primarily mechanical and chemical processes [17]. Both of the methods begin with similar preparation steps, where logs are loaded into a large rotation drum with the purpose of removing bark and branches. After this step, the logs are chipped into smaller wood chips, which are later continued with either the mechanical process or the chemical process in order to create the pulp [17].

During the chemical process, the wood chips produced in the initial stages are boiled at high temperatures in a chemical solution. This process causes the lignin, a glue-like substance that binds the fibers together, to separate from the cellulose fibers. As a result, strong and intact cellulose fibers are released [17]. The separated lignin is then burned together with other residual products, such as bark and branches, in a recovery boiler, generating energy for the P&PM [19].

Today, the chemical process is the most used method in pulp making, more specifically, the sulfate process[17]. The chemical process also has, as previously mentioned, the possibility to generate heat that can later be used to produce electricity for use within the mill, and also to dry the pulp before further processing. In addition, the chemicals used in the process can be recovered and reused [17].

The mechanical pulp process separates the fibers instead by using mechanical force in large refining machines. Compared with chemical pulping, this process is more electricity-intensive because it relies heavily on large machines, which require large amounts of electricity [17]. The fibers extracted from this process is more damaged, affecting the properties of the final product [17].

The processes are carried out in different ways and therefore have different energy demands in order to operate. The chemical process generates energy within its own process, whereas the mechanical process instead has a high demand for electricity [17]. In 2024, the pulp industry in Sweden produced approximately 6,139 GWh of electricity and purchased around 10,670 GWh [20].

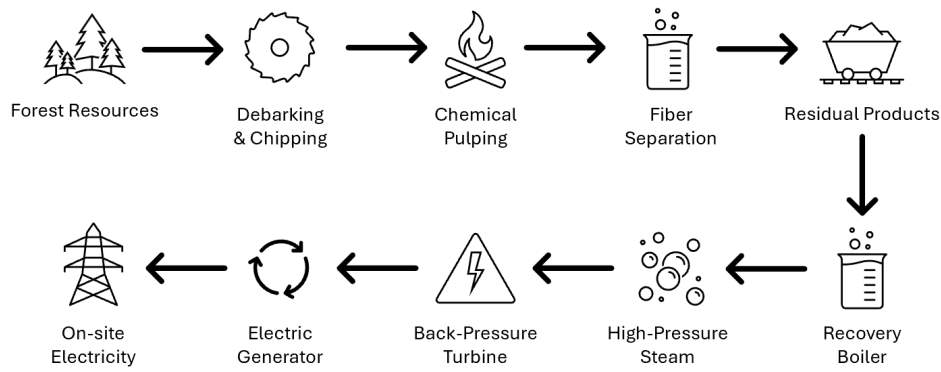


Figure 2.1: Simplified production line and energy recovery process of a chemical pulp mill. The figure illustrates the integrated flow from raw forest resources to the final products of paper pulp and on-site electricity.

2.1.3 Externalities

As mentioned, the chemical pulping process has historically utilized residual products for internal energy recovery, national climate strategies now encourage a transition toward "Waste-to-Value" applications. This strategic shift creates both critical opportunities and systemic challenges which are described in the roadmap provided by Fossilfritt Sverige [21]:

Positive Externalities:

- **Material Substitution:** Extracting byproducts like lignin enables the production of advanced biofuels and bioplastics, directly substituting fossil-based materials in hard-to-abate sectors .
- **Carbon Storage:** Refined biomaterials create long-term carbon storage, which is identified as the forest industry's primary climate contribution.

Negative Externalities:

- **Loss of Internal Generation:** Diverting waste streams from recovery boilers to biorefineries reduces internal back-pressure power generation, depriving the regional grid of stable, dispatchable electricity.
- **Increased Grid Dependence:** If mills transition from a high internal energy production of electricity, their peak capacity demands increase, exposing them to larger regional capacity tariffs.

2.2 Sweden’s electricity system and flexibility demand

The Swedish electricity market was fundamentally reformed in 1990 and implemented in 1996. This reform introduced a clear separation between competitive and regulated activities. Generation and retail were opened to competition, while transmission and distribution remained regulated by natural monopolies [22]. As a result, wholesale electricity pricing became market-based, while the physical operation of the grid remained centrally coordinated by SvK [22]. Following the reform, Sweden became part of a highly integrated Nordic electricity market, where cross-border trade and interconnector capacities play a central role in price stability [23]. Today, electricity trading primarily takes place on the Nordic power exchange, Nord Pool, across several time horizons [24]. Because electricity is traded across national borders, domestic prices in Sweden are not solely determined by national factors, but are heavily influenced by supply, demand, and transmission capacity in neighboring countries [25].

However, the seamless trade of electricity is constrained by the physical grid. When transmission capacity between different regions in Sweden is limited, congestion occurs, preventing electricity from flowing freely from low-price to high-demand areas. To manage these physical bottlenecks, Sweden is divided into four electricity bidding zones (SE1–SE4). These structural constraints can lead to temporary price divergences due to regional imbalances in production and consumption [26, 23]. Ultimately, the price differences between these four zones are a core feature of the market design, serving as critical economic signals indicating where grid reinforcements, local flexibility resources, or new generation capacities are needed [26, 23]. Furthermore, because electricity cannot be economically stored in large quantities within the transmission system, it must be consumed at the exact moment it is produced. This fundamental characteristic means that the financial electricity markets are inextricably linked to the physical realities of the grid [25]. The ultimate responsibility for managing this continuous real-time balance and ensuring the operational security of the national system lies with SvK [27].

2.2.1 The physical grid and grid operators

Svk determines how much transmission capacity can be made available for market trading without jeopardizing system security. The transmission network, which SvK owns and operates, consists of two interconnected high-voltage systems operating at nominal voltages of 220 kV and 400 kV. These lines transport electricity over long distances between major generation facilities, consumption centers, and interconnections with neighboring countries [26]. Below the transmission grid, electricity is distributed through regional and local grids. The regional grid typically operates at voltage levels between 40 and 130 kV and transfers electricity from the transmission grid to large industrial consumers and local distribution networks [28].

Due to their immense electricity demand and high-capacity requirements, P&PM

typically bypasses local networks entirely and connects directly to the regional grids. The specific grid level of this connection is highly significant from an economic perspective. The grid tariff structures and pricing models on the regional grid differ fundamentally from those on local distribution networks, creating distinct financial conditions for industrial consumers, which is further examined in section 2.4.1 [29].

2.2.2 The wholesale electricity markets

The largest market is the day-ahead market, where electricity is traded one day in advance for the following delivery day. Market participants submit their bids before 12:00 each day, specifying how much electricity they are willing to buy or sell and at what price. These bids are matched in an auction, where supply and demand determine the market-clearing price, commonly referred to as the spot price. The prices for the following day are published shortly before 13:00. As of October 1, 2025, the market operates on 15-minute trading periods, allowing prices to reflect short-term variations in supply and demand with greater accuracy than the preceding hourly-based framework [30]. In addition to the day-ahead market, the intraday market allows participants to adjust their positions closer to real time, while balancing markets are used to manage remaining imbalances during operation [31].

While bidding zones reflect structural transmission limitations, temporary variations in supply and demand still occur within each zone. As mentioned, actors can partly adjust their positions closer to real time on the intraday market [32]. However, even after intraday trading closes, real-time imbalances may still occur. These are managed through ancillary service markets, where SvK procures balancing services from actors capable of rapidly increasing or decreasing production or consumption. SvK projects that the demand for such flexibility resources will increase in the coming years, creating additional economic opportunities for actors capable of responding quickly to system needs [33].

2.2.3 Increasing demand for flexibility

Sweden aims to reach net-zero carbon emissions by 2045. At the same time, electricity demand is projected to reach 330 TWh by 2045, compared to approximately 170 TWh today, while peak demand is projected to reach 49 GW [34, 35].

Meeting this new demand will require significant investments in both electricity generation and grid infrastructure. If no new investments are made, parts of the existing production infrastructure will reach the end of their technical lifespan, which in turn would create a substantial gap between future electricity demand and available supply. Grid updates alone are estimated to cost around 1000 billion SEK [34].

A significant portion of the required new capacity is expected to consist of variable renewable energy. However, as emphasized in [36], this structural shift introduces the critical challenge of intermittency. An electricity system increasingly dominated by weather-dependent sources, such as wind and solar power, suffers from volatil-

ity in generation and a reduction in natural rotational inertia [36]. Because this intermittent production fluctuates independently of consumer demand, maintaining the real-time 50 Hz balance of the grid becomes substantially more complex and vulnerable to weather patterns [36].

Currently, 63 % of Sweden’s electricity production is renewable, with a large portion of it already consisting of variable renewable energy. Managing the growing intermittency is crucial [37, 36]. The Swedish Energy Authority [38] identifies flexibility as a primary mechanism for maintaining grid stability and optimizing system costs. According to [38] flexibility is defined as the ability to balance demand and supply through:

- **Adjustable Production:** Dispatchable sources, such as hydropower, that modulate output based on demand.
- **Energy Storage:** Utilizing energy storage systems, BESS or hydrogen, to shift energy supply over time.
- **Demand-Side Flexibility:** Adjusting end-user consumption patterns to align with generation peaks .

2.3 Power system frequency and balancing services

Frequency is a key operational indicator in the Nordic synchronous power system. The system is operated around a nominal frequency of 50 Hz, and the frequency must be kept within narrow limits to maintain secure operation. Frequency deviations occur when there is an instantaneous imbalance between total generation and total consumption (including imports and exports) [39].

The physical reason is that synchronous machines link electrical frequency to mechanical speed. When demand suddenly increases or generation is lost, the missing power is initially supplied by the kinetic energy stored in rotating masses of connected synchronous machines [40]. This slows down the machines, and the frequency decreases. The opposite happens during surplus generation. The amount of rotational energy in the system, therefore, affects how quickly the frequency changes after a disturbance, often expressed as the rate of change of frequency (RoCoF). Systems with lower rotational inertia experience faster frequency dynamics, which increases operational challenges and raises the need for fast-acting frequency support [40].

A growing share of inverter-based generation can reduce the available rotational inertia in the power system. Inverter-connected wind and solar power units normally do not provide rotational inertia and can displace conventional generators and their rotating machinery [41]. As a result, frequency dynamics become faster, making frequency control more challenging. To address this, a range of mitigation mea-

asures has been developed, including faster and more dynamic frequency control and the participation of storage-based resources in frequency containment reserves [41]. Synthetic rotational inertia (“inertia mimicking”) from wind and solar power units, as well as storage units, has also been identified as a mitigation option [42].

To manage both small continuous imbalances and large disturbances, the TSO procures balancing services with different response times. In Sweden, SvK uses several products that together form a hierarchical “layered” defense. This structure is designed to address different phases of a disturbance, starting with very fast support to arrest steep frequency drops, followed by reserves that stabilize the frequency, and finally products that restore the system to its nominal operating point [43].

2.3.1 Fast Frequency Reserve (FFR)

FFR is designed for the initial, very fast phase of frequency drop when system inertia is low. The product is activated automatically and reaches full response within a second (depending on the chosen activation threshold). The service is intended to prevent the frequency from reaching critical levels before slower reserves can fully activate [44].

2.3.2 Frequency Containment reserve (FCR)

FCR is the first continuously acting reserve that stabilizes the frequency following deviations from 50 Hz. Activation is local and proportional to the measured frequency deviation. In the Nordic market, FCR includes a symmetric product for normal operation (FCR-N) around 50 Hz as well as disturbance products for larger deviations (FCR-D up and down), each defined by frequency activation ranges. FCR-N is a symmetrical product, whereas FCR-D, along with the slower restoration reserves (aFRR and mFRR), are asymmetrical products procured specifically for either upward or downward regulation [42].

Unlike aFRR and mFRR, FCR does not have a single full activation time. Full activation refers to reaching the contracted power at the edge of the activation frequency range, while the required speed of response is specified through dynamic performance criteria (e.g., response levels evaluated at defined time instants in prequalification tests)[42].

2.3.3 Frequency Restoration Reserves (aFRR and mFRR)

While FCR mainly arrests and contains the deviation, restoration reserves are used to bring the system back towards the normal operating point and to release FCR capacity. aFRR is centrally controlled and automatically activated, with full activation required within minutes and an endurance requirement of one hour [45].

mFRR complements aFRR by providing additional balancing when imbalances are larger or persist over time. mFRR is activated through market-based energy activation and must reach full activation within 12,5 minutes, with endurance requirements that depend on the activation type [46, 30].

2.3.4 Implications for battery energy storage

BESS are technically well-suited for fast frequency services because they can change active power output quickly and with high precision. This makes BESS particularly relevant for very fast products such as FFR and for containment services such as FCR. Furthermore, batteries are uniquely advantageous in these markets because they can seamlessly provide both upward and downward response [47, 41].

At the same time, battery participation is constrained by limited energy capacity and by the state of charge (SOC), which must be managed to ensure availability for the contracted service. For instance, under the Nordic TSOs requirements for Limited Energy Reservoirs (LER), a BESS providing FCR-D must be able to sustain continuous full activation for a minimum of 20 minutes. This creates operational trade-offs when combining reserve provision with other value streams such as peak shaving or energy arbitrage, as the SOC must be actively managed (e.g., through Normal State Energy Management) to comply with these stringent endurance rules [47, 42].

2.3.5 Developments in FCR and mFRR markets

It has already been established that the increasing share of variable renewable energy in the Swedish electricity system has increased the need for frequency regulation services. Historically, this has driven up prices in SvK ancillary service markets, particularly for FCR and mFRR, creating strong financial incentives for investments in BESS [36].

However, unlike the intraday energy market, where demand grows alongside societal electrification, the demand for frequency reserves is strictly limited by technical system requirements. SvK procures only the exact power volume necessary to ensure grid stability, and the increasing volume of new flexibility resources creates an imminent risk of market saturation [36]. Once the aggregate capacity of BESS and other flexibility providers exceeds SvK's static procurement needs, the market will transition from being supply-constrained to highly competitive. This saturation will lead to significant price drops in returns, which could pose a financial risk to actors investing in flexible resources with historical price levels [36].

Specifically within the mFRR market, the transition from an hourly to a 15-minute time resolution on March 4, 2025, as part of the Nordic Balancing Model, enables price signals to reflect short-term fluctuations in supply and demand with significantly higher precision [48]. This increased granularity should allow the market to more effectively manage the volatility and imbalances introduced by a growing share of variable renewable energy.

2.4 Market access for industrial flexibility

While the previous sections describe the technical need for flexibility and the balancing services that BESS can provide, technical capability alone does not guarantee

market participation. For P&PM, this flexibility must also be made available to electricity markets through specific contracts or via specific aggregators. This is important because revenues from ancillary services are not created automatically when a mill installs a BESS, the asset must also comply with market requirements and be connected to the appropriate actors.

2.4.1 Contracts between P&PM and grid operators

The relationship and contract structure between P&PM and regional grid operators are shaped by the economic characteristics of the electricity grid. Because regional grids function as natural monopolies, their pricing models are strictly regulated by the Swedish Energy Markets Inspectorate (EI) to ensure objective and cost-reflective tariffs [28]. A defining feature of grid operations is the dominance of residual costs, where substantial sunk investments in infrastructure, such as high-voltage lines and transformers, account for the vast majority of a grid operator's expenses [49]. To finance these fixed costs, regulations dictate that industrial consumers must pay a fixed capacity fee based on a pre-determined subscribed power limit, typically locked in through annual contracts [50, 51, 52]. This is exemplified with figure 2.2 below.

Effektabonnemang regionnät	T130	L130	T130T40	T40	L40	I30T10	40T10	
Anslutningsspänning	132	132	33-55	33-55	33-55	6-24	6-24	kV
Fast elnätavgift	36	36	36	36	24			tusen kr/år
Fackavgift	300	130	75	75	75	38	38	tusen kr/år, fack
Effektavgifter								
Årseffekt (avtalad)	121	244	217	339	448	414	558	kr/kW, år
Överuttag årseffekt	20,2	40,7	36,2	56,5	74,7	69,0	93,0	kr/kW, vecka
Fritt reaktivt uttag	15%	15%	25%	25%	25%	15%	25%	av årseffekten
Max fritt reaktivt uttag	15	15	15	15	15	15	15	MVar
Fri reaktiv inmatning	5%	5%	10%	10%	10%	5%	10%	av årseffekten
Max fri reaktiv inmatning	5	5	5	5	5	5	5	MVar
Förhöjd reaktiv effekt (avtalad)	40	40	40	40	40	40	40	kr/kVAr, år
Avgift Reaktiv effekt	16	16	16	16	0	16	16	kr/kVAr, månad
Rörlig elnätavgift, fastställd	1,40	2,00	1,50	2,10	2,80	2,10	2,90	öre/kWh
Rörlig elnätavgift, spotpris	0,00%	0,31%	0,02%	0,33%	0,64%	0,33%	0,66%	% av spotpris

Figure 2.2: Regional grid provider Ellevio's regional grid tariff structure borrowed from their 2025 tariff levels [50].

Consequently, a P&PM facility pays for the right to a maximum capacity regardless of its actual utilization, rendering this expense a sunk cost from the mill's perspective. Furthermore, while these contracts offer no or limited reductions for temporarily lowering consumption below the subscribed limit, they impose large penalty fees for any power withdrawals that exceed it [52, 51]. This rigid structure incentivizes industrial actors to deliberately over-subscribe and hoard capacity as a safety margin against potential penalties, a behavior that contributes to the phenomenon called virtual grid congestion, where capacity is legally bound but physically unutilized [53]. Ultimately, this traditional contract design prioritizes revenue security

for grid operators and currently lacks the dynamic economic incentives required for P&PM facilities to offer short-term flexibility to the broader energy system [49]. However, this rigid tariff design has come to EI's attention and will possibly see a structural reform in the coming years. The widely mentioned government inquiry highlights these very shortcomings, stating that the current uniform tariff structures are inadequate for addressing local capacity challenges [36]. The inquiry formally recommends that EI evaluate how grid fees are transferred between voltage levels and investigate the implementation of clearer locational signals and more transparent energy fees. By doing so, EI could create the predictability needed for industrial customers to properly value and deploy flexible resources, such as BESS, to alleviate grid congestion [36].

2.4.2 Contracts between P&PM and electric markets

The contracts between paper and pulp mills (P&PM) and the electrical system in Sweden is structured through defined institutional roles within a liberalized market [54]. Actors do not participate in the electrical balancing markets through direct agreements with the grid operator. Instead, participation is mediated through formal roles as Balance Responsible Party (BRP) and Balancing Service Provider (BSP). These contracts carry both specific legal and operational responsibilities [54].

Prior to 2024, the Balance Responsible Party (BRP) and Balancing Service Provider (BSP) roles were not formally separated, and participation in ancillary service markets was institutionally tied to balance responsibility. This increased both administrative complexity and financial exposure for actors providing balancing services. The reform that was introduced in May 2024 separated the roles of BRP and BSP, allowing actors to deliver ancillary services without the need for imbalance responsibility, thereby reducing institutional entry barriers for industrial flexibility providers [54].

Following the separation of BRP and BSP roles, now only registered BSPs may offer ancillary services such as FCR, aFRR, and mFRR to the TSO [55, 23]. While industrial actors can register BSPs directly with the TSO, participation frequently occurs through external BSPs or independent aggregators. Direct participation requires formal delivery obligations toward the TSO as well as compliance with technical and reporting requirements [55]. Indirect participation via an external BSP allows industrial actors to outsource these responsibilities while retaining access to ancillary service revenues [56].

In addition to participation in the balancing market, P&PM engage with the electricity system through procurement contracts [56]. These contracts define price exposure and imbalance responsibility, and may include power purchase agreements (PPAs) to manage price risk and secure electricity supply [57].

2.4.3 Aggregators

Aggregators combine flexibility from electricity consumption, generation or storage into marketable units that can be offered in electricity markets. By pooling several resources, they enable smaller and more distributed assets to participate in a more coordinated way. In the Swedish and European regulatory context, aggregation refers to the combination of multiple loads or production resources for sale, purchase or auction in electricity markets. Aggregators have become more relevant as power systems include more variable renewable generation and a larger number of flexible distributed resources [58].

Within industrial demand response, aggregators act as intermediaries between flexibility providers and power markets. Their role is not limited to bidding, but also includes portfolio coordination, dispatch, control signals, and support during implementation. This is important in industrial settings because technical flexibility does not automatically lead to market participation. Knowledge of market requirements, internal coordination, and access to suitable market channels are often needed before flexibility can be commercialized [59].

In Sweden, aggregation has been given a more formal role in the electricity market, while participation in ancillary service markets is tied to market roles such as BSP. Balancing services are therefore delivered either by actors that hold a BSP agreement themselves or through cooperation with an approved BSP. This structure improves the conditions for smaller and more distributed resources that would otherwise face difficulties in meeting market requirements on their own [58, 60].

The economic value of aggregation depends on the conditions of the surrounding market. Profitability is shaped by factors such as market structure, asset characteristics, electricity prices, and remuneration in ancillary service markets. Aggregation should therefore be understood as a way to access and coordinate flexibility in electricity markets rather than as a guarantee of profitability in itself [59, 61].

2.5 BESS in Sweden and its applications

Energy storage in the form of battery systems has become a crucial part of Sweden's grid stability due to their ability to respond quickly to changes in electricity supply and demand. [62]. Electricity users can use BESS for several applications, including ancillary services, peak shaving, arbitrage and backup or island operation. These applications may create new revenue streams or reduce electricity costs for the industry [63].

2.5.1 Lithium-Ion Battery Technology

Parameters to be considered when selecting which type of battery for BESS include energy density, power density, safety, life cycle durability, and cost [64].

Most batteries used in BESS are often of the lithium-ion (Li-ion) type, since they of-

fer significantly higher energy density compared to alternatives such as lead-acid and nickel-metal hydride batteries [65]. Within lithium-ion batteries different chemistries are used depending on its application. For stationary large-scale BESS, Lithium Iron Phosphate (LFP) batteries is commonly preferred because it offers more cost-effective, long life cycle, and higher safety batteries compared to Nickel-Manganese-cobalt (NMC) batteries [64, 66]. NMC batteries are instead preferred in electrical vehicles due to their high energy density [66].

Lithium-ion batteries (LIB) are rechargeable batteries, where energy is stored and released through the movement of lithium ions between two electrodes during charge and discharge [65]. This makes them suitable for repeated cycling in applications such as energy storage.

2.5.2 System Architecture and Efficiency

An industrial BESS consists of several components, where a single battery cell is the smallest functional unit. Multiple cells are connected to form a module to achieve the desired voltage, and several modules are physically stacked into a rack. The entire system is overseen by the battery management systems (BMS), which acts as the "brain", monitoring each cell to prevent overheating and overcharging. Since batteries store direct current (DC) while the power grid uses alternating current (AC), a power conversion system (PCS) or inverter is also required [65].

Lithium-ion batteries have a round-trip cycle efficiency of 75-90%, meaning some energy is lost during charging and discharging. These losses are mainly released as heat, which makes cooling systems important to ensure optimal performance and preventing accelerated aging. When integrating BESS into sensitive industrial environments such as P&PMs, safety, temperature control and grid architecture are critical considerations [64]. Large-scale BESS may use isolated network configurations, such as IT-systems, to reduce the risk of short circuits, sparks and electric arcs. These systems are monitored by insulation monitoring devices (IMDs), which detect insulation faults to alert operators of any anomalies [64].

2.5.3 Operational parameters and degradation

To safely operate and evaluate the battery, mathematical parameters are continuously monitored. A crucial variable is the State of Charge (SOC), which indicates the ratio of available electrical charge to the battery's maximum capacity. Conversely, the Depth of Discharge (DoD) indicated the percentage of the battery that has been discharged [64]. Additionally, the C-rate describes the applied current relative to the battery's maximum capacity, dictating the speed of charge and discharge [65].

Battery degradation occurs through two primary aging mechanisms: calendar aging and cycle aging. Calendar aging takes place over time, even when the battery is not actively used, and is influenced by factors such as temperature and SoC. Cycle aging is caused by repeated charge-discharge cycles and depends on factors

such as the DoD, the applied C-rate, and the cumulative energy throughput [67]. These degradation mechanisms are important because more intensive battery use can increase revenues but also reduce battery lifetime.

2.5.4 Environmental Impact and Life-cycle

To evaluate BESS from a comprehensive sustainability perspective, the entire life cycle must be considered. While BESS facilitates renewable energy integration, the production of lithium-ion batteries carries a substantial environmental footprint [68]. The manufacturing process involves mining rare metals and highly energy-intensive electrolysis. Studies estimate that the greenhouse gas emissions from producing a lithium-ion battery range between 80 and 150 kg CO₂-equivalents (CO₂e) per kWh of battery capacity, depending heavily on the energy mix used in the manufacturing region [68].

End-of-life management is also important, since recycling can reduce the need for virgin raw materials and recover valuable battery components. Several recycling methods exist, including hydrometallurgical, pyrometallurgical and direct recycling processes [66, 64]. A detailed life-cycle assessment is outside the scope of this thesis. Instead, environmental impacts are considered as part of the broader context for evaluating BESS implementation.

2.5.5 Peak shaving

In the Swedish regional power grid, grid operators use specific tariff structures to prevent grid overload. For energy-intensive industries like paper mills, the tariff usually includes two main components: a fixed annual capacity charge based on the maximum subscribed power, and a dynamic high-load demand charge. This high-load charge is heavily penalized and applies exclusively during the winter months (usually November to March) on weekdays between 06:00 and 22:00 [29]. By installing a Battery Energy Storage System (BESS), industries can utilize "peak-shaving". This strategy involves discharging the battery during these expensive winter peak hours to lower the facility's maximum power draw from the grid. As a result, the facility can significantly reduce its regional grid distribution costs without having to decrease its actual production or total energy consumption.

2.6 Simulating lifetime profitability of multi-asset systems

Accurately assessing the lifetime profitability and best use cases of a large-scale BESS investment is a complex challenge. It requires modeling the dynamic interaction between grid requirements, market volatility, and non-linear battery degradation. Specifically, the challenge of "revenue stacking", that is, optimizing simultaneous participation in multiple markets, requires advanced algorithmic solvers that static calculations cannot match [69].

The real-world behavior and profitability of these systems are highly dependent on specific operational parameters, such as battery chemistry characteristics, power conversion efficiencies, and geographical location. The geographical location determines which physical electricity markets the BESS can access. However, modern energy infrastructure increasingly co-locates BESS with renewable generation, such as solar or wind power, forming hybrid energy systems. Optimizing these multi-asset systems extends beyond simple battery management; it involves dynamically balancing internal generation, grid capacity constraints, and fluctuating market prices in real-time.

2.6.1 Modeling approaches

To evaluate operational strategies, different levels of abstraction can be applied depending on the research objective. Traditionally, tools like SimSES have been utilized to model the complex interactions within a BESS. Such high-fidelity models provide an object-oriented framework that simulates the entire energy conversion chain, including inverters, auxiliary systems, and advanced semi-empirical degradation based on precise physical states [70].

While highly accurate for hardware design and capturing dynamic efficiency losses, these holistic physical models are often computationally heavy. When the objective shifts towards long-term market simulation and financial optimization across multiple assets, a techno-economic approach is often preferred. Techno-economic models abstract deep physics into financial and operational constraints, such as simplified efficiency rates, power limits, and cost-per-cycle degradation penalties. This abstraction allows for rapid, iterative simulations of multi-market strategies over a system’s lifetime.

2.6.2 Model Predictive Control in Energy Markets

Historically, battery dispatch was often governed by simple Rule-Based Control (RBC) strategies, which rely on reactive, predefined logic [71]. However, due to the increasing complexity of multi-market participation and hybrid energy systems, Model Predictive Control (MPC) has emerged as the modern industry standard for BESS optimization [69, 71].

MPC is an advanced closed-loop algorithm that utilizes a receding horizon strategy to proactively manage battery assets. By continuously updating AI-driven forecasts for market prices and weather conditions, MPC can maximize the financial return of the operation while strictly adhering to physical limits, such as State of Charge (SoC) boundaries and local grid capacities [69]. This predictive, constraint-aware method is fundamental to maximizing asset value and serves as the core computational logic for the simulation framework introduced in the subsequent section.

2.6.3 Applied Simulation Framework with Aire Energy Platform

To conduct the operational research in this study, the simulation platform developed by Aire Energy Solutions [72] is utilized. Unlike purely physical models, this tool is structured around techno-economic parameters, making it significantly faster and highly suitable for multi-market optimization. The platform acts as a digital twin of a hybrid energy site. By using market data, local electricity consumption data, and specific user-defined constraints, such as activation costs, energy capacity, and round-trip efficiency, the platform's optimization engine determines the most profitable dispatch strategy for each hour [73]. Utilizing this tool allows the methodology of this thesis to focus on market behavior and the financial impact of revenue stacking, rather than the microscopic physical behavior of the battery.

2.7 Investment appraisal metrics

Investment appraisal is used to assess whether an investment is financially justified by comparing the required initial investment with expected future cash flows. In the context of BESS, this is particularly important because the investment requires substantial upfront capital expenditure, while the revenues depend on uncertain market conditions, operational constraints, and the ability to combine multiple value streams [74, 75].

2.7.1 Net present value

Net present value (NPV) is a discounted cash-flow metric that compares the present value of expected future cash flows with the initial investment [74]. It is commonly expressed as:

$$NPV = -I_0 + \sum_{t=1}^T \frac{CF_t}{(1+r)^t} \quad (2.1)$$

where I_0 is the initial investment, CF_t is the cash flow in period t , r is the discount rate, and T is the analysis period. A positive NPV indicates that the investment is expected to generate value above the required rate of return, while a negative NPV indicates that the investment does not meet the required return threshold. The choice of discount rate is therefore central, since it determines how future cash flows are valued relative to the initial investment.

2.7.2 Internal rate of return

Internal rate of return (IRR) is the discount rate that makes the NPV of an investment equal to zero [74]. It is therefore defined by:

$$0 = -I_0 + \sum_{t=1}^T \frac{CF_t}{(1 + IRR)^t} \quad (2.2)$$

IRR is often used to compare investment alternatives, as it expresses profitability as a rate of return.

2.7.3 Payback period and return on investment

Payback period measures how long it takes for cumulative cash flows to recover the initial investment [74]. It is a simple and intuitive metric, but it does not account for the time value of money or cash flows occurring after the payback point. Return on investment (ROI) expresses the net return relative to the initial investment and can be used as a simple measure of profitability:

$$ROI = \frac{\text{Net cash flow}}{\text{Initial investment}} \quad (2.3)$$

Both payback period and ROI are useful for illustrating investment performance, but they should be interpreted together with other metrics since they simplify the timing and risk of future cash flows.

2.7.4 Residual value and operating break-even

For assets with an economic lifetime longer than the analysis period, residual value can be included to represent the estimated remaining value of the asset at the end of the period [75]. In BESS investment appraisal, this can have a substantial effect on total net cash flow when the analysis period is shorter than the expected useful life of the battery system [75].

Operating break-even, in contrast, evaluates whether the investment can be recovered through operating cash flows during the analysis period without relying on residual value. This distinction is important because an investment may appear profitable when residual value is included, while still failing to recover the initial investment through operating revenues alone.

2.8 Externalities

Externalities occur when an activity creates costs or benefits for actors that are not fully reflected in the private decision of the actor making the investment. A negative externality exists when an activity creates costs that are not fully paid by the actor causing them. A positive externality exists when an activity creates benefits that are not fully captured by the actor making the investment [76].

This distinction is important when evaluating investment that affect both private actors and wider systems. A project may be rational from societal perspective if it

creates broader benefits, even if these benefits are not fully reflected in the investor's own revenues. In the same way, a project may appear less attractive from a private perspective if the investor carries the main cost while other actors receive part of the benefit [76].

An investment must also take into consideration externalities to provide a robust economic assessment for the project [76]. As already mentioned in the roadmap from Fossilfritt Sverige [21], the P&PM residuals have alternative economic potentials, which in turn increases the mills' external electricity demand. In accordance with economic theory, this shift could inherently increase the financial value of the BESS.

3

Methodology

This chapter presents the methodological approach used to address the purpose of the study and the research questions. The chapter is structured around the research design, the qualitative and quantitative methods applied, and a final discussion of methodological considerations, including delimitations, limitations, method critique, and ethical considerations.

3.1 Research approach and design

This study adopted an abductive research approach, in which insights from existing literature were continuously combined with empirical findings from interviews and quantitative analysis [77]. An abductive approach was considered appropriate since the study addressed a topic where both the academic literature and the practical industrial applications are still developing. Rather than applying a purely deductive or inductive logic, the study moved iteratively between theory and empirical material in order to refine the understanding of BESS in an industrial context [77].

The study was designed as a mixed-methods study, combining qualitative interviews with a quantitative simulation and investment appraisal. The qualitative part was used to explore how actors within and around the paper and pulp industry (P&PI) perceive the opportunities, barriers, and value-creation potential associated with battery energy storage systems (BESS). The quantitative part was used to assess technical and economic conditions in more detail for different mill profiles. This combined design was chosen because the research questions concern both actor perceptions and the operational and economic feasibility. A purely qualitative design would not have been sufficient to assess economic performance, while a purely quantitative design would not have captured the organizational and process-related constraints that strongly influence BESS implementation in practice [78, 79].

3.2 Qualitative methods

3.2.1 Literature study

A structured literature study was conducted in order to provide the theoretical and technical foundation for the thesis. The literature study supported the analysis in three main ways. First, it was used to build background knowledge on the Swedish electricity market, ancillary services, BESS technology, and industrial flexibility. Second, it helped identify key concepts and themes relevant to the research questions. Third, it informed the development of the interview guides and supported the interpretation of the empirical findings.

Scientific literature was identified primarily through Scopus and Google Scholar. In addition, official publications and reports from relevant authorities and system actors, such as Svenska kraftnät (SvK), were used where appropriate. Academic peer-reviewed publications were prioritized in order to ensure scientific quality, but industry reports, corporate documents, and sector-specific articles were also included when necessary. This was particularly important in relation to BESS, since both regulation and technology are developing rapidly, and some of the most up-to-date information is not yet available in peer-reviewed form.

The literature selection was guided by relevance, credibility, and recency. Recent publications were prioritized, especially in areas related to battery technology, market conditions, and regulation, where older literature may no longer reflect current conditions. However, older sources were also included when they were considered foundational or necessary for explaining central concepts.

3.2.2 Interview selection and data collection

The main empirical material in the qualitative part of the study consisted of semi-structured interviews. This interview format was chosen because the study sought to capture how different actors understand and assess the opportunities and constraints related to BESS in the paper and pulp industry (P&PI). Semi-structured interviews made it possible to cover a common set of core themes while also allowing room for follow-up questions and actor-specific discussion [78].

Interviewees were selected through a non-probability purposive sampling strategy, targeting respondents expected to contribute relevant knowledge regarding BESS implementation, mill operations, electricity markets or industrial flexibility in the P&PI [80]. Within the mills, professionals with diverse roles were included, ranging from operational and production-oriented positions to strategic and energy-related roles. This ensured variation in perspectives across different mill conditions and organizational roles. Most interviewees were contacted by email, and in some cases, a snowball sampling approach was used where contact was established through referrals from professional connections, which was considered appropriate given the specialized nature of the industry-specific competence required [80].

To provide a broader, system-level understanding, additional actors from the elec-

tricity and BESS ecosystem were included. These included a distribution system operator (DSO) with ownership experience of BESS assets, a representative from the transmission system operator (TSO), an aggregator, a BESS developer and supplier, and an energy expert from a large energy company. By including actors from different parts of the value chain, the study was able to capture interactions between industrial users, market actors, and technology providers. An overview of the interviewed actors and their labels in this report is provided in Table 3.1.

Table 3.1: Overview of actors and their labels in the report

Type of actor	Label in report
Paper and pulp mills	P&PM A, B, C, D, E
DSO and BESS asset owner	DSO
Energy system expert (Research & Development manager)	Energy expert
Transmission system operator	TSO
BESS developer and supplier	BESS actor
Aggregator and energy optimization provider	Aggregator

The interviews were based on a semi-structured interview guide and centered on recurring themes, such as the mill’s energy profile, experiences of flexibility, electricity purchasing strategies, and perceived BESS value drivers like peak shaving and ancillary services. The guides were adapted slightly depending on the actor’s role to ensure relevance. The interview guides are presented in the appendices C and D.

3.2.3 Qualitative data analysis

The interview material was analyzed using thematic analysis, following a primarily inductive approach, meaning that codes and themes were developed from the interview material rather than from a predefined coding framework [81]. After each interview had been transcribed, the material was coded in order to identify recurring patterns, similarities, and differences between respondents [81]. The coding process was conducted in pairs, and to reduce interpretive bias, each interview was analyzed by two group members who had not conducted the interview. Each of the two coders first reviewed and coded the transcript individually, after which the codes were compared and merged into a common coding structure. Any differences between the two coders were discussed until a shared interpretation was reached, and the final coding structure was adjusted accordingly. This procedure was used to reduce the risk that the analysis would be overly influenced by a single researcher’s interpretation [78]. The emerging themes were then compared with the research question and theoretical background to ensure relevance to the purpose of the study.

The coding process resulted in a set of themes related to the research questions. These themes were compiled in a shared Excel workbook, where codes and themes from the different interviews were compared and organized. A summary of the final themes, associated codes, and verbatim quotes is provided in Appendix B. The themes were partly informed by the research questions and the literature study, but they were also allowed to emerge from the empirical material. This made it possible

to capture both expected and unanticipated findings.

In line with triangulation theory presented by Patton [79] and Denscombe [78], triangulation was applied in two ways. First, interview findings were compared across different parts of the value chain in order to identify where perceptions converged and where they differed. Second, themes from the interviews were examined in relation to the literature study, in order to assess how empirical findings aligned with, complemented or challenged previous research and sector knowledge. Triangulation was therefore used both as a validation technique and to develop a more nuanced analysis.

3.3 Quantitative methods

3.3.1 Quantitative data and analytical purpose

The qualitative analysis was complemented by a quantitative assessment in order to examine the technical and economic conditions for BESS more concretely. Whereas the qualitative part focused on organizational constraints, actor perceptions and implementation conditions, the quantitative part focused on the operational and financial performance of BESS under different mill conditions. To ensure industrial relevance, site-specific data were obtained. This includes site-specific electricity usage and power subscription agreements. The data were provided by two companies representing one P&PM each. Due to the companies' explicit requests for anonymity, the raw data will not be publicly disclosed or appended to this report. Because of this, we will call the two sites Object 1 and Object 2, respectively.

The collected data were then used for simulating operations for a BESS at each site. The simulation model was provided by Aire Energy, an energy optimizer company specializing in optimizing energy resources [72]. The model simulates how the battery would perform if the company prediction model was used during a historic period. This means that the model maximizes net revenue from energy arbitrage and frequency regulation markets (revenue stacking) while strictly adhering to system constraints. This approach was chosen to manage the complexity of balancing multiple operational goals in real-time. These constraints include physical battery limitations (such as C-rates and State of Charge boundaries), grid connection limits, and the specific industrial load requirements of the P&PM. Hence, the use of site-specific data provided by P&PI actors ensures the model's accuracy and industrial relevance.

To isolate and evaluate the financial impact of different revenue streams, the simulations were conducted using two distinct scenarios for each site. The first scenario evaluated operations based solely on energy arbitrage. The second scenario incorporated revenue stacking, combining energy arbitrage with the ancillary services FCR and mFRR. While the Swedish balancing market includes several other ancillary services, the scope was restricted to FCR and mFRR, as Aire Energy's simulation tool is limited to those, and their operational experience indicates these are the most viable and utilized markets for BESS under current conditions [73]. The output of

the simulation then served as the basis for the subsequent economic evaluation, providing a realistic operational profile rather than a theoretical maximum. The results from the simulation generated input values for calculating simple payback period, net cash flow, internal rate of return (IRR), operating break-even, and simple return on investment (ROI). Using these figures, the report evaluated the financial viability of BESS and compared the different P&PMs.

3.3.2 Parameter setup and model delimitations

To accurately simulate the financial and operational performance of the BESS at the selected P&PM sites, several parameters, constraints, and operational assumptions were established. The simulation environment is divided into three main components: the Grid Node (representing the external connection and tariffs), the Industry (representing the passive mill consumption), and the BESS itself.

Load Profile Extrapolation

Due to data availability constraints, the high-resolution empirical load data provided by the P&PMs covered a period of one month. To evaluate annual profitability, this data was extrapolated to represent a full year. A direct duplication approach was avoided to prevent the distortion of operational trends. Instead, the data was extrapolated in four-week blocks. This method successfully preserved weekly variations and specific daily trends which can be seen in figure 4.1 in the result section 4.2.1

Simulation runperiod

The simulation tool was only able to run from February 2024 to the present. Because of this, we decided to run it for 2 complete annual cycles, first from February 2024 to February 2025 and the second from February 2025 to February 2026.

BESS Sizing Strategy and Technical Specifications

The physical size of the BESS for each object was determined with an iterative sizing strategy. Initially, the baseline battery capacity was dimensioned to absorb the unused power margin between the mill's maximum grid connection limit and its typical base load. Since utility-scale batteries are typically delivered in megawatt increments, the capacity was rounded up accordingly. To identify the optimal financial setup, variations of 0.75 and 1.25 times this baseline capacity were also simulated. The most profitable configuration was ultimately selected for the final results. The batteries were assumed to operate at a C-rate of 1.5, (meaning a 10 MWh capacity yields an maximal power output of 15 MW).

To maximize the cycle life of the battery, the State of Charge (SoC) boundaries were strictly set between 10% and 90%, avoiding the degrading effects of absolute minimum and maximum charge levels. The safety margin was set to 0%, and the round-trip efficiency (RTE) of the entire system, including inverter losses, was estimated at 90% [82].

Financial Assumptions and Model Delimitations

A techno-economic model requires simplifications to process long-term simulations efficiently. The following financial assumptions and delimitations outline the boundaries of the quantitative assessment.

Battery Degradation Costs: In the simulation, battery degradation is monetized as a variable marginal cost per energy unit processed. Based on recent industry benchmarks, a complete LFP system installation (including inverters and connection) has an estimated re-investment cost of approximately 125000 USD/MWh [82]. Distributed over a guaranteed 15-year cycle life and 5000 battery cycles, the pure degradation cost per full cycle is approximately 25 Euro/MWh (125000/5000). Consequently, the model applies a wear cost of 12.5 Euro/MWh for charging and 12.5 Euro/MWh for discharging. The industrial facility itself is assumed to have a degradation cost of zero, with the assumption that O&M (Operation and maintenance) costs are disconnected from the MWh throughput in this context.

Grid tariffs and exclusion of peak shaving A primary limitation regarding grid costs is the model's inability to accurately incorporate savings from peak shaving on the regional grid. The tariff design is primarily based on a fixed capacity subscription model, meaning the industry pays for a pre-booked maximum power capacity rather than facing variable penalties for individual short-term peaks [29]. Because this tariff design does not financially accommodate or reward short-term variations in energy consumption, and because the exact contractual details for the two P&PMs were strictly confidential, attempting to calculate peak shaving revenues would introduce a high degree of inaccuracy. Therefore, the simulation focuses strictly on energy arbitrage and frequency regulation markets as revenue sources.

Grid Benefit Compensation:

In the simulation model, the grid benefit compensation for energy discharged into the grid was set to a static rate of 1.0 Euro/MWh, based on Vattenfall Eldistribution's regional grid tariff prices [29]. Unlike local low-voltage distribution networks that often apply a simple static grid benefit for micro-producers, high-voltage regional grids typically employ highly dynamic, time-of-use tariff structures coupled to current spot prices and physical transmission losses [50, 52]. The simulation tool currently lacks the ability to accurately simulate this dynamic regional compensation hour by hour. Therefore, utilizing the static rate serves as a necessary and grounded simplification. This approach provides a conservative estimate of the system's profitability. Because a BESS inherently discharges during hours with high spot prices, which is when dynamic grid benefit compensations are generally at their highest, the actual revenue generated from energy export in a real-world scenario would likely be marginally higher than the model's projections.

3.3.3 Case design simplification and scenario selection

Initially, the report structure was intended to support case designs where different individual factors in the P&PM were to be present. Due to a limited time frame and the inability to acquire more site-specific data, a simplified structure was selected. The case scenarios were instead based on the inherent properties of Objects 1 and 2. The "case" phrasing will be dropped, instead, the site specific properties of Objects 1 and 2 will be explained briefly. Both are located in SE3.

The first site, Object 1, is an example of a smaller mill with a relatively low power consumption, although it is still connected to the regional grid. This site does not have any considerable power production or other assets (e.g., wind or solar) to optimize its energy profile. The consumption pattern is relatively stable during the year, and no assets or flexibility are used today.

The second site, Object 2, is an example of a larger mill with a relatively high power consumption. This site does have considerable power production capabilities; however, it has no extra assets (e.g., wind or solar) to optimize its energy profile. The consumption pattern is relatively stable over the year, although its production is used to lower costs when prices are typically high.

3.3.4 Investment appraisal approach

The investment appraisal was conducted as a monthly cash-flow model over a 24-month analysis period. The purpose of the model was to evaluate whether the simulated BESS revenues were sufficient to justify the initial investment under different market participation strategies. The model was constructed per installed MWh of battery capacity in order to enable comparison between the two mill cases, since the simulated BESS sizes differed between the sites.

Two revenue scenarios were evaluated. The first scenario included only electricity price arbitrage, where the BESS charges during low-price periods and discharges during high-price periods. The second scenario included both arbitrage and ancillary services, where the BESS could also generate revenues from frequency-related services such as FCR and mFRR. The monthly profit values were taken directly from the simulation outputs, and used as revenue inputs in the investment appraisal.

The cash-flow model included the initial investment, monthly operating profit, maintenance cost, residual value, net cash flow, and cumulative cash flow. The initial investment was included as a negative cash flow in month zero. Monthly net cash flow was then calculated as profit minus maintenance cost. In the final month, a residual value was added to account for the remaining economic value of the BESS after the 24-month analysis period.

The investment appraisal required assumptions regarding investment cost, maintenance cost, useful life, analysis period, and residual value. The base-case CAPEX was set to 650,000 EUR/MWh, representing an all-in investment cost that includes the battery system, power conversion equipment, and installation-related expenses.

This estimate is derived from an interview with a representative of a BESS developer and supplier, labeled BESS-actor in the study, who indicated a market price of 650,000 - 730,000 EUR per installed MWh. Monthly maintenance cost was set to 200 EUR/MWh, corresponding to 2,400 EUR/MWh/year, or approximately 0.37% of the assumed CAPEX per year. The estimate is based on reference literature indicating that pure technical operation and maintenance, and extended warranty amount to approximately 160 EUR/MWh per month [83]. The 200 EUR value provides a conservative safety margin. These assumptions were applied equally to both objects in order to isolate the effect of differences in simulated revenue profiles rather than differences in assumed investment costs. It is important to note that actual CAPEX is site-specific and can fluctuate based on local grid conditions and existing infrastructure.

Table 3.2: Base-case assumptions used in the investment appraisal

Assumption	Value	Unit
CAPEX	650,000	EUR/MWh
Maintenance cost	200	EUR/MWh/month
Analysis period	24	months
Useful life	15	years
Residual value	86.7	% of CAPEX
Residual value	563,333	EUR/MWh

Since the analysis period was shorter than the expected economic lifetime of the BESS, a residual value was included at the end of the 24-month period. The residual value was estimated using a straight-line remaining-life approach:

$$RV = CAPEX \times \frac{L - T}{L} \quad (3.1)$$

where RV is residual value, $CAPEX$ is the initial investment cost per MWh, L is the assumed useful life in years, and T is the analysis period in years. With a useful life of 15 years [84] and an analysis period of two years, the remaining-life share becomes 13/15, corresponding to a residual value of 86.7% of CAPEX. The residual value should therefore be interpreted as a terminal value estimate rather than as a guaranteed resale value.

No explicit discount rate or required rate of return was applied in the main investment appraisal. In a conventional discounted cash-flow analysis, the discount rate should reflect the risk of the investment. For listed firms, such a rate can often be estimated using market-based risk parameters such as beta and market risk premia. However, such estimates rely on observable market returns and are sensitive to choices regarding index, time period, and return interval [85]. In this study, the evaluated investments are project-specific BESS applications at anonymized industrial sites rather than listed companies with observable market prices. Estimating an additional project- or asset-specific risk premium would therefore require qualitative judgment and data that were not available within the scope of the study. Since

company- and asset-specific risk premia are difficult to quantify and lack generally accepted data sources, applying a single discount rate would risk introducing false precision into the analysis [86]. Net present value was therefore not used as a decision metric. Instead, the appraisal focuses on non-discounted cash-flow measures: operating payback period, operating net cash flow, total net cash flow including residual value, internal rate of return (IRR), operating break-even and simple return on investment (ROI).

Payback period was defined as the first month in which cumulative operating cash flow became positive. The payback calculation, therefore, excluded residual value, since the purpose was to assess whether the investment could be recovered through operating cash flows during the analysis period. If cumulative operating cash flow did not become positive within the 24-month period, the investment was reported as not recovered within the analysis period.

IRR was calculated based on the monthly cash-flow series, including the initial investment in month zero and the residual value in the final month. The monthly IRR was annualized to improve interpretability. However, due to the short analysis period and the inclusion of a residual value, IRR was interpreted with caution and used mainly for comparison between scenarios rather than as a standalone investment decision criterion.

Simple ROI was calculated as total net cash flow, including residual value, divided by the initial investment. It was therefore used as a relative measure of the total 24-month investment outcome, rather than as a discounted profitability measure:

$$ROI_i = \frac{NCF_i^{incl. RV}}{CAPEX_i} \quad (3.2)$$

where ROI_i is the simple return on investment for object i , $NCF_i^{incl. RV}$ is the total net cash flow including residual value, and $CAPEX_i$ is the initial investment cost per MWh.

Two types of robustness tests were conducted. First, a combined scenario analysis was used to evaluate how the investment results changed under optimistic, base-case, and pessimistic financial assumptions. In this analysis, CAPEX, maintenance cost, useful life, and residual value were changed simultaneously in order to represent internally consistent investment conditions. The optimistic scenario assumed lower CAPEX, lower maintenance cost, and a longer useful life, while the pessimistic scenario assumed higher CAPEX, higher maintenance cost, and a shorter useful life.

Second, a revenue sensitivity analysis was conducted for the combined arbitrage and ancillary services case. In this analysis, the simulated revenue level was reduced to 100%, 75%, 50%, and 25% of the original simulated value while keeping the base-case financial assumptions constant. This was done to assess how dependent the investment case was on capturing the simulated market revenues.

In addition to these discrete revenue levels, an operating break-even revenue share

was calculated for each object and reported as a percentage. This measure represents the share of the simulated 24-month arbitrage and ancillary services profit required for the cumulative operating net cash flow to equal zero during the project period, without including residual value. The break-even revenue share was calculated as:

$$p_{BE,i} = \frac{CAPEX_i + \sum_{t=1}^T MC_{i,t}}{P_i^{base}} \quad (3.3)$$

where $p_{BE,i}$ is the operating break-even revenue share for object i , $CAPEX_i$ is the investment cost per MWh, $MC_{i,t}$ is the monthly maintenance cost, T is the 24-month analysis period, and P_i^{base} is the total simulated profit per MWh from the combined arbitrage and ancillary services case at 100% revenue. Residual value was excluded from this calculation, since the purpose was to assess whether the investment could be recovered through operating cash flows during the project period. The sensitivity analysis does not represent all possible future market outcomes, but rather identifies which assumptions the investment case is most dependent on.

3.4 Methodological considerations

3.4.1 Delimitations

This study includes three delimitations in order to ensure analytical focus and methodological consistency.

First, the study is geographically limited to Sweden. The paper and pulp industry operates under significantly different regulatory frameworks, market structures, and climatic conditions across countries. Expanding the analysis beyond Sweden would introduce significant differences, reducing comparability and increasing uncertainty in the results. By focusing on Sweden, the study ensures that all analyzed actors operate under the same institutional and market conditions, which strengthens the reliability of the results.

Second, the analysis is restricted to pulp production processes based on mechanical and chemical methods. These processes represent the dominant production technologies within the Swedish industry and are therefore the most relevant when investigating the integration and impact of BESS. Other, less common production methods are excluded, as their limited use reduces their relevance for the overall conclusions of the study.

Third, the study focuses on the integration and use of BESS within existing industrial operations and does not include a full system analysis of the electricity grid. While interactions with the electricity market and ancillary services are considered, the analysis is conducted from the perspective of individual paper and pulp mills and how they can make use of BESS.

3.4.2 Method critique and limitations

The methodological choices made in this study involve certain limitations that should be acknowledged. Since the empirical material is based on actors operating within the Swedish paper and pulp industry (P&PI) and electricity system, the findings reflect Swedish regulatory, market, and industrial conditions. The results should therefore not be directly generalized to other countries.

The qualitative empirical material consists primarily of interviews, while the quantitative part of the study is based on simulations and investment appraisals using mill-specific electricity consumption data where available. While the interview-based material enables access to informed assessments relevant to the research questions, it also entails a risk that strategic considerations, confidentiality concerns, and organizational roles influence the information shared by respondents. Furthermore, the semi-structured interview format means that findings are shaped by how respondents frame and prioritize different opportunities and constraints related to BESS. Since the interviews were adapted to each actor category, respondents did not answer exactly the same questions in the same way. Consequently, the absence of a specific statement from one actor should not automatically be interpreted as disagreement or lack of relevance.

A further limitation concerns the quantitative data used in the simulation and investment appraisal. Detailed mill-specific electricity consumption data could only be obtained from two P&PMs. As a result, the simulation and investment appraisal are based on limited available data, which restricts the extent to which differences between mill types can be evaluated and limits the representativeness of the simulation-based results.

Another limitation concerns the financial assumptions used in the investment appraisal. The CAPEX and maintenance cost assumptions should be interpreted as simplified base-case estimates, rather than tailored site-specific price offers. Actual investment costs may vary depending on system configuration, grid connection requirements, and site-specific installation factors. Consequently, the investment appraisal should be interpreted as an indicative comparison between scenarios rather than as a definitive investment decision model.

A final limitation concerns the sources used in the literature study. Since BESS technologies, market conditions, and policy frameworks are developing rapidly, some findings from earlier studies may become outdated or may not fully reflect current conditions.

3.4.3 Ethical considerations

All interviewees were informed of the purpose of the study before the interview took place. Consent was obtained for recording and transcription, and respondents were informed that the material would be used only for the purposes of this thesis. To protect confidentiality, both individuals and organizations were anonymized through the coded labels presented in Table 3.1.

Audio files and transcripts were stored by the group members responsible for transcription and analysis and were not shared outside the project group. Since several respondents represented companies operating in competitive or strategically sensitive markets, particular care was taken not to disclose information that could identify individual respondents or reveal confidential business information. After completion of the thesis, the material will be retained only for as long as required for examination and in accordance with Chalmers' guidelines for handling personal data, after which it will be deleted.

4

Results

The results are presented in two main parts: qualitative and quantitative. The qualitative results are findings from the interviews conducted for this project, focusing on how participants view BESS from their perspectives, given today's conditions. The quantitative results are based on consumption data from two mills where analyses have been made by simulating potential revenue streams from BESS. Together, the results provide a basis for evaluating the barriers to BESS being implemented in P&PM today.

4.1 Qualitative Results: How actors perceive BESS and flexibility

Interview Object	Type of Mill
P&PM A	Mainly chemical
P&PM B	Mechanical
P&PM C	Mainly mechanical
P&PM D	Chemical
P&PM E	Mainly chemical

Table 4.1: Overview of interviewed P&PMs and their mill types

The P&PMs interviewed for this report operate different types of mills, either chemical or mechanical. P&PM D only operates chemical pulp processes, while P&PM A and E mainly operate chemical mills, but also have one mill using the mechanical process. P&PM B operates purely mechanical processes, whereas P&PM C primarily operates mechanical mills but also has one mill using a chemical process. During the interviews, several of the P&PMs highlighted that chemical mills generate large amounts of energy, whereas mechanical mills instead have a high electricity consumption.

4.1.1 The different processes and energy systems between the P&PM

The studied P&PMs show great variation in their operations and energy systems. These variations result in differing views on flexibility and BESS. In particular,

the differences between chemical and mechanical mills indicate that the different processes lead to varying energy profiles and technical conditions.

The interviews with the chemical pulp mills state that they have a high share of internal energy production, whereby byproducts from the process that are not used are instead burned to generate heat and electricity that can be reused in the process. Due to this, these plants have a high degree of energy self-sufficiency, and even in some cases, they produce so much energy that the plants can sell to the grid. The energy system in these plants is therefore integrated and relatively self-balanced, which can decrease the need for external electricity supply.

In contrast, mechanical mills are large consumers of electricity in their processes. Unlike chemical mills, these processes lack the ability to generate larger amounts of energy. This makes mechanical mills heavily reliant on continuous electricity supply from the market and more exposed to electricity price fluctuations.

In addition to differences in energy consumption and internal energy production, the potential use of flexibility also varies between mills. Although chemical and mechanical pulping are based on the same general principles, the specific process steps and operational conditions differ between sites. These differences affect how each mill assesses the possibility of integrating flexibility into its operations.

The mills also vary significantly in size, which affects both their ability to integrate BESS and the scale of their operations. Larger mills generally have more extensive production processes, resulting in differences in pulp production volumes, energy generation and energy consumption.

4.1.2 Process and operational constraints on flexibility

The interviews show that process and operational constraints are central barriers to flexibility and BESS implementation in the P&PI. A recurring pattern is that the mills are designed for continuous operation, where stable production is prioritized over short-term adjustments. P&PM A explains that the mill cannot be flexible in the pulp production itself, since the "mill needs to run 24/7". Similarly, P&P D states that the pulp mill and paper machines should run "at a steady pace all the time, day and night, 350 days a year", while P&PM E describes that almost all mills operate around the clock. This indicates that flexibility is often difficult to integrate into the core production process without disturbing the operational logic of the mill.

The interviews also show that the degree of flexibility varies between different process steps. P&PM B describes that one refining step can be shut down, corresponding to approximately 6 MW, but emphasizes that "the rest of the process must continue as usual". The same interviewee also notes that they cannot guarantee that this 6 MW reduction is always available. This suggests that flexibility exists, but only in limited and process-dependent parts of the operation. P&PM E expresses a similar view, stating that flexibility may be possible in smaller parts of the process, but not in the main production lines or the most important machines.

Another barrier is that several processes are slow, integrated, and difficult to start or stop. P&PM D explains that a sulfate pulp mill cannot simply be turned on and off, since "it takes three days to shut down". The same respondent also describes fuel and steam production as much slower processes, where it is not possible to "jump back and forth". This limits the possibilities of responding quickly to electricity prices or flexibility markets.

The interviews further indicate that production reliability is prioritized over flexibility. P&PM E states that the most profitable strategy so far has been to have as little flexibility as possible, meaning that the mills should keep production running continuously and minimize downtime. P&PM B had a similar view, describing how they "make more money by running the pulp production than by shutting down to provide flexibility".

Finally, several interviewees question whether BESS can meaningfully affect the core industrial process at full scale. P&PM B argues that, since the mill already operates at around 32 MW, very large batteries would be required to make a noticeable difference (and would need a lot of space). P&PM D makes a similar point, stating that batteries in relation to their consumption would represent a very small part of the peak load.

The main barriers are continuous production, slow and integrated process systems, high costs of downtime, and a scale mismatch between BESS and the industrial electricity demand. Therefore, BESS implementation can not be understood as a general solution for operational flexibility, but must be evaluated in relation to each mill's specific process structure and operational constraints.

4.1.3 Economic barriers and uncertainty

The findings from the interviews indicate that the implementation of BESS in the mills is primarily constrained by economic factors. This is based on the respondents' views on high investment costs, limited and uncertain revenue streams from BESS, and uncertainty regarding the future development of the ancillary services market.

A central finding across all of the interviews is the high cost of batteries, resulting in a high investment cost when implementing BESS in their operation. When interviewing P&PM A they clearly stated that the prices are still too high, but if the prices continue to decrease it can become interesting stating that the prices of batteries on the market are currently too high. P&PM D stated that when comparing investing in batteries in relation to flexibility in the operations, it is extremely expensive, and they can therefore regulate their process more. P&PM B also acknowledged that they think batteries are expensive, but also highlighted that they need a lot of space. The P&PMs that were interviewed can not see a need for batteries in relation to the price of them today, as they can manage their operations in other ways to regulate in relation to electricity consumption.

The cost of the batteries is not the only problem that the P&PMs see with the batteries today. The size of them is also something that is highlighted when con-

cluding the interviews. The different P&PMs states that they would only be able to store energy from a small part of the production, making it irrelevant, and another one describes that the electricity production from a P&PM is too large in relation to the batteries on the market today. The size of the batteries also relates to their price, as they store smaller volumes, the P&PM needs more batteries to be able to store more, resulting in a higher price since they are already expensive.

A majority of the P&PMs also states that the revenue streams from implementing BESS are not worth it in relation to the investment cost. When investing in something expensive, it is important that the investment pays off, but the P&PMs has a hard time seeing that with the large implementation investment. P&PM C states that it is difficult to make money from batteries only for ancillary services. In the energy market, the differences in prices from high to low are too small, and the batteries will not be able to charge in between the differences in price, making it hard to earn money from it, as stated by P&PM A. The answers from the P&PMs show that when the investment cost is higher, the companies also expect higher returns on the investment, and regarding BESS, the P&PMs does not see that it is possible right now. Either the cost of BESS has to decrease or the revenue streams from investing in BESS has to increase.

Likewise, they also state that the market for ancillary services was better in the beginning. Then there were a few market participants making the handout larger, but with time, more and more participants got knowledge of the market, wanting to become a part of it, which resulted in smaller payout, and therefore not being seen as profitable anymore. Due to this, it is seen that the prices on the ancillary services market are decreasing and are therefore not being seen as profitable anymore.

Alongside the lack of revenue streams that the P&PMs can see from their perspective they also state that it is seen as a risky investment and business. P&PM E clearly stated that nobody buys batteries if there is not a clear financial benefit, and that they at this point do not see any financial benefit. Alongside the lack of financial benefits there is also an uncertainty in the ancillary services market which P&PM B implies and follows by saying that there is a lot of uncertainty and nobody is willing to take the risk. They follow by commenting that the companies that are trying to sell the services often leave uncertain forecasts. P&PM A also comments that the best market today is the frequency regulation market and that it is difficult to predict how it will evolve. This creates an uncertainty regarding how the market and business model for BESS will evolve with time resulting in the P&PMs waiting to gain more insight and information before investing.

Today the P&PMs can see alternative solutions today that gain more revenue for them. P&PM A and B highlight that they make more money on creating pulp, and therefore, it is more profitable for them than alternative businesses such as BESS. Alongside P&PM B also states that if there were enough incitement and was profitable they would consider investing in BESS, implying that they do not believe that it is that today. There are also different types of flexibility that can be used today as P&PM C states that they choose not to buy electricity from the market

during the most expensive hours and therefore does not always produce pulp and paper around the clock during these times, saving money by doing that instead. It is clear that the mills value making pulp instead of looking into alternatives since they gain so much revenue by doing so.

4.1.4 Existing strategies reduce the perceived need for BESS

The interviews show that several P&PMs already rely on existing strategies to manage electricity costs, increase resilience, or provide flexibility. One of these strategies include an substantial on-site electricity generation, which can be used as a flexibility resource. For mills with a high degree of self-sufficiency, the value of battery storage for reducing grid dependency or managing electricity purchases may therefore be less apparent. This is especially visible in the case of P&PM E, which states that they produce more electricity than they consume. Some of their mills reach around 250 % self-sufficiency, and older mills around 180 %. This electricity surplus also covers other electricity uses within the group, which reduces the perceived need for additional storage solutions. Similarly, P&PM D states that their mill produces approximately 55-60 % of the electricity it needs internally. Although not entirely self-sufficient, the reduced exposure to the electricity market still lowers the perceived need for flexibility solutions such as BESS. In addition, P&PM A describes an ambition for all its mills to participate in frequency markets by operating their own electricity production flexibly.

Another strategy some P&PMs have implemented is to have flexibility embedded in their process operations. For example, P&PM A describes that the turbine can be shut down in order to participate in the frequency market, and P&PM C can reduce its electricity demand by around 10 MW for an unlimited period of time by shutting down a refiner. P&PM D gives the example of being able to shut down a pump for an hour and explains that their mill has an easier time regulating its own process. These examples suggest that process-based flexibility may be perceived as more practical than BESS, since it's already integrated into the operations and does not require a separate storage investment.

Financial strategies are another way for the mills to reduce uncertainty related to electricity costs. P&PM B explains that although part of the electricity is bought on the spot market, the company secures around 60–70% of its electricity several years in advance, with some volumes secured at around 0.40 SEK/kWh, compared to current prices that may reach one SEK/kWh or more. P&PM D describes a similar strategy, stating that the company mainly buys electricity through contracts and follows an electricity hedging policy to achieve stable and predictable electricity prices. These strategies reduce the mills' exposure to short-term price fluctuations, which weakens the incentive to invest in BESS for electricity price arbitrage.

The interviews show that the flexibility strategies used by pulp and paper mills do not always match the strengths of battery storage. P&PM C describes the industry's niche as endurance rather than speed, explaining that the mills already provide sustained ancillary services, although not the fastest ones. This distinction is

important, since BESS is particularly well suited for fast response and short-duration power balancing, while industrial flexibility may instead be based on larger and more sustained load adjustments. This is supported by the Energy expert, who argues that batteries are suitable for short power peaks but become large and expensive when used for long-duration power needs. For larger and more sustained power requirements, grid expansion may therefore be more relevant than battery storage.

Finally, some mills already have process-based storage or are considering other technologies that may be more closely connected to their existing energy systems. P&PM C describes pulp towers as a form of energy storage that enables time shifting to lower the cost of electricity, with one pulp tower corresponding to approximately 300 MWh. P&PM D also highlights off-grid operation as an existing resilience measure at one of its mills. By temporarily operating the mill using its own turbine, the site can maintain operation during thunderstorms or external grid disturbances. This means that one potential value of BESS, namely backup capacity and increased operational security, is partly provided through an already established solution. In addition, both P&PM B and P&PM D mention electric boilers as potentially attractive, especially during periods of low or negative electricity prices or for managing peak loads. These alternatives may reduce the perceived need for BESS by offering flexibility that is more directly linked to the mills' thermal processes and existing operations.

4.1.5 Perceived advantages with BESS

A central advantage of BESS is its ability to complement rather than replace existing industrial flexibility. The energy expert highlights that batteries are designed to support the industry's specific needs. Aggregator reinforces this, stating that the most important factor for successful integration is a deep understanding of the industry's specific processes, production, and consumption. According to the DSO, awareness has increased regarding the ability of batteries to balance the system during periods of unplanned production or consumption. Furthermore, the DSO identifies BESS as a vital tool where the power grid acts as a bottleneck, contributing to local flexibility markets and grid optimization. The TSO adds that coordinated BESS can reduce grid fees and imbalances cost while simultaneously providing necessary ancillary services. P&PM C specifically notes that while industrial process offers "indefinite flexibility", battery duration is limited by capacity, however BESS provides superior speed for frequency control and rapid activations.

The use of BESS for peak shaving is identified as a concrete advantage for lowering fixed costs. P&PM C observes that BESS investments can be justified by shaving peak demand to reduce fixed subscriptions costs, particularly given the long lead times for grid capacity upgrades. This perspective is shared by the TSO, who views peak shaving as an effective method for managing grid limitations. According to the energy expert, batteries are especially effective for managing short and rare power peaks that would otherwise drive up industrial network fees. The DSO confirms that batteries can be used for peak shaving to reduce both peak and general network costs.

From an economic standpoint, BESS is viewed as a strategic tool for navigating a volatile energy market. The energy expert emphasizes that even short outages can cause significant economic losses, making BESS a form of operational insurance. P&PM C highlights that BESS mitigates financial risks stemming from imbalance costs in a 15-minute market. Furthermore, the same interviewee notes that being a significant energy producer provides a natural hedge against price fluctuations, as they buy and sell on the same spot market. An additional economic benefit identified by P&PM C is that small-scale batteries can minimize operational wear on the equipment by preventing frequent starts and stops of large loads during brief activations. Aggregator notes that while pure arbitrage may have a long payback period of approximately 7-8 years, the profitability is significantly improved by combining multiple value streams, revenue stacking. Many interviews, BESS actor, P&PM A, and the energy expert predict that battery prices will continue to fall as the sector expands.

Another advantage of BESS is its potential to mitigate risk exposure to imbalance costs, although its effectiveness depends on the scale of the disruption. While P&PM A points out that current battery capacities are insufficient to cover massive energy swings that arise during long, unplanned outages, they note that a battery could ideally be redirected from the frequency market to reduce local imbalances if the costs were known in advance. For shorter-term market fluctuations, however, the benefit is clear. P&PM C emphasizes that the primary purpose of exploring BESS is not necessarily to make money on support services, but rather to reduce risk exposure to imbalances, particularly with the shift to a 15-minute market. The energy expert concurs, pointing out that avoided imbalance costs and intraday trading must be included when evaluating the full business case of a battery. This strategic value is further evidenced by P&PM F, whose investment plan to install BESS is heavily driven by the need to smooth out imbalance costs and optimize intraday trading.

A major advantage of BESS, highlighted by several actors, is the ability to store surplus energy from local solar panels or wind farms. P&PM A points out that they currently only consider investing in BESS in combination with their wind farms, as it creates a significant opportunity to manage imbalances. Furthermore, the BESS actor and the Aggregator emphasize that batteries provide necessary flexibility for industries that currently have, or are planning to install, solar panels. Another concrete application and economic advantage identified in the interviews is the use of BESS to facilitate the expansion of charging infrastructure. The BESS actor explains that they work with battery storage specifically to simplify the installation of chargers for electric trucks at industrial sites and to reduce peak power costs during the charging process. The energy expert concurs, noting that batteries can provide local benefits by charging electric trucks, thereby offering increased flexibility to the industrial operations.

Finally, batteries are identified as a cleaner alternative to traditional backup solutions. The DSO suggests that batteries can serve as backup power, replacing traditional diesel generators. The energy expert concurs, stating that BESS can provide backup power and improve overall operational security. Beyond energy storage, the

BESS Actor mentions that batteries can be used for reactive power, which further stabilizes the local electrical environment at the industrial site. Aggregator adds that systems can be configured to reserve a specific amount of battery capacity to ensure the up-time of critical industrial processes.

4.1.6 Policies

Unclear regulations and the lack of a unified policy create obstacles for industrial BESS investments, making it difficult for companies to plan their energy strategies. The DSO highlights that the existing tax structure often results in double taxation, applied both during charging and grid feed-in, which undermines project profitability. While tax reductions are available, the associated administrative burden remains an obstacle. Similarly, grid fee challenges emerge when electricity is traded under a single subscription. The BESS actor points out that there are no national guidelines from the TSO or the Swedish Energy Market Inspectorate, leading to different interpretations of the rules across Sweden. This lack of coordination leads to longer wait times and unclear technical requirements, where building permits and safety assessments vary depending on the municipality. These issues result in project lead times that can reach up to twelve months from contract to operation. Comparing Sweden to Denmark and Finland, the BESS actor suggests that a national framework for power charges and standardized rules would make it much easier for industries to evaluate BESS investments.

Broader political decisions regarding the national energy mix create uncertainty that indirectly hinders BESS investments. The Aggregator emphasizes that political interventions, such as subsidies or guaranteed pricing for new nuclear power, risk lowering marginal electricity prices, which would reduce the price margins necessary for profitable electricity arbitrage trading. The energy expert concurs, noting that long-term political decisions, whether concerning nuclear expansion or the pace of wind power development, affect future electricity price volatility. This makes it difficult for industrial actors to rely on the long-term profitability calculations required to justify the substantial capital expenditures associated with energy storage today.

Policy is also mentioned as a possible future driver for industrial BESS adoption. One industrial actor states that batteries may become legally required in connection with new wind-power production in the future and refers to similar tendencies in Finland. The BESS actor also highlights that EU-level technical requirements, such as the Requirements for Generators, affect how energy storage systems must be connected to the grid. In this way, the interview material presents policy-related factors both as current barriers and as possible future requirements for industrial BESS investments.

4.2 Quantitative Results

In this section, the results of the different mills' consumption data and the results of the simulations will be presented. Remember, Object 1 is the smaller mill without

its own electricity production and Object 2 is the larger mill with its own energy production.

4.2.1 Consumption patterns for the different mills

Figur 4.1 illustrates the relative variation in net grid consumption for Object 1 and Object 2, analyzed across both weekdays and individual hours of the day. Although both facilities report continuous 24/7 operations with relatively constant internal energy demands, their actual net grid consumption profiles exhibit distinct differences.

The weekday analysis reveals that Object 1 maintains a highly stable consumption profile with a narrow spread. The median consumption remains consistent throughout the week, with only a slight reduction observed on Mondays. In contrast, Object 2 demonstrates a significantly larger variance in its grid reliance, which makes sense due to its ability to regulate its energy production. The data indicates a pattern where Object 2 lowers its net grid consumption during the middle of the week (most significant on Monday through Thursday), followed by a noticeable increase during the weekends.

These differing characteristics of the mills are further emphasized in the hourly variance analysis. Object 1 displays a virtually flat mean consumption profile across all hours of the day, confirming a constant, unadjusted reliance on the external power grid. Object 2, however, exhibits a pronounced daily pattern. The grid consumption for Object 2 decreases substantially during typical daytime hours (approximately 08:00 to 15:00) and increases during the evening and night. Given that Object 2 possesses in-house power generation capabilities, the resulting data illustrate a dynamic grid interaction where net external consumption is actively reduced during daytime hours.

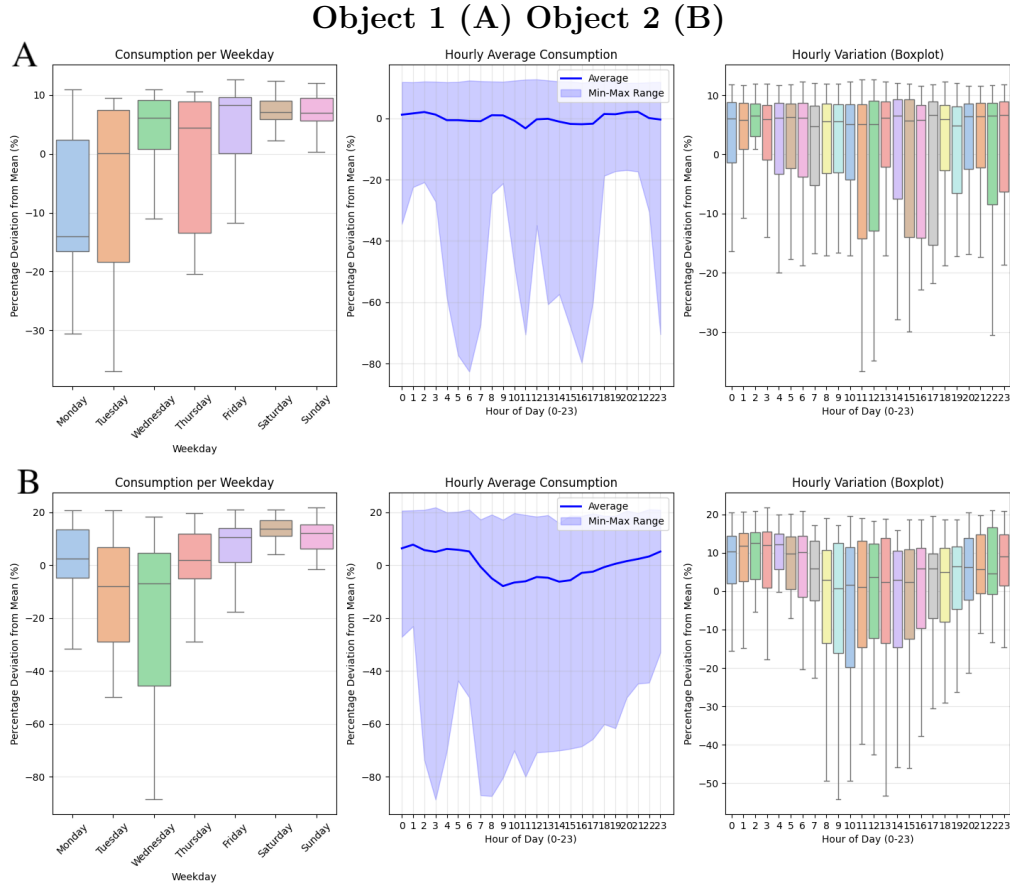


Figure 4.1: Electricity consumption analysis for object 1 & 2.

4.2.2 Simulation results

Figure 4.2 presents the proportional distribution of revenue streams generated by the simulated battery energy storage systems for both facilities over two consecutive one-year periods (2024–2025 and 2025–2026). The evaluated revenue sources include traditional energy arbitrage (Spot Market) and two distinct ancillary services: Frequency Containment Reserves (FCR) and manual Frequency Restoration Reserves (mFRR).

The data reveals a significant shift in market profitability between the two time-frames. During the 2024–2025 period, the results indicate that FCR services contributed to the absolute majority of the total revenues for both Object 1 and Object 2. However, in the subsequent 2025–2026 period, the proportion of revenue derived from FCR decreased substantially, while mFRR expanded to become the dominant revenue stream. Notably, traditional energy arbitrage accounted for a marginal fraction of the total financial yield in this scenario. For both mills, arbitrage revenues represented 0.8% of the total revenue during the first period and experienced only a slight proportional increase to approximately 2.3% in the following year. Furthermore, the visual data demonstrates that the relative distribution of these revenue

streams is similar for both Object 1 and Object 2, indicating that the proportional profitability of the battery is primarily dictated by external market dynamics rather than the differing underlying consumption profiles of the individual mills.

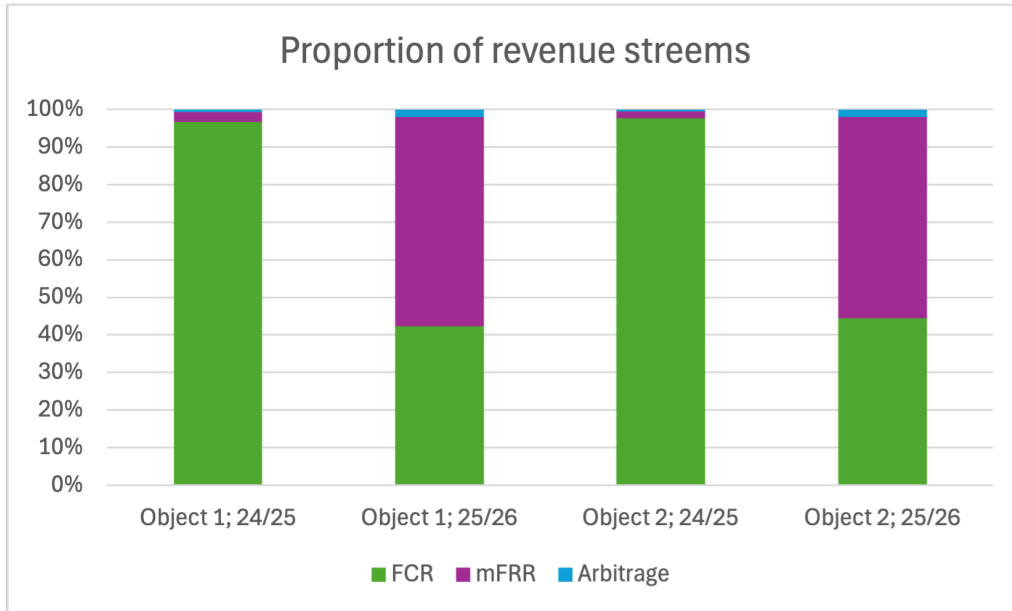


Figure 4.2: Proportion distribution of revenue streams for arbitrage and ancillary services.

Comparing the profit per MWh of installed capacity at the two sites in figure 4.3 shows a difference in the mills' ability to effectively utilize the BESS. Even though the proportional revenue streams were similar for both cases, there is a significant difference in the total profit per MWh between Object 1 and Object 2 during the 2024–2025 period. This could partly be explained by the FCR market being particularly profitable during a certain period of time and when Object 2 had the grid capacity to utilize its full potential continuously, whereas Object 1 was more constrained by its grid connection point. This discrepancy is also evident in the 2025–2026 period, although the gap is somewhat smaller. This indicates that having a greater margin in grid connection capacity during highly constrained hours significantly increases profitability.

Isolating the arbitrage-only scenario from figure 4.3 reveals something interesting. In the first period, Object 1's BESS performed better with a 4.1% profit per MWh than Object 2, while in the next period, the BESSs performed about the same. This was less anticipated, given Object 2's more fluctuating internal consumption profile; it was initially hypothesized that the mill's own power peaks would occasionally coincide with the battery's optimal charging or discharging cycles, thereby creating intermittent bottlenecks. However, Object 2's BESS rarely experienced constraints when the mill's internal consumption ramped up. This unobstructed operation can likely be linked to the mill's power subscription, which accommodates a substantial margin during the day (see figure 4.1), allowing the BESS to more often operate

independently of the facility's internal load variations. This can also be illustrated further down in figure 4.5

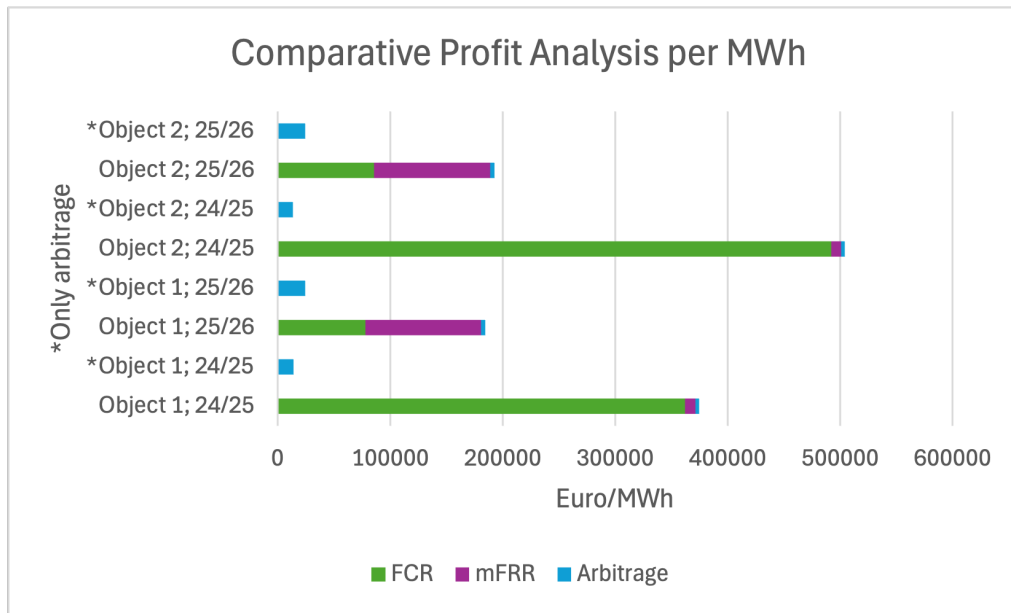


Figure 4.3: Comparative profit analysis per MWh for all simulations

Figure 4.4 is derived from the results shown in Figure 4.3, intended to visualize how much more profit revenue-stacking with ancillary services provides, as well as the differences between the two simulation periods.

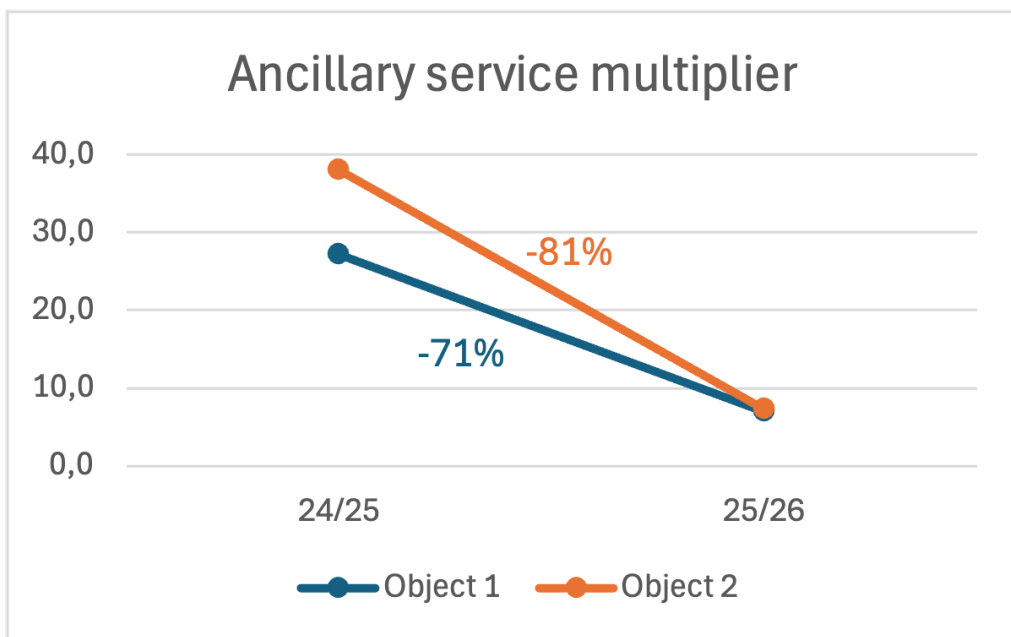


Figure 4.4: Ancillary service multiplier

Figure 4.5 below illustrates the BESS dispatch strategy for the arbitrage-only scenario. This shows well how the BESS shifts energy usage from the price peaks in the mornings (Blue) too the middle of the day and in the nights (Red).

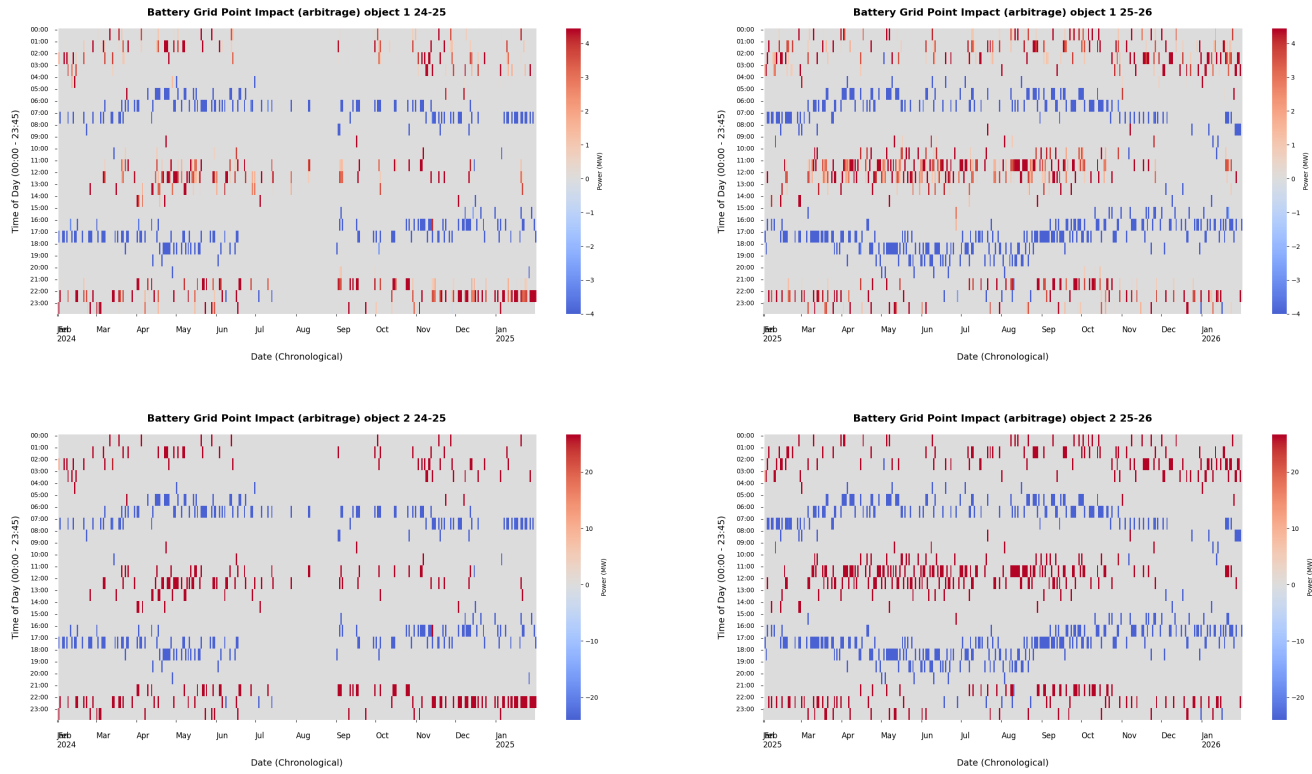


Figure 4.5: BESS dispatch profile through Feb 2024 - Feb 2026 for arbitrage only scenario. The heatmaps illustrate the intensity of battery activity across different periods.

4.2.3 Investment appraisal results

The investment appraisal evaluates the financial performance of the simulated BESS applications under different market participation strategies. The appraisal uses the monthly simulated profits presented in Section 4.2.2 as revenue inputs and combines them with the financial assumptions described in Section 3.3.4. All results are presented per MWh of installed BESS capacity in order to enable comparison between Object 1 and Object 2.

The results distinguish between operating net cash flow, which excludes residual value, and total net cash flow, which includes the residual value at the end of the 24-month analysis period. This distinction is important because operating net cash flow shows whether the investment is recovered through revenues during the analysis period, while total net cash flow also includes the estimated remaining value of the BESS.

The investment appraisal results are presented in three steps. First, the base-case appraisal compares the arbitrage-only scenario with the combined arbitrage and ancillary services scenario. Second, a scenario analysis evaluates how the results change under optimistic, base-case, and pessimistic financial assumptions. Finally, a revenue sensitivity analysis examines how reductions in the simulated arbitrage and ancillary services revenue affect the investment outcome and identifies the revenue percentage required for operating break-even without residual value.

4.2.3.1 Base-case investment appraisal

Table 4.2 presents the base-case investment appraisal results. The base case assumes a CAPEX of 650.000 EUR/MWh, a maintenance cost of 200 EUR/MWh/month, a useful life of 15 years, and a residual value corresponding to 86.7% of CAPEX after the 24-month analysis period.

The arbitrage-only scenario did not recover the investment for either object. Object 1 generated a total simulated profit of 38.397 EUR/MWh, resulting in an operating net cash flow of -616.403 EUR/MWh. Object 2 showed a similar outcome, with a total simulated profit of 38.521 EUR/MWh and an operating net cash flow of -616.279 EUR/MWh. Even when residual value was included, total net cash flow remained negative for both objects. This indicates that electricity price arbitrage alone was not sufficient to justify the investment within the 24-month period.

The combined arbitrage and ancillary services scenario improved the investment outcome substantially. For Object 1, total simulated profit increased to 544,777 EUR/MWh. However, operating net cash flow remained negative at -110.023 EUR/MWh, meaning that the investment did not reach operating payback within the analysis period. When residual value was included, total net cash flow became positive at 446.110 EUR/MWh.

Object 2 produced the strongest base-case result. In the combined arbitrage and ancillary services scenario, total simulated profit amounted to 682.038 EUR/MWh, resulting in a positive operating net cash flow of 27.238 EUR/MWh and a total net

cash flow of 583,371 EUR/MWh when residual value was included. Object 2 was therefore the only base-case alternative that reached operating payback within the 24-month period, with a payback period of 20.9 months.

Overall, the base-case results show that the investment outcome was primarily driven by the inclusion of ancillary service revenues. While both objects generated positive total net cash flow in the combined arbitrage and ancillary services scenario when residual value was included, only Object 2 recovered the investment through operating cash flows within the analysis period. This difference between the two objects motivates a more explicit break-even assessment in the revenue sensitivity analysis. Since Object 1 remained below operating break-even in the base case, while Object 2 only slightly exceeded it, the required revenue level for operating break-even was calculated separately in Section 4.2.3.3.

Table 4.2: Base-case investment appraisal results per MWh of installed BESS capacity

Object	Scenario	Total profit (EUR/MWh)	Op. NCF excl. RV (EUR/MWh)	NCF incl. RV (EUR/MWh)	Total ROI incl. RV	Annualized IRR incl. RV	Operating payback excl. RV
Object 1	Arbitrage	38.397	-616.403	-60.269	-9.3%	-4.8%	Not recovered
Object 1	Arb + Anc	544.777	-110.023	453.310	69.7%	53.9%	Not recovered
Object 2	Arbitrage	38.521	-616.279	-60.146	-9.3%	-4.8%	Not recovered
Object 2	Arb + Anc	682.038	27.238	590.571	90.9%	86.3%	20.9 months

Note: Arb = arbitrage, Anc = ancillary services, RV = residual value, NCF = net cash flow, and Op. NCF = operating net cash flow. Operating payback is calculated excluding residual value. ROI and IRR include residual value.

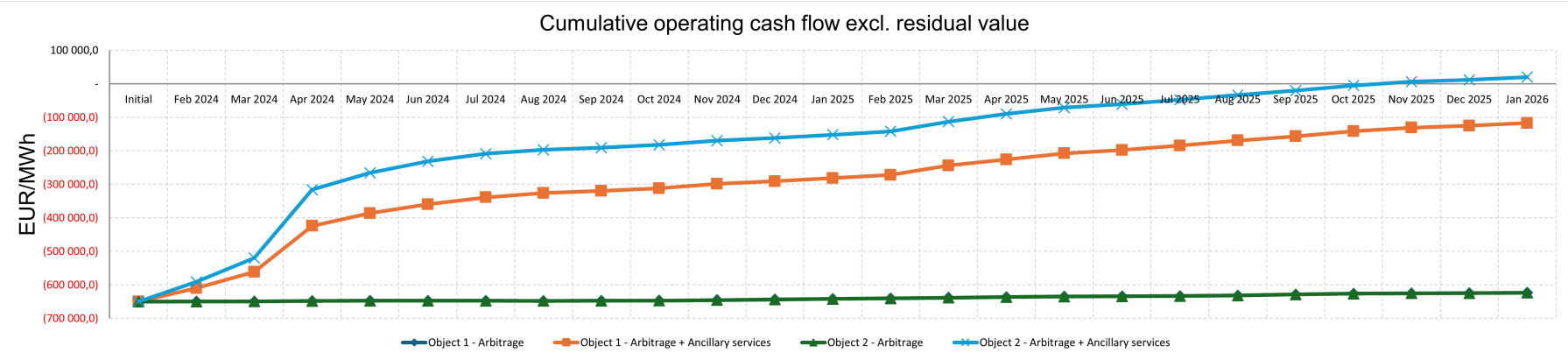


Figure 4.6: Cumulative operating cash flow excluding residual value

4.2.3.2 Scenario analysis of financial assumptions

Table 4.3 presents the scenario analysis for the combined arbitrage and ancillary services scenario. The analysis compares optimistic, base-case, and pessimistic financial assumptions for CAPEX, maintenance cost, useful life, and residual value. The simulated revenues were kept unchanged across the three scenarios, meaning that the differences in outcome are caused by changes in the financial assumptions rather than changes in market revenues.

In the optimistic scenario, both objects reached operating payback within the 24-month period. Object 1 generated an operating net cash flow of 35.177 EUR/MWh and reached payback after 20.3 months. Object 2 generated a stronger result, with an operating net cash flow of 172.438 EUR/MWh and a payback period of 12.1 months.

In the base case, the results were more mixed. Object 1 did not reach operating payback, as its operating net cash flow remained negative at -117.223 EUR/MWh. Object 2, however, reached operating payback after 21.5 months, with an operating net cash flow of 20.038 EUR/MWh.

In the pessimistic scenario, neither object reached operating payback within the analysis period. Object 1 had an operating net cash flow of -269.623 EUR/MWh, while Object 2 had an operating net cash flow of -132.362 EUR/MWh. However, when residual value was included, both objects still showed positive total net cash flow. This demonstrates that the residual value assumption has a substantial effect on the total 24-month investment result.

The scenario analysis, therefore, shows that the investment scenario is sensitive to the combined effect of CAPEX, maintenance cost, and useful life. Object 2 remained more financially robust than Object 1 across all three scenarios, but both objects became dependent on residual value under less favourable assumptions.

Table 4.3: Scenario analysis of financial assumptions for the Arb + Anc scenario

Case	Object	CAPEX (EUR/MWh)	Maintenance (EUR/MWh/month)	Useful life (years)	RV (% of CAPEX)	Op. NCF excl. RV (EUR/MWh)	NCF incl. RV (EUR/MWh)	Op. payback excl. RV
Optimistic	Object 1	500.000	100	20.0	90.0%	35.177	485.177	20.3 months
Optimistic	Object 2	500.000	100	20.0	90.0%	172.438	622.438	12.1 months
Base case	Object 1	650.000	200	15.0	86.7%	-117.223	446.110	Not recovered
Base case	Object 2	650.000	200	15.0	86.7%	20.038	583.371	20.9 months
Pessimistic	Object 1	800.000	300	10.0	80.0%	-269.623	370.377	Not recovered
Pessimistic	Object 2	800.000	300	10.0	80.0%	-132.362	507.638	Not recovered

Note: Arb + Anc refers to arbitrage and ancillary services. RV = residual value and NCF = net cash flow. Operating payback is calculated excluding residual value.

4.2.3.3 Revenue sensitivity analysis

Table 4.4 presents the revenue sensitivity analysis for the combined arbitrage and ancillary services case. The analysis was performed using the base-case financial assumptions, while reducing the simulated arbitrage and ancillary services revenue level to 100%, 75%, 50%, and 25% of the original simulated value.

4. Results

The results show that the investment case was highly sensitive to reductions in simulated market revenues. At the full simulated revenue level, Object 2 reached operating payback after 20.9 months, while Object 1 did not reach operating payback. When the revenue level was reduced to 75%, neither object reached operating payback within the 24-month period. Object 1 then had an operating net cash flow of -246.218 EUR/MWh, while Object 2 had an operating net cash flow of -143.271 EUR/MWh.

At 50% of the simulated revenue level, operating net cash flow decreased further to -382.412 EUR/MWh for Object 1 and -313.781 EUR/MWh for Object 2. At 25%, the corresponding values were -518.606 EUR/MWh and -484.290 EUR/MWh. These results show that operating payback within the 24-month period is highly dependent on maintaining revenues close to the simulated base level. To quantify this dependency more precisely, an operating break-even revenue percentage was calculated separately for each object.

Table 4.4: Revenue sensitivity analysis for the Arb + Anc scenario

Revenue level	Object	Op. NCF excl. RV (EUR/MWh)	NCF incl. RV (EUR/MWh)	Total ROI incl. RV	Operating payback excl. RV
100%	Object 1	-117.223	446.110	68.6%	Not recovered
100%	Object 2	27.238	590.571	90.9%	20.9 months
75%	Object 1	-246.218	317.116	48.8%	Not recovered
75%	Object 2	-143.271	420.062	64.6%	Not recovered
50%	Object 1	-382.412	180.922	27.8%	Not recovered
50%	Object 2	-313.781	249.552	38.4%	Not recovered
25%	Object 1	-518.606	44.727	6.9%	Not recovered
25%	Object 2	-484.290	79.043	12.2%	Not recovered

Note: Revenue level refers to the share of the simulated Arb + Anc revenue retained. Arb = arbitrage, Anc = ancillary services, RV = residual value, NCF = net cash flow, and Op. NCF = operating net cash flow. Operating payback is calculated excluding residual value. ROI includes residual value.

Table 4.5: Operating break-even revenue requirement for the Arb + Anc scenario

Object	Base simulated (EUR/MWh)	Required operating inflow (EUR/MWh)	Break-even level	Difference from 100% level
Object 1	544.777	654.800	120.2%	+20.9 pp
Object 2	682.038	654.800	96.0%	-2.9 pp

Note: The required operating cash inflow equals CAPEX plus total maintenance cost during the 24-month analysis period: $650.000 + 4.800 = 654.800$ EUR/MWh. Residual value is excluded. The break-even revenue level is calculated as required operating cash inflow divided by the base simulated profit from the combined arbitrage and ancillary services scenario. pp = percentage points.

The break-even calculation shows that Object 1 would require 120.2% of the simulated arbitrage and ancillary services revenue to reach operating break-even within

the project period. This means that the simulated base-case revenue was not sufficient to recover the investment without residual value. Object 2 required 96.0% of the simulated revenue to reach operating break-even, meaning that it only slightly exceeded the break-even threshold in the base case. This indicates that Object 2 was financially stronger than Object 1, but still sensitive to relatively small reductions in market revenue.

When residual value was included, total net cash flow remained positive for both objects across all tested revenue levels. However, the margin decreased substantially as revenues were reduced. At 25% of the simulated revenue level, total net cash flow, including residual value, was only 44.727 EUR/MWh for Object 1 and 79.043 EUR/MWh for Object 2. This shows that the positive total result under low-revenue conditions was mainly supported by the residual value rather than by operating cash flows.

Overall, the revenue sensitivity analysis confirms that the financial attractiveness of the BESS investment depends strongly on the ability to capture revenues from the combined arbitrage and ancillary services scenario. The arbitrage-only scenario was not sufficient, and reductions in simulated arbitrage and ancillary services revenues quickly removed operating payback within the 24-month period. The operating break-even calculation further shows that Object 1 did not reach break-even at the simulated base-case revenue level, while Object 2 only exceeded the break-even threshold by a small margin.

5

Discussion

5.1 Economic viability and revenue stacking

The findings indicate that the barriers to BESS implementation are not driven by a single factor but emerge from a combination of economic, strategic, and operational conditions. The most limiting of these is economic, and the financial analysis suggests that this barrier operates through a specific mechanism, namely the inability of arbitrage alone, and the dependence on combined market revenues, to recover the investment within a reasonable horizon.

The investment appraisal shows that electricity price arbitrage alone produced operating net cash flows of approximately $-616,000$ EUR/MWh for both studied sites. This finding is consistent with previous research showing that BESS profitability from energy arbitrage is highly sensitive to price volatility, operating strategy, and degradation costs [69]. In the present study, this makes revenue stacking an essential requirement rather than a complementary feature, since arbitrage alone is insufficient to recover the investment under current Swedish market conditions.

When ancillary service revenues are added, the financial picture changes substantially. One of the two studied sites reaches operating payback within the analysis period, while the other requires approximately 120.2% of the simulated revenues to recover the investment through operating cash flows alone. The qualitative results align with this asymmetry, since the mills consistently describe ancillary service revenues as the only realistic justification for a BESS investment, but also as uncertain and competition-sensitive. This combined picture clarifies the often-repeated claim that BESS is "not yet profitable" by showing that profitability is in fact achievable under specific conditions in narrow regions of the parameter space defined by site characteristics, market access, and the sustainability of ancillary service margins.

A further methodological observation is that the financial analysis excludes peak shaving revenues, partly due to the model limitation but also because of the regional grid tariff structure, which offer no or limited reduction possibilities for temporarily lowering consumption. This exclusion is conservative for the studied scenarios, but it also illustrates that the financial value of BESS is not determined by the battery technology alone. In this study, the profitability gap depends on which value streams can be quantified and accessed, particularly arbitrage, ancillary services,

and potential tariff-related savings. The observed gap should therefore be interpreted as conditional on the current market and tariff assumptions rather than as a fixed characteristic of BESS technology.

5.2 Revenue dynamics and policy uncertainty

A central observation in the financial analysis is that the dominant ancillary service revenue stream changed between the two simulated periods, shifting from FCR in 2024/2025 toward mFRR in 2025/2026. This shift is identified in the simulation results, but its underlying market causes are not analyzed in detail. It nevertheless has important implications for the investment case, since it indicates that BESS profitability depends not only on access to ancillary service markets, but also on how the relative value of different balancing products develops over time.

Several mutually consistent factors may help explain this shift. First, SvK has reported lower and more stable FCR prices during 2024, particularly for FCR-D, linked to lower market concentration, improved liquidity, and a more diversified supply of actors, including increasing participation from energy storage and wind power [87, 88]. This supports the interpretation that increased participation can diminish revenues in fast frequency products. Second, SvK has also stated that there remains a need for more mFRR suppliers, especially for down-regulation, and that this need was expected to increase with the introduction of automated mFRR balancing and balancing per bidding zone [88]. The Nordic mFRR energy activation market with 15-minute activation resolution went live in March 2025, which further indicates that mFRR was undergoing structural market development during the second simulated period [48]. These explanations should, however, be interpreted cautiously. The simulation results show a change in revenue composition, but without a separate empirical analysis of procurement volumes, bid prices, and activation patterns, the causes of the shift cannot be confirmed within this study. For this reason, the observed shift should be used as an indication of market dependence rather than as a confirmed explanation of market development. The important analytical point is that the dominant revenue stream can change within a short period. This makes BESS investment different from many traditional industrial investments. The asset may remain technically useful, while the market product that pays for the asset changes. This increases the need for flexible business models and careful risk allocation between the mill, aggregators and market actors.

The findings regarding the saturation of the ancillary market, such as FRR and FCR-D, can be interpreted through Rogers' (1995) theory on the Diffusion of Innovations [89]. Early adopters in the Swedish BESS market were able to capture high revenues during the initial phase of market introduction, a period characterized by low competition and high demand for fast frequency response. However, as the innovation moves towards the early majority phase, increased competition leads to price stabilization or decline, reducing the profit margins for latecomers. This aligns with the observations from the DSO, suggesting that while early projects were highly profitable, the current market environment requires more complex revenue

stacking strategies.

This observation has two implications. First, it shows that the financial value of BESS is not determined by static technical performance alone, such as energy capacity or power output, but by the evolving structure of the markets in which the asset participates. This strengthens the argument that BESS should be analyzed as a market-dependent investment rather than as a technology-deterministic investment. Second, it highlights that revenue uncertainty is not only a matter of price volatility within a single market, but also of structural changes in which markets become most valuable. For industrial investors, this type of uncertainty is particularly challenging, since long-term profitability depends on future market rules, procurement needs, and market saturation that are outside the control of the mill.

The qualitative results add a further dimension by showing that uncertainty is not limited to future market revenues, but also affects the earlier conditions under which a BESS project can be planned, permitted, and connected. Interviewees describe unclear and locally varying permitting requirements, ambiguous national guidance for grid connection and technical requirements, and broader political uncertainty regarding the future electricity mix as factors that extend lead times and weaken the basis for long-term profitability calculations. This is consistent with external guidance on stationary battery installations, which emphasizes that local risk assessments and possible municipal or county-level permitting requirements may affect project design [90]. In addition, participation in ancillary service markets requires prequalification and cooperation with, or registration as, a BSP, which adds further institutional requirements to the investment process [91]. The investment appraisal in this study assumes a stable institutional environment over the analysis period. This simplification is reasonable for the simulation, but becomes more problematic when the result is interpreted as a basis for real industrial capital investment decisions. The combined effect of market uncertainty and policy uncertainty, therefore, suggests that the relevant barrier for many mills is not only the expected return itself, but the difficulty of constructing a robust forecast within the decision frame typically used for industrial investments.

5.3 Scale mismatch and the business logic of BESS in mill operations

The qualitative results consistently describe a scale mismatch between commercially available BESS units and the energy demand of P&PMs, but the analytical implications of this mismatch deserve more attention than a simple observation that batteries are too small. The mismatch operates on at least three levels.

First, it shapes the business logic of BESS at industrial sites. Because typical industrial BESS installations cover only a small fraction of the mill’s continuous load, they cannot meaningfully replace grid imports during normal operation. The economic case, therefore, cannot rest on energy substitution and must instead be built on services that monetize short-duration power capability, which in practice means an-

cillary services and short-term arbitrage. The financial analysis confirms this, since it is precisely these short-duration services that drive the simulated profitability, and arbitrage on energy volumes alone produces almost negligible revenue. This means that the business case for BESS at a mill is less about reducing internal electricity consumption and more about monetizing flexibility in external markets. A mill that invests in BESS mainly for ancillary services is therefore exposed to a market with its own rules, price dynamics, and uncertainties, rather than simply acquiring a tool to optimize its existing electricity consumption.

Second, the scale mismatch shifts the investment risk profile. A BESS sized to industrial loads would require capital investments that, at current prices, scale beyond what most mills are willing to commit for a non-core asset. The respondents explicitly link the perceived risk to investment size, and the financial analysis supports this concern, since the operating payback under base-case assumptions is highly sensitive to revenue levels and to relatively small changes in CAPEX, maintenance cost, and useful life. The combination of large fixed investment and partially uncertain market revenues creates an investment profile in which the downside risk is concentrated in the early years of the asset's life, which is unattractive for investment decision-making oriented toward predictable returns. The scale mismatch also limits the strategic optionality of the investment. If ancillary service revenues decline, a relatively small BESS is difficult to repurpose toward broader site-level functions such as backup power, peak coverage, or internal energy management, since its capacity remains small relative to the mill's total load.

Third, the scale mismatch interacts with market design. Ancillary service markets primarily reward available power capacity and response capability, often measured in MW, rather than the total MWh needed to cover mill consumption. This means that even a relatively small BESS can be commercially viable if it has access to sufficiently lucrative reserve markets. It also explains why aggregator participation and BSP access are emphasized in the qualitative findings as enablers of profitability, since they allow industrial BESS units to overcome scale disadvantages by pooling capacity and lowering barriers to market participation [59]. The scale mismatch is therefore not only a technical observation but a structural feature that ties the viability of industrial BESS to the existence of well-functioning aggregation channels and to the presence of reserve markets where small assets are competitive.

Taken together, these three levels suggest that the relevant question for P&PMs is not whether BESS can replace existing energy infrastructure, but whether it can be configured as a value-added flexibility asset alongside existing operations. Framed in this way, the scale mismatch shifts from being an obstacle to being a defining characteristic that shapes how the technology must be positioned within the mill's business model.

5.4 Reframing operational constraints and the flexibility-production trade-off

The qualitative results contain a recurring framing in which flexibility is associated with adjusting or reducing production. Several mill representatives describe their core production processes as continuous and tightly integrated, and they argue that providing flexibility would conflict with the prioritization of stable output. While the description of the underlying processes is accurate, the conclusion that flexibility requires sacrificing production requires further examination.

A BESS does not require process intervention in order to deliver flexibility. Because the battery is electrically connected in parallel with the mill's load, it can charge and discharge against the grid without directly intervening in the production process. This means that the flexibility service is provided by the battery, while the mill continues to operate at its preferred set point. The qualitative results, therefore, merge two fundamentally different types of flexibility, namely process-based flexibility, which does require operational adjustment, and storage-based flexibility, which does not. The theoretical framework supports this distinction by highlighting that BESS is technically well-suited for fast frequency services through precise electrical control, which can be operated alongside the host facility's production logic.

This reframing has important implications. The mills' reluctance to engage in flexibility markets is partly explained by an assumption that flexibility participation will compromise production reliability. Once storage-based flexibility is recognized as functionally separable from process-based flexibility, the trade-off becomes primarily financial rather than operational. The relevant question is no longer whether the mill should reduce production in order to provide flexibility, but whether the BESS investment generates sufficient returns to be justified as a stand-alone or co-located asset.

This distinction is important for how the barrier should be interpreted. If flexibility is understood only as process adjustment, the mills' reluctance appears mainly operational. If storage based flexibility is considered separately, the same reluctance appears more economic and organizational. The barrier is then less about whether the mill can keep producing while offering flexibility, and more about whether the additional asset creates enough value to justify investment, integration work and operational responsibility.

The continued relevance of operational constraints lies elsewhere. They affect the willingness to host an additional asset on site, the availability of physical space, the requirements for safety and integration with high-voltage industrial environments, and the perceived organizational distance between the mill's core competence and BESS operation. These are real barriers, but they are different in kind from the trade-off between flexibility and production that some respondents emphasize.

Existing flexibility solutions, such as internal electricity generation, off-grid operation through turbines, electric boilers, and pulp tower storage, complicate the picture

but do not invalidate the reframing. The qualitative results indicate that several mills already cover parts of their flexibility needs through these solutions and therefore see limited additional value in BESS. From a system perspective, however, these process-based solutions tend to operate on slower timescales and at larger energy volumes than the fast power services that BESS is capable of providing. The two flexibility categories should therefore be understood as potential complements rather than direct substitutes, which suggests that the perceived redundancy between BESS and existing flexibility may be partly a result of how the mills evaluate flexibility against their own internal needs rather than against system-level requirements.

5.5 Private profitability versus system value

A central tension in the results is the difference between private profitability and system value. From an electricity system perspective, BESS can support frequency stability, reduce the need for short term balancing and help integrate more variable renewable electricity. These effects may create value for the wider electricity system and for society. From the perspective of an individual mill, however, these benefits only matter if they are translated into reliable revenues or reduced costs.

This tension can be understood through the concept of positive externalities. If a BESS provider improves grid stability or enables higher use of wind and solar power, part of the value may benefit actors outside the mill. The mill carries the investment cost, but the full system benefit is not necessarily captured in the mill's cash flow. This helps explain why mills can be technically capable of providing flexibility while still choosing not to invest. The barrier is therefore not only technical ability, but also the absence of market arrangements that convert system value into private investments.

The qualitative results support this interpretation. Several mills describe flexibility as possible in some form, but they also emphasize profitability, risk and the need to protect the core production process. The quantitative results show the same logic from another angle. BESS can become profitable under specific market and site conditions, but the margins are narrow and highly dependent on ancillary service revenues. This means that socially useful flexibility resource may still remain unattractive at mill level if revenue model is uncertain.

This has policy implications. If policymakers and system operators want industrial actors to provide more flexibility, the relevant issues is not only whether BESS works technically. The issue is whether market design, grid tariffs and regulatory frameworks give mills a reason to invest. Stronger and more predictable remuneration for flexibility, clearer rules for grid connection and better access through aggregators could reduce the gap between system value and private profitability. Without such incentives, BESS adoption in the P&PI is likely to remain selective and site dependent.

5.6 Site-specific conditions and BESS as a contingent business case

The combined findings from the qualitative and quantitative parts of the study indicate that the business case for BESS in P&PMs is highly conditional rather than generally applicable. The two simulated sites differ in scale, internal electricity production, and net grid-consumption profiles. Object 1 represents a smaller mill without significant internal electricity production and with a relatively stable grid-consumption profile, while Object 2 represents a larger mill with internal electricity production and a more dynamic interaction with the external grid. These differences affected how freely the BESS could be operated. When ancillary service revenues were high, Object 2 was able to utilize the BESS more continuously, whereas Object 1 was more constrained by its grid connection point. This suggests that the available operational margin between the mill's subscribed grid capacity, net load profile, and BESS dispatch requirements is an important determinant of BESS value. However, since only two sites were analyzed, this should be interpreted as an indicative finding rather than a general predictor for all P&PMs.

The sensitivity of the business case becomes even more apparent when the financial assumptions are varied. In the base-case assessment, electricity price arbitrage alone was insufficient for both sites, and only Object 2 reached operating payback within the 24-month analysis period when ancillary services were included. Object 1 remained below operating break-even, while Object 2 only slightly exceeded it. The scenario analysis further shows that the investment outcome is sensitive to the combined effect of CAPEX, maintenance cost, and useful life, as both objects reached operating payback under optimistic assumptions, while neither did so under pessimistic assumptions. Similarly, the revenue sensitivity analysis shows that a reduction to 75% of simulated revenues removed operating payback for Object 2 and left Object 1 unrecovered. This means that the investment case depends on maintaining revenues close to the simulated base level, rather than on a broad and robust profitability margin.

The implication is that BESS in P&PMs should not be evaluated as a uniform technology with a uniform business case. Instead, it should be understood as a configuration-dependent flexibility asset whose viability is shaped by the interaction between site-specific energy profiles, grid connection margins, existing flexibility resources, market access, tariff structures, and future market development. This framing helps resolve the apparent tension between system-level optimism for BESS and mill-level skepticism. BESS may be valuable from an electricity-system perspective by contributing flexibility and balancing services, while still being unattractive for many individual mills if revenues are uncertain, margins are narrow, or the asset does not align with the mill's operational and investment logic.

5.7 BESS in a broader energy transition: wind, solar, and future business cases

Battery energy storage system should not only be discussed as an isolated investment at individual P&PMs. It should also be understood in relation to the wider transformation of the Swedish electricity system. The theoretical framework shows that increasing electrification and a larger share of wind and solar power increase the need for flexibility. In that context, BESS can provide fast and controllable power that supports balancing and frequency stability. This broader use case is relevant for the P&PI, but it should not be overstated. The results do not show that all mills will benefit from combining BESS with wind or solar power. They show that BESS value depends on market access, grid capacity, existing flexibility resources and site specific energy profiles. Wind and solar power should therefore be used in the discussion as a system level context and as a possible future business case, not as a direct conclusion for all studied mills.

The results show that the current business case for BESS remains uncertain. Electricity price arbitrage alone is not sufficient, while profitability mainly depends on revenues from ancillary services. These revenues are market-dependent and may change as more actors enter the market. The shift between FCR and mFRR revenues during the simulated years also indicates that the business case is affected by changing market conditions. One possible explanation is that increased participation in FCR markets reduces prices and moves profitability toward other balancing products, such as mFRR. This can be linked to the development of aggregators, the separation between BRP and BSP roles, and changing policy conditions, which together influence how industrial flexibility can access and create value in ancillary service markets. However, the future relevance of BESS may increase if the battery is combined with other energy assets, such as wind and solar power, or with other on-site electricity production. For mills with available land, own electricity production, or large electricity flows, BESS could be integrated into the existing energy system rather than treated as a separate asset. The battery could then support several functions, such as storing renewable electricity, reducing imbalance costs, and participating in flexibility markets.

Therefore, BESS should not be viewed as a solution that fits all paper and pulp mills. Its usefulness depends on the conditions at each site, such as electricity use, grid capacity, existing flexibility, and access to relevant markets. Under current conditions, high investment costs, operational constraints, and regulatory uncertainty still make implementation difficult. This also helps explain why implementation remains limited, even though BESS has technical potential. Mills are unlikely to adopt the technology more widely before the revenue model is clearer, revenues are more predictable, and the battery can be integrated without disturbing normal production. However, BESS may become more relevant for some mills if battery costs decrease, flexibility markets mature, and renewable electricity production increases. The main implication is that paper and pulp mills should evaluate BESS as part of a broader flexibility strategy rather than as a stand-alone arbitrage asset.

6

Conclusion

The purpose of this thesis was to investigate the barriers to the implementation of battery energy storage systems (BESS) within the Swedish paper and pulp industry (P&PI). The results demonstrate that BESS is recognized as a technically capable technology for supporting system flexibility, but that several barriers currently limit its adoption within the sector.

The primary barrier is economic. The study finds that high investment costs are not matched by predicted revenue streams under current market conditions. The simulations confirm that electricity arbitrage alone is insufficient to justify an investment. Instead, profitability depends on revenue stacking through ancillary services, such as FCR and mFRR. However, the market-dependent nature of these revenues, together with increasing competition and uncertainty about future price levels, create financial risk and discourages mills from investing.

Operational and strategic constraints present significant obstacles. The P&PI is characterized by continuous 24/7 production where stability is prioritized over flexibility. Many mills already possess flexibility through internal electricity production and process-based storage, which can fulfill their short-term needs. These existing solutions reduce the perceived need for BESS. At the same time, BESS can provide storage-based flexibility without disrupting core production. The barrier is therefore not only operational, but also strategic. BESS must create enough additional value to justify investment, integration work and operational responsibility

The results also show scale mismatch between BESS and mill operations. Batteries are well suited for fast response and ancillary services, while many mills operate with large and continuous energy flows. This means that the value of BESS is not universal. It depends on site-specific conditions, such as local grid constraints electricity consumption profiles, existing flexibility resources, market access and tariff structures.

Regulatory and administrative uncertainty further increases the difficulty of implementation. unclear permitting processes, technical requirements and future market conditions can increase lead times and make investment decisions more uncertain. This is particularly important for capital-intensive industries that require stable assumptions before making large investments.

In conclusion, BESS has the potential to complement existing flexibility solutions in the paper and pulp industry, but it is not currently generally viable solution for all mills. The main barriers are high financial risk, uncertain revenues, site-specific operational fit and regulatory uncertainty. The study also highlights a tension between system value and private profitability. BESS can support grid stability and contribute to the wider electricity system, but current market and tariff structures do not always translate this system value into a sufficiently strong business case for individual mills.

For wider adoption, BESS must be evaluated as a part of a broader flexibility strategy rather than as a stand-alone technology. Future implementation will depend on clearer revenue models, more predictable market conditions, suitable site characteristics and business models that align the value of BESS with the operational and economic logic of paper and pulp mills.

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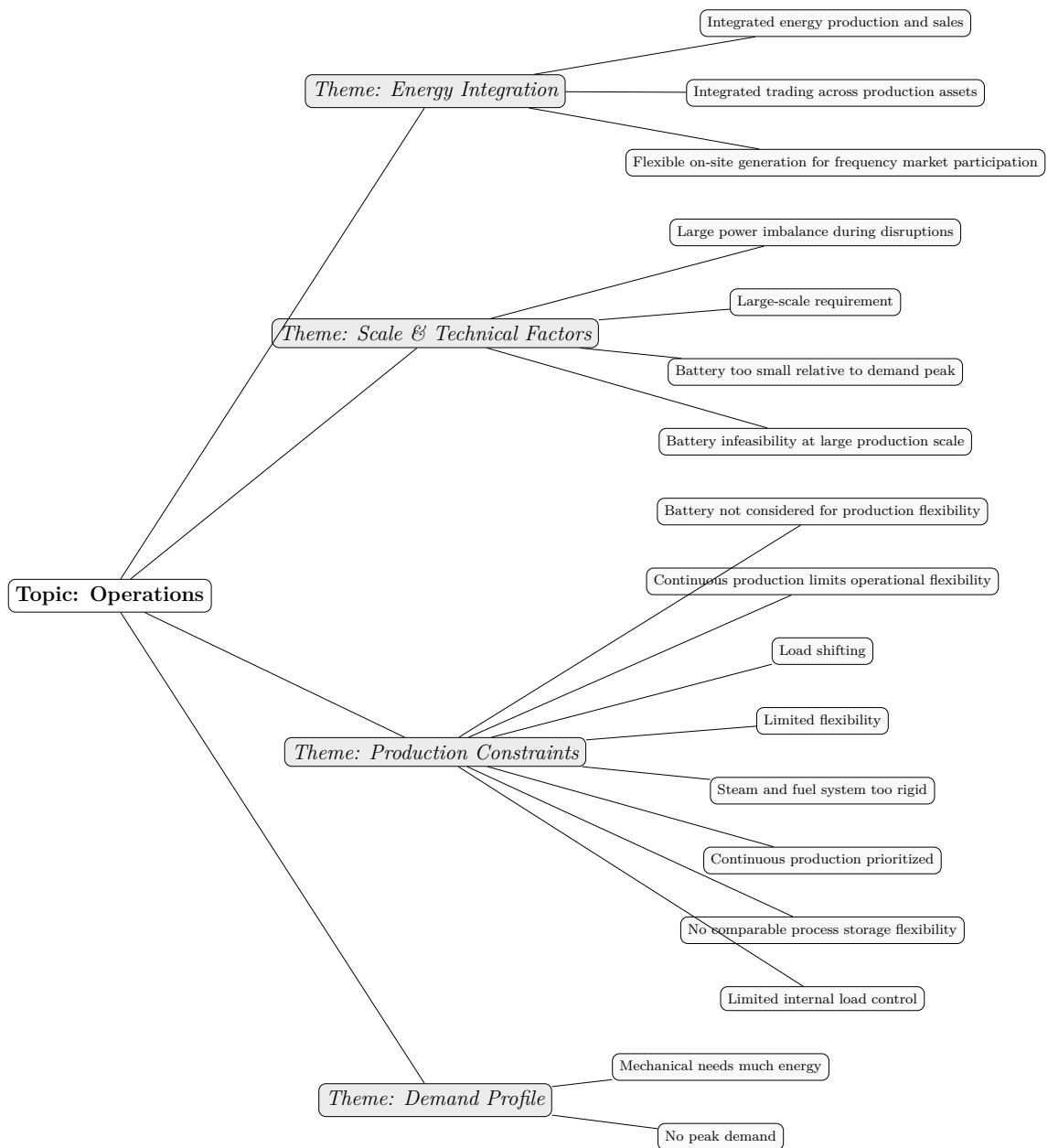
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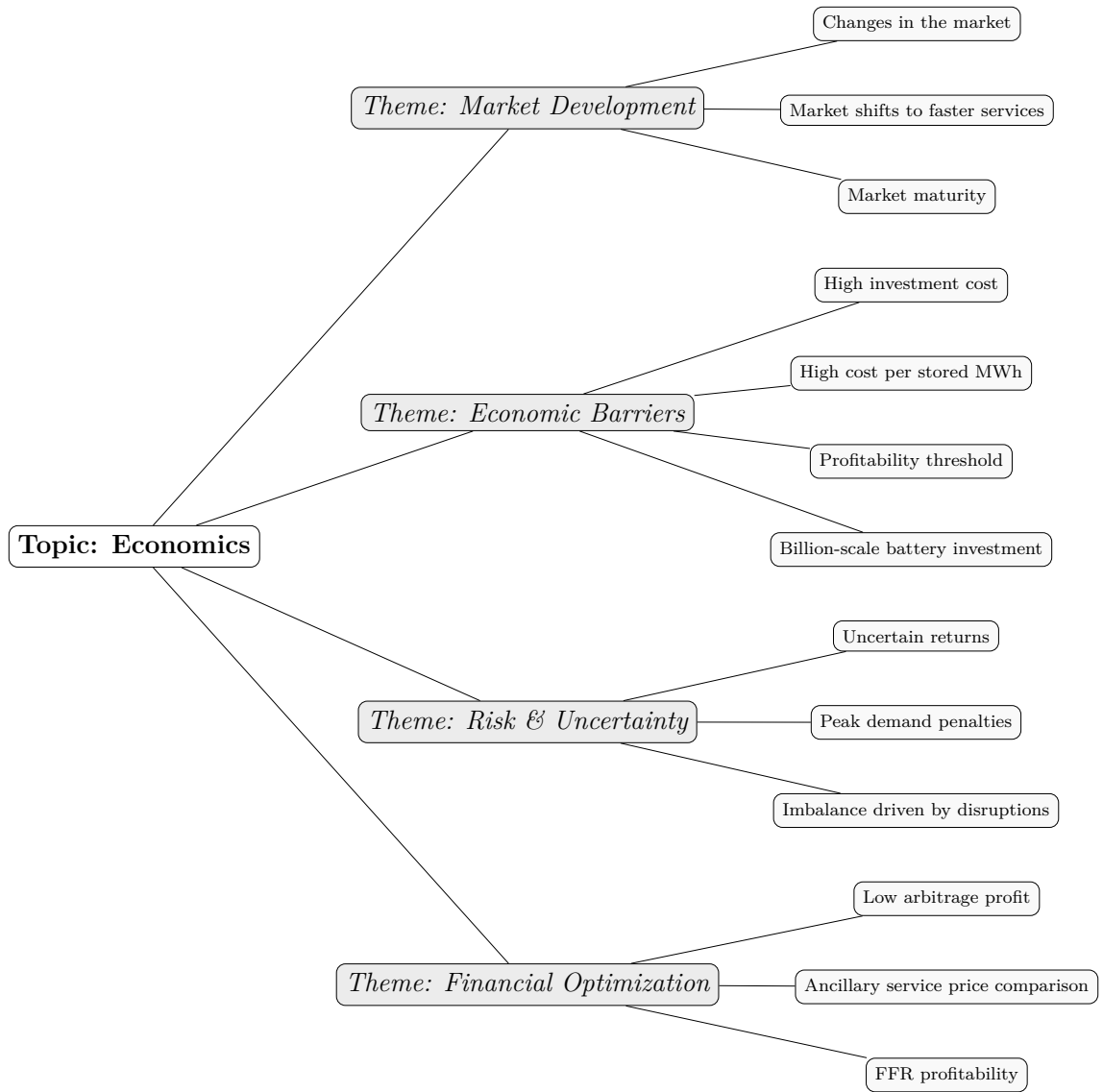
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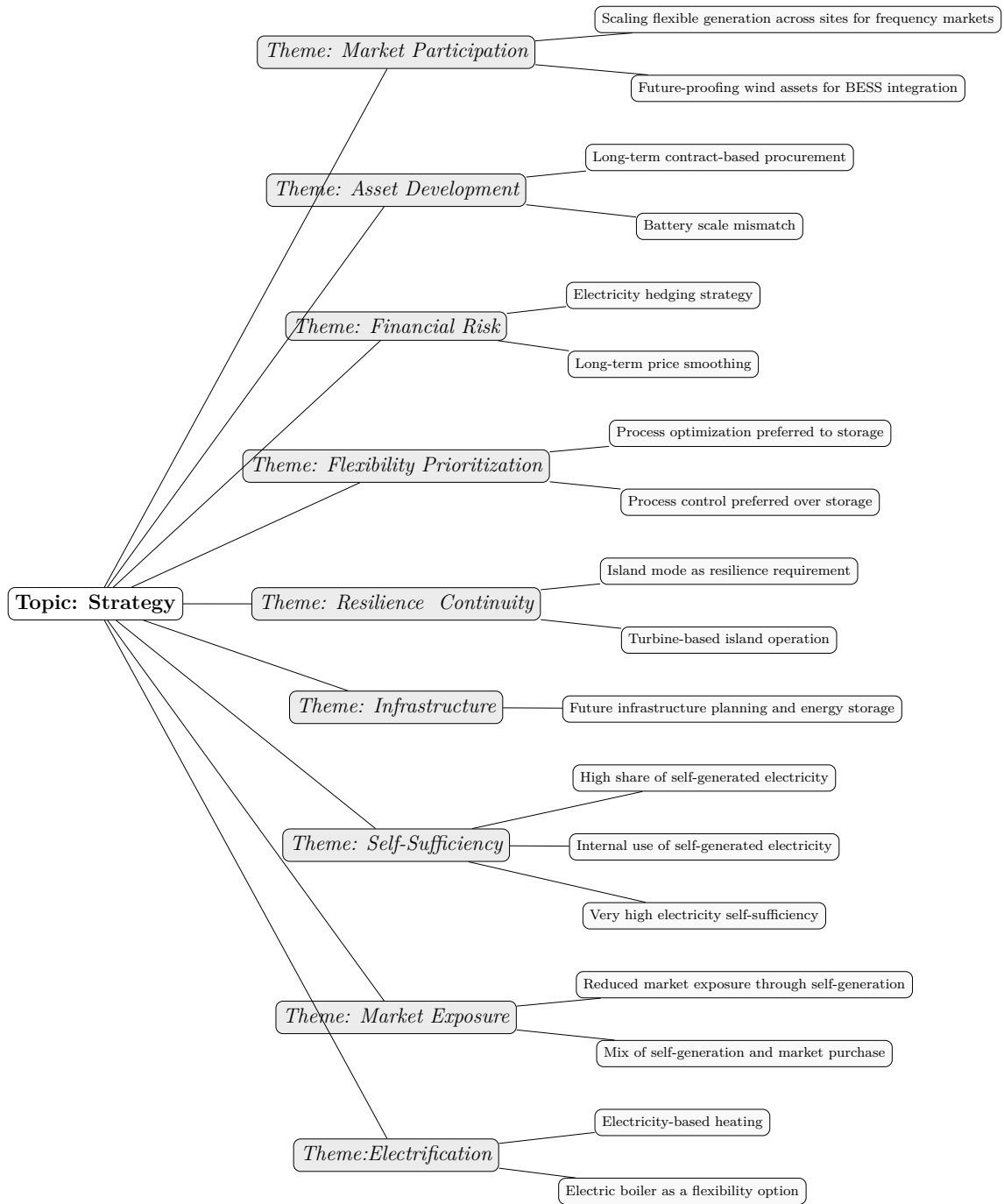
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A

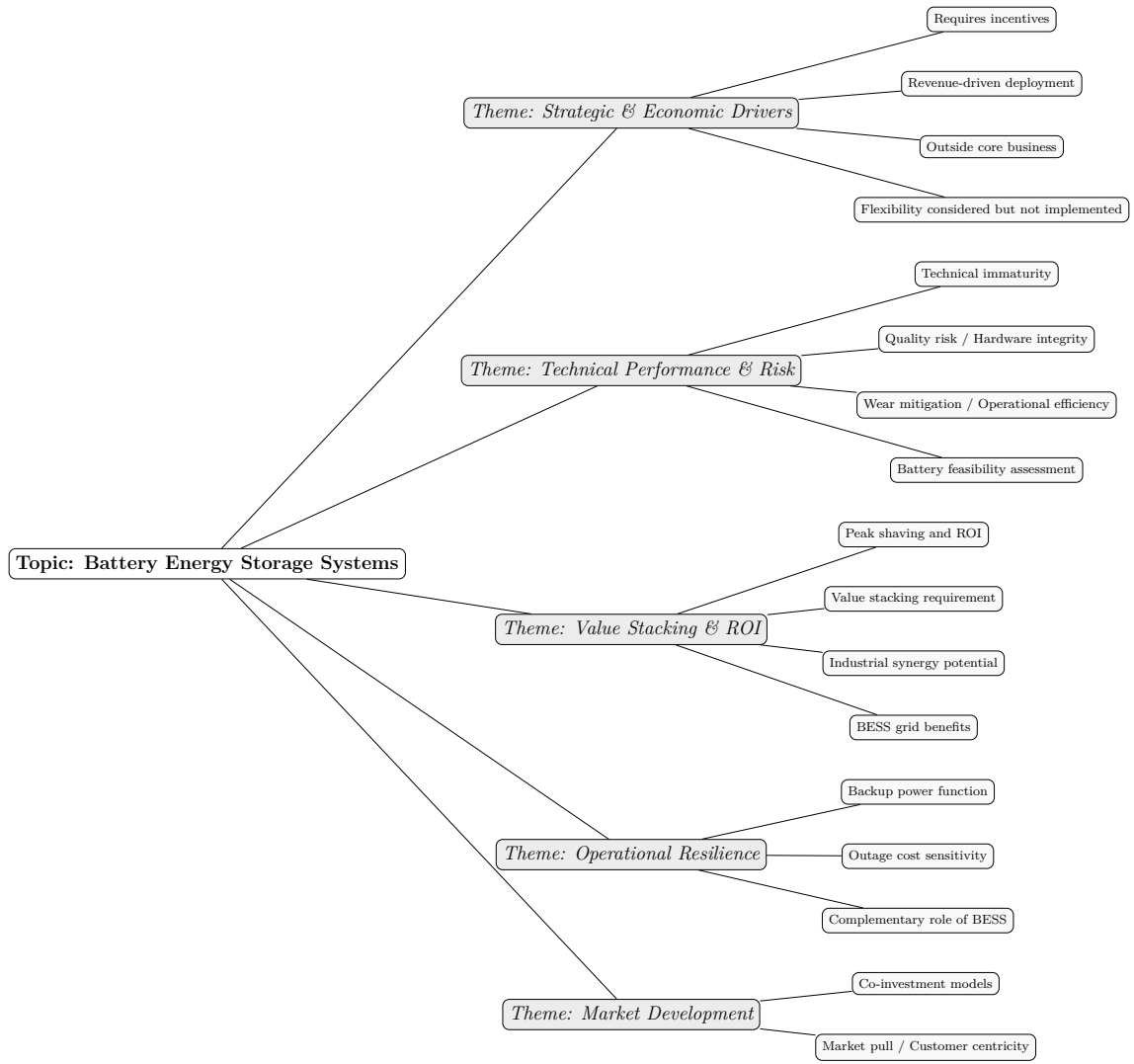
Coding Trees







A. Coding Trees



B

Thematic Analysis Summary Table

Respondent Theme		Code	Representative Quotation
Topic: Operations			
P&PM A	Demand Profile	Mechanical needs much energy	"Hela processen drar ungefär 30–32 MW... fabriken går i princip kontinuerligt."
P&PM A	Scale & Technical Factors	Large power imbalance during disruptions	"Ett oplanerat stopp i kedjan medför stora differenser, det skiljer 70 MW från produktion till konsumtion."
P&PM A	Energy Integration	Flexible on-site generation for frequency market participation	"Anläggningarna deltar i frekvensmarknaden, men produktionen är kontinuerlig och kan inte anpassas flexibelt."
P&PM B	Production Constraints	Limited flexibility	"Det är egentligen det enda vi kan stänga av; resten av processen måste gå som vanligt."
P&PM B	Production Constraints	Continuous production prioritized	"Resten måste gå som vanligt. Så vi kan inte lova att vi alltid kan gå ner 6 megawatt."
P&PM B	Scale & Technical Factors	Large-scale requirement	"Vi ligger redan på runt 32 MW, så det skulle krävas ganska stora batterier för att det ska göra någon skillnad."
P&PM C	Production Constraints	No comparable process storage flexibility	"Genom att stänga av en raffinör kan elanvändningen minskas... på obegränsad tid, till skillnad från ett batteri som töms."
P&PM D	Production Constraints	Continuous production limits operational flexibility	"Henrik Essén förklarar att ett sulfatmassabruk är svårt att reglera snabbt: 'ett sulfatmassabruk går inte att stänga av och sätta på'."
P&PM D	Production Constraints	Steam and fuel system too rigid	"När det gäller bränslen och ångsystem beskriver han dem som 'mycket trögare processer' där det inte går att hoppa fram och tillbaka."

Respondent	Theme	Code	Representative Quotation
P&PM D	Production Constraints	Continuous production prioritized	"Henrik Essén betonar att verksamheten ska gå stabilt: 'vårt massabruk och våra pappersmaskiner... ska gå på jämnt takt hela tiden'."
P&PM D	Production Constraints	No comparable process storage flexibility	"De bedömer dock att de själva saknar dessa möjligheter: 'De möjligheterna har vi inte riktigt. Vi kan inte lagra såsom vi gör'."
P&PM D	Production Constraints	Limited internal load control	"Den flexibilitet som faktiskt finns beskrivs som begränsad: 'Vi kan stänga av och sätta på lite pumpar och kvarnar här och då'."
P&PM D	Scale & Technical Factors	Battery infeasibility at large production scale	"Han resonerar om batterier i brukets fulla skala: 'Det går inte med batterier att köra det' (full drift)."
P&PM D	Scale & Technical Factors	Battery too small relative to demand peak	"Han menar också att ett batteri skulle bli för litet i relation till brukets storlek och totala energikonsumtion."
P&PM E	Production Constraints	Continuous production limits operational flexibility	"De körs i princip kontinuerligt. Nästan alla våra bruk är i drift dygnet runt."
P&PM E	Production Constraints	Continuous production prioritized	"Man undviker att stoppa maskiner... om det inte är absolut nödvändigt."
P&PM E	Production Constraints	Limited flexibility	"Hittills har det mest lönsamma varit att ha så lite flexibilitet som möjligt, alltså att hålla allt igång kontinuerligt."
P&PM E	Production Constraints	Continuous production prioritized	"Målet har varit att köra bruken med mycket hög tillgänglighet, omkring 96–97 procent."
P&PM E	Production Constraints	Limited internal load control	"Det finns vissa diskussioner om viss flexibilitet... i delar av processerna... men inte i huvudlinjerna eller de viktigaste maskinerna."
P&PM E	Scale & Technical Factors	Battery too small relative to demand peak	"Elproduktionen från ett massabruk är så stor att batterier fortfarande är för små i relation till de energimängder det handlar om."
P&PM E	Scale & Technical Factors	Battery not considered for production flexibility	"Det skulle bara kunna lagra en mycket liten del av produktionen, så i nuläget verkar det inte särskilt relevant."

Respondent Theme		Code	Representative Quotation
Topic: Economics			
P&PM A	Financial Optimization	Low arbitrage profit	"Energimarknaden kommer du att se... små prisskillnader gör batterier olönsamma."
P&PM A	Risk & Uncertainty	Imbalance driven by disruptions	"Om man ska minska obalanskostnader... de uppstår främst vid oplanerade stopp."
P&PM A	Financial Optimization	Ancillary service price comparison	"Bättre priser på frekvensmarknaden ger högre ersättning än energimarknaden."
P&PM A	Risk & Uncertainty	Peak demand penalties	"Vår konsumtion ligger på en viss genomsnittsnivå... överskridande av effektgränser leder till mycket höga kostnader."
P&PM A	Market Development	Changes in the market	"När priserna ser ut som de ser ut... köper man tillbaka el för att minska obalanskostnader."
P&PM A	Financial Optimization	FFR profitability	"Man har möjlighet att göra flera saker... men används idag enbart för FFR eftersom det är mest lönsamt."
P&PM A	Market Development	Changes in the market	"Priserna fortsätter att falla och motiverar inte i nuläget att vara attraktiva."
P&PM A	Risk & Uncertainty	Uncertain returns	"Inkomstkällan idag är framförallt från frekvensmarknaden, men framtida utveckling är osäker."
P&PM D	Risk & Uncertainty	Imbalance driven by disruptions	"Han kopplar detta direkt till förlust av intäkter vid produktionsstopp."
P&PM D	Economic Barriers	High investment cost	"När de jämförde batterier med att justera processen... sågs batterier som för dyra."
P&PM D	Economic Barriers	High cost per stored MWh	"Han förklarar också att de tittat på kostnaden per lagrad MWh och den var för hög."
P&PM D	Economic Barriers	Billion-scale battery investment	"Han förstärker detta med att fullskalig batteridrift ses som ekonomiskt orealistiskt."
BESS-actor	Economic Barriers	Profitability threshold	"Lagringskostnaden ligger på cirka 40–50 öre per kilowattimme... man måste sälja högre om arbitrage ska vara lönsamt."
BESS-actor	Economic Barriers	High investment cost	"Ett genomsnittsprojekt i Sverige kostar 7–8 Mkr per installerad megawatt."
BESS-actor	Economic Barriers	High investment cost	"En grov uppskattning är att två tredjedelar är hårdvara och en tredjedel till installation."

Respondent Theme		Code	Representative Quotation
Topic: Strategy			
P&PM A	Market Participation	Scaling flexible generation across sites for frequency markets	"Det vi kan anpassa är den egna produktionen... vi försöker att inte producera el, vi försöker sälja av turbinen för att vara del av frekvensmarknaden."
P&PM A	Market Participation	Scaling flexible generation across sites for frequency markets	"Vi jobbar för att alla våra bruk ska delta i frekvensmarknaden genom att styra sin egen produktion."
P&PM B	Financial Risk	Electricity hedging strategy	"Vi köper det på spoten. Men just nu har vi försökt att binda upp ungefär 60–70 procent... för att få förutsägbara priser."
P&PM C	Asset Development	Battery scale mismatch	"Industrins nisch är uthållighet snarare än snabbhet."
P&PM D	Infrastructure	Future infrastructure planning and energy storage	"Vi är öppna för andra tekniker som flödesbatterier... då de är vana vid stora volymer flytande material."
P&PM D	Self-Sufficiency	High share of self-generated electricity	"I det här bruket så gör vi ungefär 55–60 procent av den elen vi behöver gör vi själva."
P&PM D	Asset Development	Long-term contract-based procurement	"I stället beskriver han en inköpsstrategi med kontrakt: 'Vi köper el på kontrakt mest'."
P&PM D	Financial Risk	Electricity hedging strategy	"Han förklarar också att företaget har 'en policy för elhedging' för att få 'stabila och förutsägbara elpriser framåt'."
P&PM D	Resilience Continuity	Turbine-based island operation	"En annan lösning de redan använder är ödrift. 'Ödrift har vi på ett av våra bruk, det är Bäckhammar och det kör vi när det åskar'."
P&PM D	Resilience Continuity	Island mode as resilience requirement	"Han betonar att detta är nödvändigt: 'det måste man ha för annars blir man alldeles för åskkänslig'."
P&PM D	Flexibility Prioritization	Process control preferred over storage	"I stället framhåller han att de 'har lättare att reglera vår egen process istället'."
P&PM E	Self-Sufficiency	High share of self-generated electricity	"Totalt sett producerar vi mer el än vi använder."
P&PM E	Self-Sufficiency	Very high electricity self-sufficiency	"Ett exempel är Kemi massabruk, som ligger på ungefär 250 procents självförsörjningsgrad i el."

Respondent	Theme	Code	Representative Quotation
P&PM E	Self-Sufficiency	Internal use of self-generated electricity	"Sammantaget täcker detta även annan elanvändning inom koncernen."
P&PM E	Market Exposure	Reduced market exposure through self-generation	"Om man redan har ett mycket stort elöverskott blir nyttan med batterier sannolikt mindre."
Energyexpert	Infrastructure	Future infrastructure planning and energy storage	"För större effektbehov är nätutbyggnad oftast en bättre lösning."
BESS-actor	Flexibility Prioritization	Process optimization preferred to storage	"Batterilagret kan användas för att hantera effekttoppar... Exakt hur man balanserar dessa nyttor beror på fabriken's förutsättningar."

Respondent Theme		Code		Representative Quotation
Topic: BESS				
P&PM B	Strategic Economic Drivers	&	Outside core business	"Det är inte vår kärnverksamhet, vi är bäst på att producera pappersmassa."
P&PM B	Strategic Economic Drivers	&	Requires incentives	"Om det fanns tillräckliga incitament och det blev lönsamt skulle vi kunna överväga det."
P&PM D	Strategic Economic Drivers	&	Flexibility considered but not implemented	"Nej, det skulle jag inte säga... men han tillägger att de har 'tänkt på det' och 'tittat på det'."
P&PM D	Strategic Economic Drivers	&	Revenue-driven deployment	"Där finns möjlighet att växla beroende på pris: 'är det jättebillig el imorgon eller inte, då har vi möjlighet att skifta'."
P&PM D	Strategic Economic Drivers	&	Flexibility considered but not implemented	"Om stödtjänster säger han att det finns som en möjlig framtidsfråga: 'det där har vi som en bubblare'."
P&PM D	Strategic Economic Drivers	&	Revenue-driven deployment	"Samtidigt konstaterar han att andra lyckas väl med det: 'framförallt tjänar väldigt mycket pengar på det'."
P&PM D	Strategic Economic Drivers	&	Outside core business	"Om inköpsstrategin för koncernen säger han att 'den svenska elen för alla de svenska bruken går på samma kontrakt'."
P&PM E	Strategic Economic Drivers	&	Flexibility considered but not implemented	"Det finns vissa diskussioner om att viss flexibilitet skulle kunna utnyttjas i delar av processerna... men inte i huvudlinjerna."
P&PM E	Value Stacking & ROI		Industrial synergy potential	"Däremot äger vi ingen egen sol- eller vindkraft."
P&PM E	Technical Performance & Risk	Per- &	Battery feasibility assessment	"För ett fristående kartong- eller tissuebruk kan batterilagring kanske vara mer relevant än för ett integrerat massabruk."
P&PM E	Technical Performance & Risk	Per- &	Battery feasibility assessment	"Från ett perspektiv verkar det mest relevant att titta på ett bruk som inte har så stor egen elproduktion."
BESS-actor	Market Development	Devel-	Market pull / Customer centricity	"Extrema händelser som Ukrainakrisen eller kalla februarimånader kan också påverka priserna dramatiskt."
BESS-actor	Market Development	Devel-	Market pull / Customer centricity	"Industrin fortsätter växa, och det kommer skalfördelar... Vi kan förvänta oss en kostnadsminskning på några procent per år."
BESS-actor	Market Development	Devel-	Market pull / Customer centricity	"Det viktigaste är att förstå kundens behov, både historiskt och framtida."
BESS-actor	Market Development	Devel-	Co-investment models	"Vi ser möjligheter i alternativa affärsmodeller där vi delar på investeringen eller finansierar den tillsammans med kunden."

Respondent	Theme	Code	Representative Quotation
BESS-actor	Market Development	Market pull / Customer centrality	"Ja, medvetenheten har ökat... ett nationellt regelverk för effekttariffer skulle göra det mycket lättare."
BESS-actor	Technical Performance & Risk	Wear mitigation / Operational efficiency	"Om man främst använder batteriet för stödtjänster sliter det inte mycket. Vissa system har garanti på 15-20k cykler."
BESS-actor	Value Stacking & ROI	Value stacking requirement	"Reaktiv Effekt, Ja, om man dimensionerar batteriet för det kan det fungera utmärkt... det ger nya intäktsströmmar."
Aggregator	Technical Performance & Risk	Quality risk / Hardware integrity	"En annan utmaning är kvaliteten på batterier. Många batterier som importeras är inte fullt produktifierade."
Aggregator	Technical Performance & Risk	Technical immaturity	"Batterier som inte är fullt produktifierade kan leda till problem som balanseringsfel eller driftstopp."
P&PM C	Technical Performance & Risk	Battery feasibility assessment	"Vi har studerat energilagring och har idag inga batterilösningar för industribehov, men har reservkraft."
P&PM C	Technical Performance & Risk	Wear mitigation / Operational efficiency	"Ett mindre batteri skulle kunna användas för att undvika start och stopp av stora laster vid korta aktiveringar."
P&PM C	Value Stacking & ROI	Peak shaving and ROI	"Investeringar kan motiveras om batterier kan kapa abonnerad effekt under korta stunder. Det tar dock tid att få effekt."
TSO	Value Stacking & ROI	BESS grid benefits	"Om det fungerar koordinerat kan BESS (1) minska nätavgifter och obalanskostnader."
Energyexpert	Operational Resilience	Complementary role of BESS	"Batterier ses som ett komplement snarare än en ersättning för processflexibilitet."
Energyexpert	Strategic & Economic Drivers	Revenue-driven deployment	"Batterier byggs redan eftersom vissa tjänster har tillräckligt höga priser."
Energyexpert	Value Stacking & ROI	Industrial synergy potential	"Om batterier kan skapa synergier med industrins verksamhet blir det mer intressant att placera dem där."
Energyexpert	Value Stacking & ROI	Value stacking requirement	"Batterier blir mer attraktiva om de kan bidra med flera nyttor samtidigt: stödtjänster, arbitrage och lokal nytta."
Energyexpert	Operational Resilience	Backup power function	"Batterier kan fungera som reservkraft och skydda känsliga industriprocesser."
Energyexpert	Operational Resilience	Outage cost sensitivity	"Strömavbrott kan vara mycket kostsamma även om de är korta."

C

Interview guide: Paper & Pulp Industry

1. Vilka typer av bruk (t.ex. massa-, pappers- eller integrerade bruk) ingår i er verksamhet?
2. Har ni specifika processer i produktionen som är mer energikrävande än andra?
3. Finns det processer som kräver särskilt hög effekt, exempelvis vid uppstart av specifika maskiner eller anläggningsdelar?

Flexibility

4. Arbetar ert bruk med flexibilitet idag? Om ja, på vilket sätt?
5. Har ni avtal med Svenska Kraftnät (SvK) för att reglera produktionen (t.ex. förbrukningsfrånkoppling)?
 - Hur ser avtalet ut gällande effekttariffer och ersättning?
6. Hur anpassar ni verksamheten till fluktuerande elpriser? Finns det möjlighet att köra bruken flexibelt utifrån marknadsläget?
7. Har ni egen lokal elproduktion (t.ex. solceller, vindkraft, mottrycksturbiner)?
 - Om ja: Vart styrs den egenproducerade elen främst? Finns det specifika processer som prioriteras?
8. Hur ser er inköpsstrategi för el ut?
 - Hur stor andel köps på spotmarknaden kontra fastprisavtal eller egenproduktion?

BESS (Battery Energy Storage Systems)

9. Har ni undersökt möjligheten att implementera batterilagring (BESS) i er verksamhet?

OM JA:

- Finns det någon specifik process i bruket som bedöms kunna gynnas särskilt av batterilagring (t.ex. för effektkapning)?
- Hur bedömer ni lönsamheten och återbetalningstiden för en investering i batteri- eller energilagring?

OM NEJ:

- Har ni utvärderat andra typer av energilagring? I så fall vilka, och varför valdes de framför BESS (eller varför valdes lagring bort helt)?

D

Interview guide: TSO, DSO, Energy Expert, Aggregator & BESS Actor

TSO

1. Hur bedömer ni att BESS-etableringar vid tung industri bäst kan skapa nät-nytta?
2. Hur ser framtidsutsikterna ut för industriella aktörer på stödtjänstmarknaderna (t.ex. FCR och mFRR)?
3. Vilka eventuella utmaningar ser ni för denna typ av flexibilitet?

DSO

System Stability & Market

1. Vilken roll spelar storskalig batterilagring för systemstabiliteten, särskilt med tanke på den ökande andelen förnybar energi?
2. Hur ser marknadsutvecklingen ut för batterilager och de olika stödtjänsterna (FFR, FCR, mFRR, aFRR)?
3. Hur ser nätnyttan ut för batterilager i regionnätet, och hur kompenseras den i förhållande till nätavgifter?

Technology & Location

4. Vilka faktorer styr valet av plats vid etablering av batterilager (t.ex. effekt, mark och bullerkrav)?
5. Hur ser teknikutvecklingen ut framåt gällande batterityper (t.ex. LFP vs. Natrium)?

Obstacles & Growth

6. Vilka är de största hindren (ekonomiska, regulatoriska eller tekniska) för industrin att satsa på egna energilager?
7. Kan batterier hjälpa industrier att växa i områden där elnätet utgör en flaskhals?

Politics & Trends

8. Hur tror du att politiska beslut, som satsningar på kärnkraft, kommer att påverka batteri- och frekvensmarknaden?
9. Vilka framtida trender ser ni inom flexmarknader, spänningsreglering och beredskapstjänster?

Energy Expert

Stability & Ancillary services

1. Vilken roll ser ni att storskalig batterilagring spelar för systemstabiliteten när andelen väderberoende elproduktion ökar?
2. Ser ni en förflyttning i lönsamhet från frekvensmarknader mot arbitrage framöver?

Heavy industry & energy flexibility

3. Hur kan ni som energiaktör stötta tung industri (t.ex. pappersbruk) att integrera BESS i sin verksamhet?
4. Ser ni en trend där industrier går från att vara passiva konsumenter till aktiva deltagare som säljer flexibilitet till nätet?
5. Finns det fördelar med att kombinera batterier med befintlig utrustning i fabrikena, exempelvis som backup power vid strömavbrott?

Profitability & Investment

6. Vilka är de viktigaste faktorerna ni tittar på för att se om ett batteriprojekt blir lönsamt för en industri (t.ex. "Kombination av nyttor")?
7. Vilka är de största hindren för att industrin ska våga satsa på egna energilager idag?
8. Kan batterier fungera som stöd för stor tung industri som behöver betydande kapacitetsökningar (t.ex. 30 MW+)?

Aggregator

Earnings & Incentives

1. Hur ser ert grundläggande erbjudande ut till en stor industrikund som ett pappersbruk?
2. Kan ni optimera mer än bara batterier?
3. Har ni några konkreta exempel eller referenser där ni jobbar med tung, storskalig processindustri idag?
4. Ett pappersbruk planerar årtionden framåt. Hur ska de våga lita på era intäktsprognoser idag när ingen vet hur marknaden ser ut om fem år?
5. Om er mjukvara gör en felbedömning, eller om vårt internet går ner en stund, är det vi eller ni som betalar böterna från staten?

Practicable Problem

6. Hur ser möjligheterna ut för Hybrid-optimering (Batteri + Industriell flexibilitet)?
7. Hur integreras ni rent praktiskt med brukens befintliga system?
8. Går det att sätta lokala "hårda spärrar" i er mjukvara?
9. Är ert system låst till vissa tillverkare?
10. Är det några problem ni har sett i projekt i industriella skalor som inte tagits upp?

Market development & Arbitrage

11. Hur ser ni på skiftet från stödtjänster till arbitrage?
12. Hur påverkar framtida kärnkraft er affär?
13. Hur påverkas ni av 15-minutersmarknaden?
14. Vad är er spaning på prisvolatiliteten i branschen och är utvecklingen olika i olika prisområden?
15. Vad är det största hindret idag för att ett pappersbruk ska säga "ja" till att koppla upp sig mot er?

BESS-Actor

Flexibility & Revenue

1. Hur kan storskaliga batterilager bidra till flexibilitet och systemstabilitet i industriella miljöer?
2. Vilka intäktsströmmar (stödtjänster, arbitrage, peak shaving) är mest relevanta idag och hur har detta förändrats?
3. Hur påverkar lokala flexibilitetsmarknader och effekttariffer kalkylen för en industriell kund?

Dimensioning & Cost

4. Vilka faktorer är viktigast vid dimensionering av ett batterilager (MW vs. MWh) för en industriell aktör?
5. Vad är den uppskattade investeringskostnaden per installerad MW för ett batteriprojekt idag?

Practical & Business Obstacles

6. Vilka är de största praktiska och affärsmässiga hindren (t.ex. nätanslutning, bygglov, brandsäkerhet) för att implementera batterilager i industrin?
7. Hur kan tröskeln för investering minskas, exempelvis genom riskdelning mellan kund och leverantör?

Technical Special Questions

8. Hur påverkas batteriets livslängd och slitage av aktivt deltagande på olika marknader?
9. Kan BESS hantera problematik med reaktiv effekt och spänningsreglering på ett pappersbruk?
10. Finns det risker för driftstopp eller andra tekniska komplikationer vid installation av batterilager i befintlig industriell miljö?

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