Fathima Basheer

Examining the development of multilevel value streams and infrastructure for Distributed Energy Storage applications, with a focus on policy and regulatory frameworks in the Nordic electricity market

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Fathima Basheer

UNIVERSITY OF VAASA
School of Technology and Innovations
Author : Fathima Basheer
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Abstract

With the increasing development of renewable energy and the need for more flexibility by grids, DES is becoming a crucial component of smart grids in the next generation. The following thesis unpacks how DES can create value on manifold levels, from households trimming their peaks to communities building resilience and the broader system providing ancillary services. It maps the regulatory and market landscape shaping DES deployment in the Nordic electricity landscape. Using a qualitative approach, the work combines a thorough literature sweep, analysis of EU and Nordic policy texts, and comparative case studies of Smart Otaniemi in Finland, EnergyLab Nordhavn in Denmark, and NorFlex in Norway.

What the study finds is that, despite solid technology readiness and growing pilot projects across the Nordics, large scale DES uptake is slowed by ongoing regulatory fragmentation, unclear asset categorization, the double taxation of stored energy, and uneven participation rules in flexibility markets. Case studies show distinct national strides, Finland allows battery participation in Frequency Containment Reserves (FCR). Denmark is forging ahead with digital interoperability through its Flexibility Market Roadmap and Norway is piloting cross border market coordination. These are unbalanced and still do not show uniform qualification standards at present for

distributed assets. This review also states that existing policy frameworks do not pay enough attention to how local flexibility services interact with system level markets, further tempering DES's ability to realize its full multilevel value. This work, therefore, provides a synthesized view of how DES technologies, policy levers, and market structures must come together in order to drive Nordic smart grid development forward. Coordinated governance, interoperable data systems, and harmonized access rules are required to unleash the potential of DES for flexibility, energy security, and inclusive participation in the energy transition.

Keywords - Storage, Smart Grids, Distributed Energy Storage, Nordic Electricity Market Energy Policy, Market Regulation

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Abbreviations

DES	Distributed Energy Storage
DoD	Depth of Discharge
DSO	Distribution System Operator
DSO	Distribution System Operator
EaaS	Energy as a Service
EMS	Energy Management System
EU	European Union
FCR	Frequency Containment Reserve
FED	Fossil-Free Energy District
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
P2P	Peer-to-Peer
REPowerEU	EU Renewable Energy Acceleration Plan
SDG	Sustainable Development Goals
TSO	Transmission System Operator
VPP	Virtual Power Plant

1 Introduction

Distributed Energy Storage (DES) is a central technology for the modernization of electricity systems to more efficient and more flexible ones. By facilitating the storage of energy close to the point of utilization at homes, industries, or community grids, DES maximizes the use of renewables, stabilizes the grid, and facilitates active consumer engagement in energy management (IEA, 2023). Distributed storage systems, unlike centralized storage units, operate on various levels in the grid and generate local as well as system benefits. Distributed storage systems help in frequency regulation, load balancing, and peaking shaving, along with enabling market participation through flexibility and ancillary services (IRENA, 2022). The growth in installation of DES marks a radical shift in the control and valuation of the energy system.

Modern power systems are no longer defined by just centralized production but more digitalized and distributed systems where consumers are prosumers (Parag & Sovacool, 2016). Such systems produce multilevel value streams technical, economic, and social through the coordination of flexibility with participation in the market (Lund et al., 2022). As new battery technologies are implemented and costs reduce, distributed storage has been proved to be an important method of enabling renewable incorporation and implementing energy transformation goals, mainly in areas with variable generation arrangements like the Nordic electricity market (Nordic Energy Research 2023). Policy and regulation are at the advanced stage of this change.

The European Union's Clean Energy for All Europeans Package (European Commission-2019) and Energy Storage Action Plan (European Commission-2023) directly identify storage as an individual investment category for market flexibility and decarbonization enabling. In the Nordic nations, where market opening and high levels of renewables penetration exist, Transmission System Operators (TSOs) and regulators are formulating plans for distributed storage to participate in balancing and flexibility markets (Fingrid

2023; Energinet, 2023). Nevertheless, policy interpretation inconsistencies, e.g., the classification of storage as generation or consumption, and double taxation still remain a stumbling block for DES scalability (IEA, 2023).

From the business aspect, Distributed Storage presents potential new revenues with stacked value streams whereby the same asset can be used for several purposes the balancing of the network, capacity providing, and management of consumer energy (IRENA, 2022). The Finnish project Smart Otaniemi and the Fossil Free Energy Districts (FED) in Sweden give examples of technical performance combined with economic and social value (VTT, 2021, Chalmers University of Technology, 2022). Therefore, P2P trading of power delivers an example of how decentralized architectures may enable customers to trade locally generated renewable power with the cooperation of digital platforms and smart contracts (Guerrero et al., 2021). Although P2P trading is not the primary subject of this research study, it offers an operational example of decentralized participation and the market potential offered by DES.

Despite such developments, there also exist some challenges. Integration of DES in the energy markets, which require the simplifying of regulation, standardized network interconnection and digital interoperability (European Commission; 2023). Economic viability relies on transparent pricing and multiple value streams being reflected in the market design (European Commission, 2023). Further, though pilot projects prove technical viability at scale, large scale replication is constrained by investment risk and policy incoherence (Nordic Energy Research, 2023).

This study thus centers on the analysis of the development of multilevel value streams and infrastructure for distributed energy storage in the Nordic electricity market with particular reference to the enabling or disabling policy and regulatory regimes that facilitate or obstruct such growth. By embracing the global to local approach, the research hopes to discern how distributed storage can enable systemic flexibility at the same time that it enhances market efficacy and supports sustainable transitions in the

energy space. Peer-to-peer energy trading shall be used as one such example of decentralized participation in the market in order to ground how distributed energy storage engages with dynamic market architectures.

Problem statement

The rise of renewable energy sources has changed the operational aspects of power systems, posing challenges in sustaining grid stability, market flexibility, and energy reliability. Distributed Energy Storage (DES) has been viewed as one of the strategic solutions to address these challenges through the provision of flexibility and accommodating renewable integration. However, despite its technological advancements and economical feasibility, DES integration into electricity markets remains insufficient due to regulatory, institutional, and infrastructural obstacles.

Globally and within Europe, energy markets are inherently designed for centralized generation and transmission, which are not readily accommodated by the decentralized and flexible nature of DES. Consequently, distributed storage operators are hindered from entering balancing markets, engaging in ancillary services, as well as monetizing multiple value streams at the same time. Even the Nordic electricity market, while highly developed in integration of renewables as well as cross border trading, still experiences comparable structural problems. Uncertainties in categorizing storage assets, twin taxation, data sharing constraints, and market access barriers still prevent mass deployment.

Further, the existing market design also favors individual services like frequency regulation or peak shaving without acknowledging the entire potential of DES to deliver combined technical, economic, and social values through multilevel value streams. This decentralized approach restricts investment incentives and decelerates the path toward distributed, flexible energy systems. While new ventures such as P2P energy trading and community scale energy systems present that decentralized

engagement is possible, these systems are still at growing stages and lack a supportive policy or market framework.

The major area of concern remains incompatibility between preparations at the organizational level and technological viability. While the promise of the distributed power storage is to scale up flexibility, improve efficiency, and enhance sustainability within the power network, the inconsistent regulated regimes and non standardized market structures defer complete integration. It addresses the development of multilevel value streams and infrastructure for distributed energy storage within the Nordic power market and the policy and regulation regime governing their development. Through the identification of major knowledge gaps, barriers, and areas of potential, the research proposes to elucidate the evolution of the technical notion of distributed energy storage into the strategic aspect of smart and sustainable power markets of the future.

Objectives

The principal aim of this thesis is to critically assess the potential for future innovation, flexibility and democratization of European smart grids through peer-to-peer (P2P) energy trading and decentralized energy storage technologies. It seeks to know how these decentralized methods impact market mechanisms, roles of stakeholders, and grid reliability, particularly in the context of regulatory frameworks and business model sustainability.

Particularly, the study will follow the following research goals.

1. To determine and evaluate the primary technical features and reasonableness of decentralized energy storage technologies for acceptance within society oriented smart grid platforms, considering peer-to-peer models as one illustrative example.

2. To analyze the likely role and operating demands of decentralized energy storage for enabling electricity market functions like demand response, flexibility services, and integration of renewable energy.
3. To assess current and future policy frameworks, regulatory tools, and standards influencing the installation of P2P energy trading and storage systems in Europe, focusing on the Nordic region.
4. To identify practicable business models and market systems for ensuring the scaling, trust, and interoperability of P2P transactions and decentralized storage platforms.

Research Objectives and Questions

The methodology is structured to respond to the following objectives.

To identify and evaluate the technical, economic, and regulatory factors that determines DES adoption in the Nordic electricity market. To review current business and ownership systems those facilitate or constrain DES deployment. To examine policy frameworks and regulatory barriers that influence multilevel value creation.

The aim is to develop a conceptual model for integrating the technological, market, and policy dimensions of distributed storage in Nordic contexts. The corresponding research questions guiding the methodological process are:

- How do technological and infrastructural developments enable DES integration in decentralized electricity markets?
- What policy and regulatory mechanisms facilitate or hinder DES participation in value creation at multiple levels?
- How do existing Nordic pilot projects demonstrate the operational and market feasibility of DES?

What conceptual framework best captures the interaction among technology, market design, and regulation for DES expansion?

2 Distributed Energy Storage (DES) in the Nordic electricity market - Literature review

Distributed Energy Storage (DES) is rapidly emerging as the cornerstone of modern electricity systems since it will enable the required temporal balancing, local flexibility, and sector coupling for the integration of high shares of variable renewable energy. Global assessments, significant diminutions in battery costs and amplifying evidence of storage value at the system level, particularly in frequency regulation, peak management, and congestion mitigation, have been put forward by IRENA (2022) and IEA (2021).At the European level, storage integration has gained increased attention in recent policy frameworks. For instance, the EU Clean Energy Package and the Energy Storage Action Plan point out the need to classify storage as a separate asset category and eliminate regulatory barriers such as double charging and restricted market access (European Commission, 2019, European Commission, 2023). Evidence from several Nordic demonstration projects, such as Smart Otaniemi, EcoGrid, FED, Flex4Grid, and NorFlex, underline strong technical feasibility. Still, persistent policy and design frictions limit large scale deployment (Heiskanen et al.2020; Kopsakangas Savolainen et al.2021). The following literature review synthesizes recent peer-reviewed studies, institutional reports, and project evaluations focused on DES technologies, multilevel value streams, and related regulatory frameworks, and points out gaps that motivate the empirical focus of this thesis. Existing literature on DES identifies various interrelated themes that inform the development and implementation of DES. A progressive increase in studies are documenting the technological capabilities of DES and its value creation potential at different levels, ranging from local peak shaving and reliability support to the system level, such as frequency regulation and congestion management. The existing policy and market design literature looks at how regulatory clarity, asset classification rules, tariff structures, and market access provisions determine the extent to which these value streams can be realized. In the Nordic context, project evaluations and policy analyses have underlined not only high

technological readiness but also persistent regulatory and institutional barriers to large scale DES uptake. Together, this body of work provides state of the art understanding needed for analyzing DES integration in the Nordic electricity market.

2.1 Evolution of Smart Grids and Distributed Energy Storage (DES)

The gradual development of modern power systems from centralized generation towards decentralized and smart grids has been one of the evolving trends in the global energy market. Historically, electricity systems were built around large central generating plants that delivered energy through one way transmission and distribution networks. While this model did give factors of reliability and scalability for many decades, it also had inefficiencies, significant transmission losses, and very little consumer engagement with the energy value chain.. Growing use of renewable energy sources such as wind and solar, disturbing this traditional framework by adding variability and intermittency to power generation and creating the need for more flexible and responsive grid frameworks.

The smart grid was a response to such challenges. Smart grid entails integration of digital communication, automation, and control technologies with the existing base of grid infrastructure to enhance real time monitoring, optimize power flows, and provide the means for DER integration. In the opinion of the International Energy Agency (IEA, 2023), smart grids enable coordination of generation, storage, and consumption through data based control systems to allow energy systems to operate more productively and sustainably. Smart grids transform consumers into active participants, or "prosumers," to generate and consume electricity, allowing new business and operating models.

Distributed energy storage (DES) was a key element of this revolution. Unlike the centralized storage facilities, DES units are located closer to the point of use such as homes, neighbourhoods, or factories, allowing local grid support and increasing system resilience. With increasing integration of renewable energy, storage was required to

reduce temporal mismatches between demand and supply. Studies by Parag and Sovacool (2016) and IRENA (2022) indicate that distributed storage can offer services on several different levels, from local level short term voltage support and balancing up to load shifting, peak shaving, and frequency regulation on the system level. This multilevel ability has extended DES's value proposition from a mere backup capacity to an energetic promoter of intelligent energy markets.

In addition to technological advancement, the policy and regulation environment has been at the lead of shaping the development of distributed storage. The European Union's energy transition framework, as presented in the Clean Energy for All Europeans Package (2019), discovers storage as a key flexibility tool and promotes market based operation for energy storage providers. The Nordic market, covering Finland, Sweden, Norway, and Denmark, has been most active at integrating these frameworks owing to its heavy presence of renewable generation, good interconnectivity, and liberalized electricity markets. For example, Nordic Transmission System Operators (TSOs) have developed balancing markets and flexibility platforms to enable storage providers to supply ancillary services and demand response, thus enhancing system reliability. However, literature also identifies lasting barriers. Regulatory uncertainty of the treatment of storage as generation or consumption, grid access charges, and taxation models continues to constrain investment incentives. In addition, infrastructure preparedness, interoperability standards, and data exchange models are still under development across many of the Nordic nations. According to the European Commission, 2023, complete unlocking of the full potential of distributed energy storage necessitates that technical standards such as interoperability and data exchange protocols are aligned with clear market access rules. This would then facilitate assurance that storage assets participate reliably in various market segments while stakeholders are consistently engaged along the deployment process.

Smart grids and distributed energy storage indicate an increase of a broader movement towards decentralized, digitalized and distributed energy systems. Transition, besides introducing technological innovation, has also changed the roles of policy, market

design, and governance. The Nordic experience provides a representative context to comprehend how favorable regulatory and infrastructural contexts can achieve the multilevel value streams of distributed storage. The following sections will continue to explore the technological basis, policy frameworks, and business models underpinning the successful deployment of DES in future electricity systems.

2.2 Technological Characteristics and Applications of Distributed Energy Storage (DES)

DES have been defined as energy storage technologies sited near the point of consumption, rather than at central utility facilities, in buildings, industries, district systems, or community level energy networks. DES allows local balancing, peak reduction, and integration of distributed renewable generation by technologies such as batteries, thermal storage, and mechanical systems (IRENA, 2022, Lund et al., 2021). Electrochemical storage especially lithium-ion battery systems are expanding expeditiously due to falling costs, modularity, and suitability for both short term balancing and fast frequency response (IEA, 2021, Zakeri & Syri, 2015).In the Nordic region, deployment has been intensifying through residential batteries, district level thermal storage, and hybrid solutions supporting flexibility markets (Fingrid, 2023, Energinet, 2022).

Nordic DES technologies show high technical readiness, while the significant barriers relate to interoperability, grid fee structures, and the insufficiency of standardized participation rules for local flexibility services (Heiskanen et al.2020; Kopsakangas-Savolainen et al. 2021). Research also shows future growth driven by increased electrification, integration of EV charging, and sector coupling in heating and mobility (Nordic Energy Research. 2023). The literature enumerates DES as a technologically mature but policy sensitive element of decentralized energy systems, emphasizing both technological proficiency and enabling regulatory environments as crucial for wider adoption.

2.2.1 Overview of DES Technologies

DES technologies can be classified into a number of categories based on the class of energy stored- electrochemical, mechanical, thermal, and chemical. Out of these, electrochemical storage, specifically battery energy storage systems or batteries, is the most frequent in distributed applications because of their flexibility, component based design, and fast response.

Typical DES technologies include

- Lithium-ion batteries - Efficient and extensively used because of their high energy density, long life, and reducing costs. They could be implemented at residential, commercial, and grid support scales.
- Flow batteries (e.g: vanadium redox, zinc bromine) – Identified by scalability and long storage, these are best applied at the community scale and industry implementations.
- Sodium sulfur and lead-acid batteries - Applied for medium and short duration storage, progressively being replaced by newer technologies because of efficiency and cost constraints.
- Mechanical and thermal storage (flywheels, compressed air or hybrid systems) - While less frequent at the distributed level, they are increasingly paired with batteries for improved energy flexibility.

Technological growth have considerably enhanced battery efficiency, control systems and lifecycle economics. The observed reduction of more than 80% lithium-ion batteries costs since 2010 (IRENA 2022), has brought distributed storage to a commercially competitive level of allowing integration of renewable energy.

2.2.2 Technical Characteristics of DES

Some technical characteristics identify the value and performance of distributed storage systems:

- Energy capacity (kWh/MWh) - Describes the amount of energy stored and operational time.
- Power rating (kW/MW) - Specifies the rate of delivery to or absorption from the grid of energy.
- Round trip efficiency – Defines energy conversion performance, commonly 85 to 95 % for lithium-ion.
- Response time - Indicates how rapidly the system reacts to changes in grid conditions, new DES respond in millisecond.
- Cycle life and degradation rate - Influence the system's lifespan and economic capability.
- Depth of discharge (DoD) - Suggests the amount of total capacity that can be utilized without compromising battery health.

Evolved energy management systems (EMS) today optimize charging and discharging cycles based on real-time data, predictive algorithms, and intelligent control algorithms. These systems enable DES to communicate independently with the grid, stabilize fluctuations, and deliver both technical and market services.

2.2.3 Applications of DES

DES provides a broad range of applications that extend across technical, economic, and policy frontiers, at the base of multilevel value streams.

Technical Applications-

Frequency and voltage regulation - DES ensures system stability through balancing supply demand fluctuations.

Peak shaving and load shifting: Energy is collected during off-peak hours and used during peak hours for reducing the stress in the grid.

Integration of renewable - Supports the integration of additional solar and wind energy by addressing inconsistency concerns.

Reliability and resilience – Offers backup electricity during outages, especially for small or isolated grids.

Economic Uses-

Energy arbitrage - Storage owners purchase electricity at low cost and sell during high cost .

Prolonged infrastructure investment - Mitigate the need of expensive grid investments by managing local peaks in requirement.

Demand charge reduction and self consumption - Optimize economic savings for businesses and consumers.

Market and Policy Uses-

Flexibility markets participation- In the Nordic countries, DES units are involved in balancing and ancillary service markets run by Transmission System Operators (TSOs).

Community energy systems and aggregation models- Local DES enables local energy trading and collective flexibility management on the neighborhood scale.

Support for decarbonization policies-Distributed storage is complementary to EU and Nordic carbon neutrality targets by increasing system flexibility.

2.2.4 Nordic case examples

The Nordic region has numerous substantiated examples of DES applications that have been demonstrated to provide both technical functionality and economic benefits. Finland's Smart Otaniemi project integrates distributed battery storage with technologically advanced smart grid technologies to cater for local balancing, data driven energy management, and flexible demand side services (Heiskanen et al. 2020). In Sweden, the Fossil Free Energy Districts (FED) programme fuses DES with district heating and cooling networks, enabling optimized energy flows, peak load abatement, and emissions curtailment through integrated energy system governance approaches (Johansson et al. 2020). In Denmark, the EcoGrid project on the island of Bornholm investigates the participation of distributed generation and storage units in real-time markets and their interactions within a self regulating microgrid environment (Energinet 2022, Nielsen & Möller 2021).

These projects substantiate how DES support multilevel value streams in augmenting local flexibility, improving system level stability, and allowing market oriented innovations. Harmonized operations across the broader Nordic region create aligned regulatory and institutional structures for data exchange and for uniform access protocols to energy storage units (Nordic Energy Research 2023, Kopsakangas Savolainen et al. 2021).

2.3 Regulatory and policy framework for Distributed Energy Storage in the Nordic market

Empirical regulatory research demonstrates that whether DES takes off depends largely on how a country shapes the rules for storage within its electricity market. The EU Electricity Market Directive ((EU) 2019/944) makes this explicit, member states must eliminate double charging, allow storage to compete across all market segments, and ban discriminatory grid tariffs. All of these rules have a direct impact on the profitability of DES. In the Nordic region, regulatory reviews suggest that even with very strong technology readiness, DES deployment is slowed by inconsistent patchwork rules. For example, the Nordic Council of Ministers (2023) asserts that Finland and Denmark still have no consistent procedures for connecting small scale storage to local grids and that Sweden still questions the legality of DSOs owning or procuring storage assets. Research by Strbac et al. (2020) and Newbery et al. (2022) adds that without standardized participation rules in flexibility markets mean baseline methods, metering, and how aggregators access the market, a distributed storage is unable to effectively monetize services that could be offered to the power system. These various regulatory constraints taken together imply that DES deployment in the Nordic electricity market is more driven by clarity, stability, and coherence of policy on market entry, ownership, and operating rights than by pure technological capability.

2.3.1 European and global policy context

Energy storage worldwide is being viewed as a high priority enabler of clean energy transitions. Regulatory reliability and market design are regarded as essential factors in

establishing investment in storage infrastructure, as per the International Energy Agency (IEA, 2023). The Paris Agreement (2015), and the United Nations Sustainable Development Goals (SDG 7 Affordable and Clean Energy) emphasize the importance of resilient technologies such as DES for energy access and decarbonization.

Regionally, the EU has set a far reaching policy framework aimed at expediting the integration of energy storage. The Clean Energy for All Europeans Package (2019) and the EU Regulation 2019/943 on the internal electricity market are the pillars of Europe's flexibility plan. The policies clearly define energy storage as a standalone asset class with generation, consumption, and system services capabilities. In addition, the EU Energy Storage Action Plan (2023) is demanding the dismantling of policy and budgetary obstacles, e.g., double taxation and grid charges that impede the entry of storage operators into electricity markets. The REPowerEU Plan (2022) reinforces this strategy even further by prompting member states to adopt distributed and community scale storage solutions as one part of their renewable growth plans.

2.3.2 Market frameworks and Nordic policy

The Nordic energy market, covering Finland, Sweden, Norway, and Denmark, has initiated a policy relaxation of energy markets and cross border coupling (Nordic Energy Regulators 2022). Its well developed transmission grid, high share of renewables, and sophisticated market coupling provide an exemplary testing ground for distributed flexibility options (Nordic Council of Ministers 2023). Each of the Nordic countries has followed different regulatory paths for DES integration, led by national priorities as well as system characteristics.

Finland - The framework driven by Fingrid, the Transmission System Operator (TSO), permits distributed storage operators to supply Frequency Containment Reserves (FCR) and balancing markets (Fingrid 2023). Finland's National Energy and Climate Strategy (2022) highlights storage as a flexibility enabler, though grid tariffs and taxation of behind the meter storage are outstanding issues.

Sweden - In Sweden, the regulation body is Svenska kraftnät, under which ancillary services in the DES and the Fossil Free Energy Districts all fall within a single strategy; Svenska kraftnät, 2023. The dominating policy issues have been about local flexibility and energy communities, and at present reforms are underway that will facilitate schemes of third-party ownership.

Norway - Statnett has concentrated on synchronizing DES participation with its balancing power market, as well as investigating how storage can facilitate offshore renewable integration (Statnett, 2022). Nevertheless, Norwegian legislation continues to categorize storage ambiguously, and investors are left uncertain.

Denmark - With Energinet being the system operator, Denmark has progressed with high levels of regulatory flexibility. Its DataHub and Flexibility Market Roadmap (2023) encourages digital integration between storage and demand response, enabling DES to be involved in several value streams.

As per Nordic Energy Research (2023), while policies in favour of renewable generation are in place across all Nordic countries. Energy storage is widely provided indirectly under general flexibility or demand side frameworks and not as a specific regulatory category. Fragmentation results in uneven market opportunity and restricts the scale up of DES application across the region.

2.3.3 Regulatory barriers and opportunities

While policy work continues, a patchwork of regulatory barriers still holds back the broad use of DES across the Nordic electricity system. Reviews, EU assessments, and Nordic energy agencies consistently identify a number of stubborn hurdles.

- Uncertain Asset Definition : In most Nordic countries, DES is not explicitly recognized either as generation, consumption, or a network asset. This ambiguity

clouds licensing, taxes, and access rights (NordREG, 2022, Nordic Council of Ministers, 2023).

- Double Taxation: Most storage operators have to incur taxes on imports and exports of electricity in most EU and Nordic markets. This is greatly reducing returns and deterring investment (ACER, 2022; European Commission, 2023).
- Grid Access and Tariff Structures: The high connection fees, non cost reflective tariff schemes, and lack of consistency in the procedures at the DSO level hamper the participation of small scale and community storage projects (Fingrid, 2023; Energinet, 2023).
- Data and Interoperability Issues: Nordic studies note that standardized data formats and metering requirements are missing, which are deemed necessary for DES to sustain effective market positioning compete in ancillary services and flexibility markets (Statnett, 2022; ENTSO-E, 2023).
- Ownership restrictions: In Sweden and Finland, unbundling related rules inhibit DSOs from owning or operating any storage assets, labeling storage as generation and thus limiting system wide deployment. Svenska kraftnät (2023); Finnish Ministry of Economic Affairs (2022)

These are real barriers, yet they exist alongside growing opportunities. The EU Fit for 55 package, the 2023 Energy Storage Action Plan, and Nordic national flexibility market roadmaps are gradually easing DES integration through the clarification of asset definitions, market access, and pushing standardized data infrastructure.

2.3.4 Linking policy to multilevel value streams

Integrating multilevel value streams from household level peak shaving to societal resilience and grid level support services, requires appropriate regulatory frameworks that detail DES participation at each tier of the electricity system. According to several studies, DES is capable of offering local services like voltage support, optimization of self consumption, and neighbourhood balancing, in addition to national frequency containment and congestion management (IRENA, 2022; Lund et al., 2021). Therefore,

policy clarity remains imperative for defining technical requirements, metering rules, and market access provisions that allow DES to interact with various levels of the grid.

Nordic regulatory advancements offer concrete illustrations. Updated market rules from Fingrid in Finland allow small scale batteries to participate in Frequency Containment Reserves, thereby illustrating how regulation can enable system level services from distributed assets (Fingrid, 2023). At the community level, Sweden's energy community legislation and the FED project give examples of how DES supports district heating integration and local balancing (Svenska kraftnät, 2023; FED Project, 2021). Denmark's Flexibility Market Roadmap underlines digital interoperability and standardized data exchange, prerequisites for DES to deliver value concurrently to households, DSOs, and national reserve markets (Energinet, 2023). Taking all the above examples together, it appears that policies related to asset classification, data standards, and market entry conditions form the bedrock for allowing DES to function across different value streams. Their effective regulation will not only unlock technical capabilities but align their local benefits around resilience and demand management with wider market and system level objectives in the Nordic context.

2.4 Business and Market Models for DES

The deployment of Distributed Energy Storage is equally an economic and institutional challenge as it is a technical one. Technology alone does not create long term market adoption, there must be successful business models and market mechanisms that can capture and deliver DES's multiple streams of value. This chapter synthesizes the dominant business models in practice, the market mechanisms that enable or limit these models, and how different models affect who captures value in the electricity system. The aim is to make this magic disappear in terms of explaining how market design and commercial arrangements intersect with regulatory settings to condition the scalability of DES in the Nordic market.

2.4.1 Defining value: stacked and multilevel value streams

DES has a set of services that can be individually or in bundles commercialized. Representative service categories include, energy arbitrage, demand charge reduction and peak shaving, frequency and voltage regulation, reserve and balancing services, congestion management, and local customer resilience or back up services They map to multilevel value streams local (household/community), distribution system (DSO level), and system level (TSO/wholesale market). Business models differ by which streams they target and how they stack them.

1. Single service models concentrate on single remunerated market (e.g. frequency regulation).
2. Stacked value models try to monetize two or more revenue streams at once (e.g. arbitrage + ancillary services + local congestion relief).
3. Non monetized social value (resilience, local energy security, community benefits) can be secured indirectly (lower outage costs, social acceptance) and in some instances requires public finance/new remuneration schemes.

DES financial sustainability is founded on stacking value streams, whereby customers are charged for stand alone services only, but a number of DES projects cannot produce bankable returns.

2.4.2 Common business models for DES

Literature and pilot experience indicate several recurring ownership and commercial archetypes:

a) Utility (TSO/DSO) owned model

Utilities own and manage storage facilities to provide grid services (voltage support, congestion relief, balancing). The model can capture system benefits and circumvent coordination issues among parties, but it is problematic in terms of regulatory neutrality and private sector crowding out. In the Nordics, ownership regulations and

unbundling obligations tend to limit utility ownership or place strict operational limit.

b) Customer owned model

Individual customers or companies invest in behind the meter storage mainly for self use, demand charge avoidance, and backup. Market participation revenue can be achieved through aggregation. The model is conducive to prosumer empowerment but usually requires aggregation in order to have availability to wholesale or balancing markets.

c) Aggregator or Virtual Power Plant (VPP) model

Aggregators collect numerous small DES units and run them as one asset in wholesale and ancillary services markets. Aggregation opens market access to small assets and facilitates stacked value approaches. Success depends on market rules allowing combination and on data or communications infrastructure to synchronize assets in real time.

d) Community model or Cooperative model

Local socities or energy cooperatives collectively own and coordinate shared energy storage operations. Advantages are local value capture, improved social acceptance, and area specific local services. Legal and tariff structures need to enable shared ownership and unbiased benefit distribution for the model to scale.

e) Third party 'Storage as a Service' model

Commercial vendors finance, deploy, and run DES for customers on a service contract basis. This reduces initial capital expenditure for buyers and can promote faster adoption when funding is an impediment. Contracts need to properly distribute operating revenues and risks.

Each model has distinct impacts for risk policy incentives structures shaping participant engagement, investment cost, and risk allocation. The Nordic experience indicates that hybrid structures utility backed projects with third party operation, or customer assets

bundled by commercial providers are emerging where market signals and regulatory conditions are favorable.

2.4.3 Market mechanisms and compensation schemes

Sustainability of business models hinges on market mechanisms that appreciate and compensate for DES services. Some of the most important mechanisms are,

1. Wholesale energy arbitrage - DES purchases energy during off peak periods and releases during peak periods. This demands adequate price volatility and contiguity to wholesale markets.
2. Ancillary services and balancing markets - Joining frequency containment, reserve, and balancing markets is essential for commercializing fast response resources. There has to be clear definition of products and procurement rules.

3. Local flexibility markets - Third party or DSO operated platforms that buy local flexibility to handle congestion and voltage problems can generate new revenues for DES at the distribution level.

4. Long term contracts and capacity markets - Steady revenue streams from power purchase or storage agreements or capacity mechanisms lower investment risk and ensure bankability.

5. Tariff design and grid tariffs - The way in which storage is charged for its use of the network and how tariffs are used (e.g. ownership of stored energy vs energy flows) significantly influence economics. Disadvantageous tariff treatment or double charging render projects uneconomical.

2.4.4 Distribution of benefits and stakeholder incentives

Distribution of benefits between actors (households, aggregators, DSOs, TSOs, investors) relies on technical deployment as well as rules of the institution. In most pilot instances,

- Consumers gain by way of cheaper bills, greater resilience, and engagement in community initiatives, but are not necessarily capturing full market value in the absence of aggregation or positive tariff treatment.
- Aggregators make money by maximizing asset portfolios and marketing services in structured markets, their margins are a function of transaction costs, access to the market, and platform stability.
- DSOs/TSOs achieve system: wide gains (deferred investment, congestion relief), but might have regulatory constraints to benefiting commercially directly.
- Investors need stable revenue streams and unambiguous asset classification to insure capital.

A lack of congruence between who provides flexibility and who is paid for it causes incentive issues. For example, if DSOs delay investments because of local storage, but are unable to compensate storage providers, there is not much of an incentive for private actors to invest.

2.4.5 Connecting Business Models to Multilevel Value Creation

The connection between DES business models and value creation is naturally multidimensional. A system owned by a utility can essentially provide system level reliability, while a community based model brings both social and economic value at the local level. Aggregator driven models, in their turn, facilitate wholesale market participation while adding value to grid flexibility. By aligning technical ability with innovative business design, distributed storage has the potential to unleash cross layer benefits simultaneously throughout the energy system. The Nordic experience, with its robust regulatory environment, digital market infrastructure, and energy collaboration culture, holds keys to understanding how DES can transform from disconnected assets to fully integrated elements of a sustainable and resilient electricity market.

2.4.6 Obstacles and Drawbacks in Existing Business Model Research

Though the body of research on distributed energy storage business models and value creation has increased significantly in recent times, various limitations continue to exist in both theoretical and applied settings. Most studies so far merely consider centralized or large scale applications of storage, whereas corresponding studies on distributed, community based, and peer-to-peer structures are sparse. This results in a knowledge gap as to how smaller, decentralized players can engage profitably in emerging energy markets.

Another important limitation is the disjointed analysis of policy, technology, and market forces. Most studies examine these variables in silos that is, measuring regulatory hurdles without considering economic or technical feasibility. This separation can ignore the interdependencies characteristic of DES success. In addition, most profitability studies, e.g., those of Baumgarte et al. (2020), utilize normalized European or U.S. market information and do not represent the distinctive Nordic regulatory system, despite the fact that electricity trade, taxation, and cross border balancing services here have special structures.

Technological and data related limitations also pose challenges to model scalability. Several pilot projects are shown to be locally successful but do not have a standardized format for scaling business models by regions or combining various stakeholders. Moreover, research regarding revenue stacking and flexibility services is usually not combined with societal value creation like resilience, equity, and local empowerment which are becoming increasingly vital in Nordic sustainability objectives. These constraints underscore the imperative for research that synergizes technological viability, regulatory harmonization, and multi level value creation within the distributed storage economy. Mitigating these difficulties is necessary for crafting feasible, policy enabled, and socially inclusive business models for next-generation smart grids.

2.5 Gaps in Research Identified

Findings from IRENA 2022, Nordic Energy Research 2023, IEA 2021, and diverse Nordic TSOs explicate the enlarging evidence around DES in terms of decarbonization, flexibility, and market oriented technological innovation. Yet, despite this growing body of research, a number of important knowledge gaps remain, particularly in the area of aligning DES with multilevel value creation in evolving electricity markets.

(1) Gap in technological and operational coordination

While multiple scholarly works have examined DES technologies and their technical performance, including IRENA 2022, Zakeri & Syri 2015, many fewer investigate how distributed storage interacts with grid operations at different system levels. By and large, existing research has concentrated on either device level optimization, battery performance, or single use applications, whereas limited evidence exists.

- Synchronized dispatch of DES with DSO operations
- Integration of DES into congestion management and local flexibility market.
- Stacking under Nordic grid constraints (Fingrid 2023; ENTSO-E 2023).

This creates a significant gap in understanding the operational frameworks that are needed for DES deployment beyond individual or pilot settings.

(2) Gap in regulatory and policy integration

Policy reviews acknowledge recurring challenges like the unclear classification of assets, double taxation, grid tariffs, and ownership restrictions (ACER 2022, European Commission 2023, NordREG 2022) but there is limited analysis of

- How the regulatory barriers interact with market design elements such as balancing markets, capacity markets, and demand response programs.
- It compares how regulatory standards for demand side energy resources .DES differ across Nordic countries. (Statnett's 2022 , Energinet's 2023) .

- How cross border integration within Nord Pool could allow for DES participation in cross system flexibility services.

Most of the established research focuses on national regulatory developments, leaving a gap in the analysis of regional governance and harmonization essential to scalability for Nordic DES.

(3) Gap in business models and multilevel value frameworks

While DES is regularly analyzed through technological or regulatory lenses, few studies provide comprehensive frameworks that integrate technology, regulation, market design, and consumer participation into a logically integrated multilevel value structure. Aggregator based participation, community storage, hybrid energy systems, and transactive energy are business model innovations that remain inadequately investigate in Nordic contexts (Heiskanen et al., 2020, Kopsakangas Savolainen et al., 2021).

Understanding how DES creates value simultaneously at the household, community, DSO, and TSO levels is currently fragmented across the literature. Filling this gap is important for a conceptualization of DES as an integrated flexibility resource rather than isolated technical projects.

3 Methodology and conceptual framework

This chapter aims to outline the methodological approach of this research by detailing the design of the research, data sources, the analytical framework, and the conceptual structure that enables answering the research objectives. This chapter also describes the rationale behind the methodological decisions taken, the characteristics of the data collected, and the strategies followed for their analysis. The research investigates the development of multilevel value streams and supporting infrastructure for DES within the Nordic electricity market. A qualitative comparative research design has been adopted to attain this, combining archival data from policy documents, regulatory reports, and pilot projects through analytical evaluation based on a conceptual model proposed by Baumgarte et al (2020). The methodological outline links three core perspectives,1. technological and operational factors of DES, 2. policy and regulatory environments, and 3. business and market design models. These dimensions provide an integrated view of how DES can facilitate flexibility, endurance, and market participation in decentralized energy systems.

3.1 Research Design and Approach

This research is a qualitative comparative case study. The method has been selected because the research problem necessitates contextual and interpretive understanding rather than quantitative generalization. Multiple factors at the institutional, regulatory, and market levels influence the integration of distributed energy storage in the Nordic region, which cannot be captured with numerical data.

The comparative design facilitates the evaluation of multiple pilot projects across different Nordic countries, such as Smart Otaniemi (Finland), FED (Sweden), NorFlex (Norway), EnergyLab Nordhavn (Denmark), and Flex4Grid (cross Nordic). Each case provides unique findings about technology applications, business models, and policy environments. Evaluating them reveals patterns and divergences in the development of

DES related value streams and governance structures. This qualitative orientation also supports with a constructivist research philosophy, focused on the understanding of social and institutional meanings leading to policy and market behaviors. This enables the researcher to join regulatory texts and project impacts to broader energy transition goals.

3.2 Data Collection

3.2.1 Data sources

Data sources will be based mainly on three groups of secondary qualitative data.

1. Regulatory and Policy Documents.
    - EU legislative texts, especially the Clean Energy for All Europeans Package or the Fit for 55 Package.
    - Research outputs from Energinet, Fingrid, Statnett, Svenska Kraftnät about Nordic energy agency.
    - National energy strategies and white papers from Finland, Sweden, Norway, and Denmark.

2. Business and Market Reports.
    - Reports from Nord Pool, ENTSO-E, and the Nordic Energy Regulators (NordREG).
    - Technical papers and industry analyses on distributed storage markets and flexibility services.

3. Pilot Project Documentation.
    - Technical and summary reports from Smart Otaniemi, FED, NorFlex, EnergyLab Nordhavn, and Flex4Grid.
    - Academic and policy reviews of the results of each project.

These diverse sources ensure triangulation of information, making it possible to compare policy intentions with technical demonstrations and real world challenges.

3.3 Pilot Project Identification and Analysis

Pilot projects are necessary to demonstrate the behavior of DES under real-life conditions in terms of tech, policy, and market. As this study focuses on how multilevel DES value streams materialize in practice, we chose a small representative set of Nordic pilots for a comparative look. Within the last ten years, numerous smart grid and flexibility pilots have been hosted in the Nordic region. These span demand response, electromobility, sector coupling, and energy communities. Yet, only a narrow subset place distributed energy storage at the core and publish documentation suitable for methodical comparison.

Using these criteria, five pilots were chosen:

- Direct DES relevance : Storage battery, thermal, or hybrid plays a central operating role.
- Nordic geographic spread : Finland, Sweden, Norway, and Denmark are included to reflect policy and market diversity.
- Availability of detailed technical, regulatory, and market documentation to support comparative analysis.
- Evidence of multilevel interactions with local grid, community, aggregator, TSO/DSO relevant for the research questions.
- Recognition in national or EU innovation programs, ensuring methodological credibility.

The selected projects are:

- Smart Otaniemi (Finland)
- Fossil Free Energy District – FED (Sweden)
- NorFlex (Norway)
- EnergyLab Nordhavn (Denmark)
- Flex4Grid (Cross Nordic)

These cases together cover a wide range of tech architectures, market designs, and regulatory contexts. Their differences help to highlight how infrastructure readiness, policy landscapes, and business model innovation shape the DES related value streams.

3.3.1 Selected Pilot Projects

Smart Otaniemi, Finland

Smart Otaniemi, led by VTT Technical Research Centre of Finland is a Northern Europe leading energy innovation ecosystem (VTT, 2020). Operating in Espoo, the project combines research institutions, private businesses, and local governments to make an actual smart energy district. The project includes making renewable energy, energy transport, and demand response flexibility (VTT, 2021).

One of the main focuses of Smart Otaniemi is field testing battery storage integration with solar PV and electric vehicle charging networks for optimal local grid stability and consumer self sufficiency (VTT, 2020, Energinet et al., 2021). The project also examines the use of digital twins and advanced data analytics to forecast energy flows (VTT, 2021). Policy wise, the initiative promotes national smart grid goals in Finland's Climate and Energy Strategy, promoting energy efficiency, open data, and customer led market models (Government of Finland, 2022). But Smart Otaniemi findings also reveal issues, whereas Finland's law is favorable for integrating renewables, ownership models for storage are ambiguous, especially regarding how energy storage is treated among grid operations (Heiskanen et al., 2020). It introduces uncertainty regarding grid fees and taxation for energy arbitrage (Kopsakangas-Savolainen et al., 2021). Still, the project provides a tangible case for how local flexibility can be leveraged for stability on the grid and business innovation (VTT, 2021).

Fossil free Energy District (FED), Sweden

Gothenburg's FED project, which is run by Johanneberg Science Park and supported by the EU's Urban Innovative Actions initiative, seeks to offer fossil free supply of energy at the district level (Johanneberg Science Park, 2020, Urban Innovative Actions, 2020). The project integrates a network for electricity, heating, and cooling through an inte-

grated local market. Distributed electrical and thermal energy storage is central to balancing the district's renewable generation and variations in demand (FED Project Report, 2020).

FED is innovative through its multi energy marketplace, in which buildings play the role of market players, selling and purchasing excess energy using automated systems (Lindgren et al., 2021). The system incorporates battery storage, heat pumps, and combined heat and power (CHP) units, and this shows how DES enables both sector coupling and local flexibility markets.From a regulatory approach, Sweden has a facilitating conditions for experimentation through pilot exemptions (Swedish Energy Agency, 2021), but issues continue with double taxation of stored energy and the shortage of systematized market involvement for reduced flexibility providers (NordREG, 2022). Despite that, FED shows how DES can function as an interface between urban sustainability objectives and nationwide decarbonization policies (Johanneberg Science Park, 2020).

NorFlex, Norway

The NorFlex project, initiated by Agder Energi in partnership with Statnett and other stakeholders, targets establishing regional flexibility markets in the south of Norway (Agder Energi, 2021, Statnett, 2021). The purpose is to add distributed resources such as storage, demand response, and fleets of electric vehicles into local balancing systems. The project's original contribution is its market design, which supports aggregators and prosumers to provide flexibility services to DSOs and TSOs (NorFlex Final Report, 2022).

Technically, NorFlex tests flexible automated trading platforms that allow real time dispatch of flexibility from residential and industrial assets (Agder Energi, 2021). The configuration reduces congestion on the grid and improves system reliability in high levels of renewable generation (Statnett, 2021). Norway's regulatory framework is currently making progress in the roll out of renewables, however, for a long period of time, it

lacked clear concepts regarding DES participation (NordREG, 2022). The pilot demonstrates the case for updating national market rules to recognize storage operators as active market participants, not passive players (NorFlex Final Report, 2022). It also underlines the importance of transparent data and interoperability standards if flexibility markets are to grow (Nordic Energy Research, 2023).

EnergyLab Nordhavn, Denmark

EnergyLab Nordhavn in Copenhagen is a flagship initiative investigating urban transition of energy in one of Europe's most sustainable city quarters (EnergyLab Nordhavn, 2020). It is supported by Innovation Fund Denmark and brings together renewable energy, storage, electric mobility, and building energy management in a unified district scale demonstration (Innovation Fund Denmark, 2021). The project assesses the contribution of battery storage and thermal energy storage in balancing local renewable generation with power quality and reliability (EnergyLab Nordhavn, 2020).

EnergyLab Nordhavn is unique for placing priority on cross sector integration, integrating electricity, heating, and transport systems on a single data driven management platform (DTU Electrical Engineering, 2021). It also ventures into consumer participation through adjustable tariffs and dynamic pricing schemes, corresponding to Denmark's progressive digital infrastructure and deregulated energy market (Danish Energy Agency, 2022). Nevertheless, even with Denmark's optimal national policies for renewables, ownership and revenue models of distributed storage are underdeveloped. The project points out that the lack of explicit policy incentives for local storage investment can postpone full market participation and prevent the formation of multilevel value streams (EnergyLab Nordhavn Final Report, 2022).

Flex4Grid (Cross Nordic)

Flex4Grid is a Horizon 2020 initiative of the European Commission, where Finland, Germany, and Sweden joined forces. It aims to provide digital frameworks for enabling

DES or distributed energy systems to fit within market dynamics. The project investigates real-time data exchange, standardization, and automation so DES can offer grid services like voltage control or frequency regulation (European Commission, 2020).

The pilot project shows that the interoperability of data is a key facilitator of storage scalability. By bringing prosumers, DSOs, and energy communities together on cloud based platforms, Flex4Grid facilitates new business models for shared flexibility services (Flex4Grid Final Report, 2021). Its findings emphasize the need to align European and Nordic regulation regimes in order to facilitate cross border trade of flexibility.

3.3.2 Analysis Framework

The analysis of the pilot projects adheres to four main dimensions that coincide with the scope of this research.

Technical and Operational Capabilities -

Evaluating the technologies deployed (battery, thermal, and hybrid systems), the amount of storage available, control systems, and how well they work with distributed generation.

Policy and Regulatory Context -

Examining how national energy acts, EU directives, and regulatory sandboxes affected the project implementation and ability to grow.

Market and Business Models -

Assessing the structural composition of local flexibility markets, and the value streams reflected by DES (energy arbitrage, ancillary services, and capacity), and the stakeholder incentive framework.

Institutional and Stakeholder Roles -

Examining how the DSOs, TSOs, municipalities, and community cooperatives help run and govern the operation of DES systems.

3.3 Data Collection Procedure

The data collection was done through desk research in a systematic manner from June to October 2025. Keywords such as distributed energy storage, Nordic electricity market, policy frameworks, flexibility services, and business models were used to search official databases, institutional websites, and peer reviewed academic journals. The inclusion criterion considered was

- Relevance to distributed or community based storage
- Recency - 2018 to 2025, to ensure policy relevance.
- Geographical focus on Nordic or European contexts, and
- Reliability - officially or peer reviewed sources.

3.4 Data Analysis and Interpretation

Qualitative in nature, the study used thematic content analysis to interpret findings from documents and reports of pilot projects. The data was coded into recurring themes that aligned with the research objectives, technology and infrastructure, policy and regulation, and market and business model. Data organization were conducted manually using Microsoft Excel and Word.

Three steps were followed in the analysis.

- Extraction - Organizing important parts of documents such as text segments, tables, and structures.
- Categorization - Sorting the data obtained from conceptual categories.
- Interpretation - Integrating meanings and relationships between categories.

A comparative cross case analysis was subsequently carried out to identify general enablers and barriers among the Nordic projects. This demonstrates how differences in policy settings and market structures can shape different conditions for the success of distributed storage models.

3.5 Conceptual Framework

The conceptual framework applied in this study is adapted from Baumgarte et al. (2020) and is used to structure the analysis of distributed energy storage (DES) in the Nordic electricity market. The framework organises the evaluation into three analytical layers.

- Technological Layer - Operational capabilities of DES, viz., storage type, control systems, and digitalization.
- Market and Business Layer - stakeholder participation, ownership models, and multi value approach.
- Policy and Regulatory Layer - Institutional rules and subsidies enabling DES adoption.

These three layers connect dynamically, technological capability defines possible applications, regulation determines market accessibility, and market mechanisms support technological investment.

3.6 Validity, Reliability and Ethical Considerations

The methodological process was based on assuring research quality and ethical integrity. Reliability was guaranteed by consistent procedures for data collection and transparent documentation of sources. Validity was enhanced through triangulation of data from different categories, that is, policy documents, market analysis, and project reports, and cross verification of the interpretations with multiple sources.

Because this study is based solely on publicly available data and institutional documents, it establishes no ethical risk to individuals. Yet, correct academic citation practices were followed with regard to each data source. The researcher also remained sensitive to the analytical bias inherent in qualitative analysis, which was minimized through reflexivity and systematic coding.

3.7 Limitations of the Methodology

The study's qualitative design focuses on depth rather than breadth, hence, findings are context specific to the Nordic electricity market. An in depth quantitative financial modeling of DES economic viability lies beyond the scope of the study, with emphasis placed on regulatory, policy, and business model dimensions.

The reliance on secondary data results in limits regarding real time metrics on operational or economic performance. This potential limitation is mitigated by the diversity and reliability of official and peer reviewed sources.

4 Technological and Business Landscape of Distributed Energy Storage

Prior to examining the impacts of DES incorporation within the Nordic electricity market, it is important to account for the technological and business environment that governs DES development. This chapter outlines the framework by providing a broad overview of evolving technologies, commercial structures, and value chain participants propelling the adoption of storage solutions. It places the operational realities of DES within broader industrial and market systems, thus bridging both the conceptual framework and empirical analysis in this respect. The Nordic power sector, with its high penetration of renewables, high digital maturity, and cross border market integration, is especially conducive to fast storage technology evolution both in terms of technology development and business model creation but the actual path of development will be shaped by the technical capabilities and characteristics of the available storage technologies, the strategic choices made by main market actors, and the incentives provided by the prevailing market design (EA Energianalyse, 2022).

4.1 Overview of Distributed Energy Storage Technologies

The DES technologies are very diverse, with wide ranges in chemistry, scale, and duration of application. Though lithium-ion batteries dominated the most recent deployments due to cost efficiency and fast response times, some of the hybrid and long duration solutions under consideration in the Nordic region include flow batteries, hydrogen based systems, and thermal storage.

Storage Type	Duration	Applications	Nordic Examples	NEW Global Examples
Lithium-ion	Hours	Balancing, EV integration	EnergyLab Nordhavn (Denmark)	Hornsdale Power Reserve (Australia)
Flow Battery	4–10 hours	Industrial backup	Chalmers University (Sweden)	Sumitomo Vanadium Flow Battery (Japan)
Hydrogen Storage	10 hrs–multi-day	Seasonal, P2G	HYBRIT (Sweden), FlexH2 (Norway)	Energiepark Mainz (Germany)
Thermal Storage	Hours to weeks	District heating	Kalundborg Symbiosis (Denmark)	Varanto Cavern TES (Finland)

Table 1 - Overview of key distributed energy storage Technologies with Nordic and selected global deployment examples.

Most Nordic DSOs are still in the early stages of integrating distributed storage directly into their operational planning directly. Community level batteries and EV to grid schemes, however, demonstrate the emerging flexibility potential.

4.2 Digital Infrastructure and System Integration

Digital readiness is one of the hallmarks of the Nordic market. Advanced metering infrastructure, smart grid management devices, and data hubs like Datahub in Finland form a basis for coordinating DES. Digitalization allows near real time forecasting and optimization but also introduces a number of challenges with respect to data ownership, privacy, and interoperability (Nordic Council of Ministers, 2020).

Nordic TSOs have set up flexibility platforms in which distributed assets can compete to provide balancing services. The flexibility platforms represent one of the first examples of how conventional power-system control is being combined with market participation by small, dispersed units (ENTSO-E, 2022). Interoperability remains

limited: each country's platform follows slightly different protocols and market access thresholds (EA Energianalyse, 2022).

4.3 Business Models for Distributed Energy Storage

The economic viability of DES depends on the structure of the business models translating technical performance into financial value. Currently, three core groups of models stand out in the Nordic region.

Utility owned model - The utilities or DSOs own and operate the storage assets to defer grid investments and improve stability. Example: Vattenfall's Battery@Pyhänselkä in Finland.

Aggregator Model - Distributed batteries are pooled by independent service providers that sell aggregated flexibility to the markets. Example: Fingrid Pilot on Aggregator Participation (Finland), Elisa’s virtual power plant (VPP) service.

Community/Cooperative Model - Local energy communities mutually own storage to manage shared renewables and reduce bills. Example: FED Project; Gothenburg.

Each of these models is unique in its revenue logic, be it utilities relying on cost deferral, aggregators on service fees, or communities on energy savings. Hybrid models, for instance, utility community partnerships or aggregator advanced cooperatives, indicate methods of scaling without losing local ownership.

4.4 Economic Drivers and Market Opportunities

The Nordic electricity market offers the following value streams for DES:

- Arbitrage - charging in the low-price hours and discharging at peaks.
- Ancillary services - Frequency containment and reserve markets are opening up to smaller assets.

- Capacity Deferral - Deferring expensive reinforcements in constrained areas.
- Firming Renewable - Management of variability from wind and solar generation.
- Energy as a Service - The emerging business model where the vendors are offering flexibility services and not hardware ownership.

There are, however, still some major economic barriers: an absence of standard mechanisms for revenue stacking; limited access of small participants to balancing markets; and regulatory uncertainty over the cost recovery of community assets.

4.5 Institutional and Stakeholder Dynamics

Up to the present, the stakes of the many implementers of DES have often been in conflict with one another, comprising those of TSOs, DSOs, aggregators, technology suppliers, municipalities, and prosumers (NordREG, 2021). Mostly, DSOs are driven by grid reliability, TSOs by frequency control, and aggregators by commercial optimization (Fingrid, 2020). Policy makers are related with enforcing consumer rights and decarbonization, while technology emphasize on making their products more flexible. Although there is a strong tradition of public-private coordination in the Nordic region, which forms a facilitating environment, there are also a number of impediments including unclear asset classification between TSOs and DSOs, interoperability standards, and fragmented data exchange differing national tariff structures, and inconsistent participation rules for aggregators(EA Energianalyse, 2022; Heiskanen et al., 2020). Multilevel coordination in this context involves creating transparent stakeholder dialogue and data sharing frameworks for better alignment of incentives across levels.

4.6 Challenges in Scaling the DES Business Ecosystem

While technology costs continue to decline, several non technical barriers impede growth:

- Investment Risk - Limited long term revenue visibility.

- Regulatory Unpredictbility- Unclear rules on ownership and structure of grid fee.
- Interoperability Issues - Non harmonization of data standards at country levels.
- Public awareness - the low energy literacy in the community has restricted the adoption of cooperative models.
- Environmental Issues - Much better policy integration is needed concerning the sourcing of batteries and their end-of-life management.

4.7 Emerging Trends and Innovation Pathways

Key innovation directions shaping the DES landscape include:

- Sector Coupling - Heat, transportation, and hydrogen production linked with storage.
- AI and Predictive Analytics - Using AI to improve the optimization of multiple asset portfolios.
- Second Life Batteries - Recycle of EV batteries for stationary implementations
- Blockchain and Smart Contracts - Certain P2P settlement and trust in decentralized markets.
- Hybrid Flexibility Platforms - Combine physical storage with digital demand response resources.

These new developments are redefining the creation and distribution of value in energy markets: from centralized asset ownership to distributed service ecosystems.

4.8 Strategic Outlook for Nordic DES Development

The Nordic region is a pilot environment for next generation energy systems, with abundant renewables, cross border interconnections, and technological expertise (Nordic Energy Research, 2023). To consolidate this advantage: Policy makers need to assure there is consistency in regulatory frameworks across borders (EA Energianalyse, 2022). It is a matter of utmost importance that market actors pursue collaborative

models of economic efficiency coupled with community participation. The evaluation of system level benefits and environmental performance for distributed storage should continue among researchers (IEA, 2022). With improved compatibility, digital clarity, and inclusive business involvement, the Nordics can drive a global transition toward sustainable, distributed, and participatory energy systems.

5 ANALYSIS AND DISCUSSION

The integration of DES into the Nordic electricity system represents one of the most progressive transitions in Europe's clean energy landscape. Drawing from the conceptual framework established in Chapter 3, this chapter undertakes an in depth analysis of how, within the Nordic region, DES technologies, business models, and policy frameworks interact in creating or constraining multilevel value streams. The similar objectives of carbon neutrality, grid flexibility, and regional market integration through the Nord Pool electricity market for Finland, Sweden, Norway, and Denmark contrast with different approaches to DES in institutional design, regulatory maturity, and market participation mechanisms. The differences therefore provide a unique opportunity to understand how different policy and market environments shape the implementation of DES and how they can support the development of a common Nordic approach. Analysis in this chapter focuses on three interlinked dimensions derived from the conceptual framework.

Technological Integration - the extent to which DES technologies are deeply embedded in national and regional electricity systems.
Market and Business Model Development - Development of the ownership structure, value creation mechanisms, and commercial viability of DES.
Policy and Regulatory Alignment - The degree to which institutional frameworks in each market layer support or hinder DES participation.

This chapter applies these dimensions to a cross country analysis of DES pilot projects, regulatory documents, and academic studies. By doing so, it explores both the vertical integration between local, regional, and system level value streams and the horizontal alignment between the mechanisms of technology, market, and policy. The findings presented herein contribute directly to addressing the objectives of the thesis,

opportunities, challenges, and requirements for the development of distributed energy storage in the Nordic electricity market.

5.1 Application of the Conceptual Framework

Chapter 3 elaborates a conceptual framework that provides a multilayered perspective through which DES implementation may be analysed. The framework interlinks technological, market, and policy dimensions to capture the interdependencies involved in how distributed storage operates within complex electricity systems.

At the technological layer, DES acts as a flexibility enabler. Evidence from pilot projects in Smart Otaniemi, Fossil Free Energy Districts, NorFlex, and EnergyLab Nordhavn illustrates the technical characteristics of the systems deployed on site in terms of storage capacity, response time, and integration with renewable generation. These have facilitated experiences on how different technologies, lithium-ion, flow batteries, and hybrid storage operate to support system stability and localized energy independence. Value creation and capture are discussed between the different levels within the electricity system in detail by the market and business layers. In the framework, these structures of markets are unpacked, together with configurations of business models, including community ownership, aggregator based flexibility services, and hybrid public–private arrangements. Economic viability is assessed under this section, paying particular attention to how the generation of value is influenced by tariff structures, ancillary service market availability, and revenue stacking opportunities, a recurring theme across the projects.

The policy and regulatory standard delivers the institutional setting within which DES performs and analyzes how asset possession, data management, and grid availability are specified through legislative and market frameworks. Examples of policy documentation will involve the Clean Energy for All Europeans Package 2019, the Nordic Energy Cooperation Strategy, and the national energy transition plans of Finland, Sweden, Norway, and Denmark. This structure allows a comparison to be made of the

regulatory maturity and the identification of inconsistencies that could act as a barrier to regional integration of DES. The application of the analytical framework follows a qualitative comparative method, which involves thematic coding under the three dimensions from a selection of data from policy texts, project reports, and market analyses. Each of the case studies is evaluated against the following four key indicators.

- Technological advancements - Readiness and flexibility of DES technologies.
- Economic viability - Financial sustainability and flexibility of structural business models.
- Regulatory Compliance - Working with energy policies on regional and national levels.
- Systemic Value - Involvement in grid flexibility, reliability, and carbon reduction.

The emerging cross country matrix allows for a systematic examination highlighting best practices and gaps within the Nordic region. The framework connects technical and policy evidence with market performance, setting a basis for deeper country wise analyses that follow in subsequent sections.

5.2 Country Wise Analysis of Nordic DES Implementation

5.2.1 Finland

Technological Integration

Finland has been at the forefront of incorporating distributed energy storage within a progressively digitalized and integrated electricity grid. Strong investments in smart grid infrastructure and flexibility technologies reinforce the country's energy transition and are mainly coordinated through Fingrid Oyj, the national TSO. Projects such as Smart Otaniemi and Bulevardin Kiertotalouskortteli have demonstrated how DES systems are deployed within community and urban environments for variable renewable generation management, especially solar and wind. The technological focus has been on BESS, almost exclusively lithium-ion, although increasing attention is being

given to hybrid solutions combining thermal and electrical storage. Finland also enjoys highly developed ICT infrastructure, and research collaboration with the VTT Technical Research Centre of Finland has enabled effective real-time data exchange and demand side management in support of grid balancing and congestion mitigation.

Market and Business Model Development

The Finnish DES market is developing but remains in the pilot phase, business models are dominated by aggregator led flexibility services and community based projects. In Smart Otaniemi, energy storage assets are co-owned by local stakeholders, for example, and operated through a digital flexibility platform that enables energy sharing and self consumption optimization.

Fingrid has initiated various market based flexibility pilots in their operations that enable aggregators to participate in FCR and balancing markets. The commercial scalability of these models is still constrained by small scale economics and evolving tariff structures. Revenue stacking is also difficult for DES operators since multiple market layer participations are often restricted by either regulation or technical protocols.

Policy and Regulatory Context

Although the Finnish regulatory framework supports energy innovation, it still remains quite cautious in full liberalization with regard to DES participation. The National Energy and Climate Strategy 2035 concentrates on flexibility, sector coupling, and digitalization, while it does not have any specific legislation concerning ownership and taxation of distributed storage. Currently, double taxation could exist for DES assets as both consumers and producers of energy, though discussions on reform have started. The Ministry of Economic Affairs and Employment and the Energy Authority are preparing guidelines regarding the proper treatment of DES in grid codes and access to markets. Another important move toward more transparency and interoperability is

that Fingrid's Data hub offers one common database for all electricity market participants.

Key Opportunities and Challenges

Opportunities - A robust technological foundation, a well developed data infrastructure, and favorable policy support.

Challenges - Regulatory uncertainty around DES ownership and revenue stacking, confined private investment.

Outlook- Finland's DES integration is likely to scale when regulatory reforms allow for wider market participation and aggregation models become more mature.

5.2.2 Sweden

Technological Integration

Sweden's DES development is closely related to its progressive decarbonization targets and very high share of renewables, particularly hydropower and wind. DES projects in Sweden focus on grid flexibility, renewable balancing, and urban decarbonization. A key example of Sweden's integrated approach is represented by the Gothenburg Fossil Free Energy Districts, which combine electricity, heating, and cooling systems with distributed storage and mechanisms for P2P trading. District heating networks with thermal storage, complemented by battery systems, may be additionally enhanced by multidimensional flexibility. Operational efficiency was further developed through research at Chalmers University of Technology for advanced control algorithms and local energy management systems.

Market and Business Model Development

DES is supported in Sweden in a hybrid market model, with participation from municipalities, DSOs, and research institutions. The FED project demonstrated the technical feasibility of local energy markets where distributed assets autonomously optimize energy flows. Full scale commercial deployment remains limited by the fact that current market regulation does not allow for localized electricity trading outside of

experimental settings. Privately owned companies like Vattenfall and E.ON Sweden have started to introduce DES into grid optimization and renewable integration portfolios via the aggregator model and flexible tariff schemes. Community level initiatives are becoming more visible, while incentives remain weaker compared to Germany or the UK.

Policy and Regulatory Context

Energy policy in Sweden is set by the Energy Policy Agreement 2016 and the National Climate Act, renewable expansion is supported but storage only indirectly. The Swedish Energy Markets Inspectorate and Svenska Kraftnät (TSO) are presently revising the network codes to include DES participation in balancing markets. Sweden's participation in the Nord Pool and NordREG frameworks are regional cooperation arrangements that have nonetheless not yet defined consistent rules for small scale storage. Double charging and the lack of common metering parameters remain market hindrances.

Key Opportunities and Challenges

Opportunities - strong sector coupling potential, municipal engagement, and well formed renewable framework.

Challenges - Shortage of clarity around local energy market regulations, relatively few incentives for storage directly.

Outlook - DES development will continue to depend on the future energy market reforms in Sweden, which would allow and incentivize local trading and energy community participation.

5.2.3 Norway

Integration of Technologies

The DES landscape in Norway is influenced by the hydro dominated energy system that inherently provides flexibility. However, distributed storage gains in importance due to the electrification of transport and their local grid constraints. The NorFlex project is

one of the largest flexibility pilots in Norway, it will demonstrate how battery systems, industrial loads, and EV chargers together can provide balancing capacity. The main DES technologies deployed in Norway are hybrid configurations that include stationary batteries, EV infrastructure, and smart demand side management tools. Emphasis is not put on household scale systems but rather on grid stability and ancillary service provision.

Market and Business Model Development

The new aggregator based market model of NorFlex implies that FSPs offer aggregated capacity to the TSO Statnett and the local DSOs. In addition, the model allows digital platforms to enable distributed storage assets to participate in balancing markets. The very first results show large potential for cost reduction and emission savings, however, commercial participation is still on a pilot basis. Private players like Agder Energi Flexibility Platform and Enfo have pioneered flexibility marketplaces on digital platforms, which promise to reach a stage of commercial viability. However, without stable long term regulation and tariff adjustments, profitability is far from certain.

Policy and Regulatory Context

Through systemic alignment with the EEA, Norway sustains only limited access to the EU's electricity directives, which encompass flexibility measures. The 2020 Regulation on Electricity Markets established standards from the EU but without explicit DES legislation. Statnett's Flexibility Strategy in 2023 emphasizes the importance of technology neutral structures and clear aggregator standards. Moreover, there is still regulatory fragmentation between the TSOs, DSOs, and municipalities. Data privacy concerns and absence of standardization are holding back wider diffusion of flexibility platforms. However, government initiatives like the Green Platform Initiative and the current revision process of the Energy Act point to advancement in terms of integrated distributed flexibility.

Key Opportunities and Challenges

Key opportunities - advanced hydro integration, aggregator led flexibility pilots, and strong digital readiness.

Challenges - limited policy harmonization, unclear licensing of aggregators, and lack of standardization.

Outlook - The Norwegian DES market currently is at a stage of transition from pilot to pre-commercial. With policy clarity, it could turn out to be a regional leader in aggregated flexibility.

5.2.4 Denmark

Technological Integration

Denmark can be a role model in this respect for the integration of renewables and smart energy systems. The EnergyLab Nordhavn project in Copenhagen and projects like EcoGrid 2.0 are just examples of the innovative effort that Denmark pursues in sector coupling, distributed storage, and digital flexibility markets. DES technologies are often integrated into multi vector energy systems combining heat pumps, electric vehicles, and building management systems. Today, the storage ecosystem in Denmark focuses on hybrid flexibility, namely, its use of both centralized and decentralized assets. Highly advanced digital infrastructure enables real-time communication between prosumers and DSOs through open APIs and cloud platforms.

Market and Business Model Development

In Denmark, a range of DES business models have been enabled by the liberalized energy market. Aggregators, such as GridFlex and Energinet, operate distributed assets via open access digital platforms that enable participation in the balancing and capacity markets. The EnergyLab Nordhavn project represented a public-private collaboration that integrated research institutions, DSOs, and technology companies into the design of scalable business frameworks for DES operation. While peer-to-peer trading remains confined within experimental zones, EaaS and storage on subscription models are

spreading fast, particularly in the urban enclaves. These models drop investment risks for consumers while facilitating efficiency across the system.

Policy and Regulatory Context

The energy policy framework of Denmark strongly advocates for flexibility and distributed storage. The Danish Climate Act of 2020 and the Integrated National Energy and Climate Plan commit to carbon neutrality by 2040, underlining firmly digitalization, interoperability, and demand side management. TSO Energinet is the central player regarding coordination of flexibility by providing open data interfaces and flexibility tenders. Its policy system is the one most in line with EU policy, hence it is the most developed Nordic country when it comes to DES integration.

Key Opportunities and Challenges

Opportunities - Developed policy environment, advanced sector coupling, and digital compatibility.

Counterbalancing Challenges - Market saturation in renewables, balancing multiple flexibility markets, equitable participation.

Outlook - Denmark is a good Nordic example for the incorporation of DES, providing both policy and technical frameworks that could help with regional coordination.

5.3 Comparative Synthesis Across the Nordic Region

While a proportional analysis of Finland, Sweden, Norway, and Denmark reveals outstanding technological capability and policy objectives in the Nordic region for distributed energy storage, the speed and specific focuses vary significantly in national implementation. While DES is identified across all countries as a strategic component of the energy transition, rules on market access are uneven, as are regulatory clarity and investment incentives.

Technological Maturity

All four systems demonstrate high technical readiness, with dominance by lithium-ion batteries and growth of hybrid thermal electrical systems and EV based storage. Finland and Denmark lead regarding digital interoperability, and Sweden in sector coupled applications, while Norway applies hydro based flexibility to complement DES. The vital regional strength is the common foundation in digital and ICT infrastructure that allows real-time control as well as coordination across borders through Nord Pool.

Market Structures and Business Models

Three broad business trends emerge.

Aggregator led flexibility - Finland and Norway provide scalable access to balancing markets.

Community and municipal models (Sweden and Denmark) - improve the local value creation and social acceptance.

Hybrid Energy as a Service models- already seen in Denmark and now spreading to Finland, reduces capital barriers for consumers.

However, profitability is constrained by fragmented tariff systems and limits on revenue stacking. A common Nordic market would offer improved commercial viability with clear rules for aggregator participation.

Alignment to Policy and Regulation

Policy harmonization is partial. Of the three, Denmark's system most closely reflects EU directives, while Sweden and Finland still consider storage ambiguously as both generation and consumption. While Norway is not a member of the EU, their laws integrate through EEA agreements though they are not fully coordinated. Double taxation, incomplete metering standards, and unclear data sharing protocols between regions are commonly occurring issues. These gaps may be resolved by the continuing NordREG work on Harmonized flexibility markets, if extended to include distributed assets.

Institutional and Cultural Factors

The Nordic cooperative ethos underlines community participation, while the institutional roles are different. The governance is more TSO-DSO-centric in Finland and Norway, municipal leadership in Sweden, and public-private innovation in Denmark. Any future regional framework must take these strengths of each institution into consideration for inclusive and scalable development.

5.3.1 Comparative Assessment Matrix

Dimension	Finland	Sweden	Norway	Denmark
Technological readiness	High digital grid pilots, hybrid storage	High sector coupling	Medium to High hydro + batteries	Very High sector coupled smart grids
Market model maturity	Emerging aggregator pilots	Moderate local markets experimental	Emerging aggregator pre-commercial	Advanced open flexibility markets
Regulatory clarity	Partial double taxation unresolved	Limited no local trading law	Evolving under EEA reforms	High explicit DES provisions
Community participation	Moderate research-driven	High municipal projects	Low industrial focus	High prosumer and cooperatives
Overall DES maturity	3/5	3.5/5	3/5	4.5/5

Table 2: Nordic Comparative Framework for Distributed Energy Storage Integration.

5.3.2 Regional Overview

Complementarity: Norway's hydro can balance the variable renewables of Denmark and Finland through cross-border trade.

Integration gap: A limited number of uniform data platforms restricts DES aggregation across national borders.

Policy momentum: Denmark's digital market design confers a template for regional harmonisation.

Investment potential: Finland and Sweden have strong bases for R&D and manufacturing as complements to deploying storage technology.

5.4 Technological and Business Landscape: Distributed Energy Storage

Innovation, regulation, and market development are strongly intertwined in the technological and business environment of DES in the Nordics. The current analysis illustrates that technological maturity has already reached a high level for lithium-ion and hybrid battery systems, while emerging innovation trends clearly point toward long duration, sector-coupled solutions such as hydrogen and thermal storage. This reflects the shift from technology practical validation to system level optimization, which now requires policy frameworks to move beyond pilot oriented support toward coordinated infrastructure planning. Key barriers include interoperable digital standards lacking across the Nordics, although systems such as Finland's Datahub have showcased the value of unified platforms, fragmentation in data and communications standards remains one of the main obstacles to aggregation potential, raising transaction costs related to DES service integration.

From a market and business perspective, DES deployment depends largely on models capable of converting flexibility into reliable revenues. Aggregator based models seem to be the most scalable, as they pool different distributed assets and efficiently participate in balancing markets. In contrast, their success is constrained by inconsistent regulatory rules for market access and settlement. While utility based models assure reliability, they often lack incentives for efficiency enhanced market

engagement. Community based models strongly reinforce social value and local participation, they are usually faced with financing challenges, metering, and administrative impediment. Among such structures, hybrid structures consolidating utilities or aggregators with community stakeholders appear most resilient because they are able to pool technical competence, capital resources, and local legitimacy. A related trend at the level of energy services is the emergence of Energy as a Service approaches, as already seen in Denmark and Finland, where consumers procure flexibility services rather than owning storage assets, which reduces investment risk and accelerates DES adoption.

Institutional coordination remains a persistent challenge. Fragmented roles of TSOs, DSOs, regulators, and aggregators diminish systemic efficiency, particularly when mandates and data access rules are mismatched . Pilot programs like NorFlex show that coordinated environments, where DSOs, aggregators, and technology providers collaborate provide much clearer insights for the work on regulatory harmonization. Municipal involvement is also becoming increasingly important, local authorities enhance acceptance, ensure fair participation, and mediate between public and private concerns while underlining the fact that DES is at least as much a governance challenge as a technical one.

Digitalization plays the dual role of an enabler and a source of new vulnerabilities. While AI based forecasting and blockchain supported market transactions improve transparency and operational optimization, they also raise concerns about cybersecurity and data governance. Without shared standards and strong protection frameworks, public trust. particular in community level DES models may be shaken. This leads to a double challenge for Nordic regulators: innovation is to be fostered while keeping data integrity and consumer confidence safe. Altogether, the analysis underlines that DES value in the Nordic market emerges only when technological capability, business model viability, and regulatory clarity operate in alignment. Technology defines what is possible, business models determine what is profitable, and

regulation establishes what is permissible. When these dimensions are combined, DES evolves from a technical add on into an integrated part of the Nordic energy transition. With this, the ground is laid for the next section: the investigation of how such aligned conditions serve as enablers of multilevel value creation across technical, economic, policy, and social domains.

5.5 Discussion of Multilevel Value Creation Opportunities

DES will create value at many different layers of the electricity system, technical, economic, institutional, and social. In the Nordic context, these are interlinked value streams where progress within one dimension influences opportunities in others. Indeed, evidence from pilot projects indicates that DES comes fully into its own when technological innovation goes hand in hand with supportive policy, market design, and community participation.

5.5.1 Technical and Operational Value

DES creates value for system flexibility by peak shaving, frequency regulation, and congestion management. In projects like Smart Otaniemi in Finland and EnergyLab Nordhavn in Denmark, it is evident that distributed storage effectively integrates variable renewables and enhances grid stability. At the same time, digital technologies supporting smart meters, forecasting, and energy management systems complement these technical benefits and turn DES into a multi use asset for a distributed energy system.

5.5.2 Economic and Market Value

Economically, DES creates new revenues through the participation in balancing markets, reserve services, and energy arbitrage, it also offers indirect value via grid deferral and efficiency improvement. Nordic flexibility markets provide an early indication of the emerging aggregators and community based models, while present market structures remain biased to favor large actors. The lack of multi-service remuneration and

unequal access to the market prevents the full value of DES from being monetized. Market reforms are required to reflect the full economic value of distributed resources.

5.5.3 Policy and Institutional Value

Policy frameworks put in place the conditions within which DES can work as a flexibility resource. Even though EU and Nordic strategies recognize DES as crucial for decarbonization, implementation generally varies: Finland and Sweden have moved along with much clearer mechanisms of distributed flexibility while Norway and Denmark remain more centralized. The value of policies can be further improved due to regulatory harmonization, clear ownership rules, and coordination in planning by TSOs, DSOs, and local authorities.

5.5.4 Social and Community Value

DES facilitates community based energy actions and peer-to-peer involvement, democratizing energy systems. Project interventions like FED in Sweden shows storage can help community level collaboration and active energy consumer involvement. Public value is contingent upon accessible participation models, facilitative licensing systems, and increased digital and energy literacy. Without these enablers, community DES measures will remain non integrated experiments.

5.5.5 Synergistic Value Creation

The highest value is achieved when technical, economic, policy, and social dimensions align in synergy. Pilot projects demonstrate how technological flexibility may enable market participation, provided it allows policy adaptation and community engagement. Conversely, value is lost by misalignment for instance, inconsistent tariffs or unclear aggregator rights. There is an actual need for integrated policy and market design to maximize cross sector benefits.

5.5.6 Barriers to Multilevel Value Realization

Key barriers remain:

- Regulatory uncertainty over DES ownership and participation
- Unpredictable tariff structures and lack of revenue stacking
- Technical limitations of data exchange and interoperability
- Social barriers to participation, trust, and distribution of fair benefits.

Overcoming these challenges requires coherent action across institutions and policies that appreciate DES as multi dimensional assets beyond purely technical components.

5.6 Policy and Market Integration Analysis

Policy frameworks and market structures are the key factors in DES deployment in the Nordic region. The Nordic market is technologically sophisticated and highly interconnected, although it still faces regulatory inconsistencies and disparate market access that hamper scaling on a decentralized flexibility level. This section summarizes how regulation, market participation, and business models interact to drive DES integration

5.6.1 Regulatory Clarity and Consistency

This has resulted in the ambiguous treatment of DES as both a producer and consumer, with double taxation and burdensome licensing procedures being one of the major regulatory challenges. Though storage is identified as a separate flexibility asset in EU directives, this is implemented variably at the national level. Finland and Sweden have begun exempting small scale storage from double charges, but Norway and Denmark still classify storage under consumption based tariffs. Such divergent approaches make cross border aggregation difficult and delay the much needed harmonized rules on grid connection, metering, and balancing services.

However, the majority of the regulations in Nordic countries presently are focused on centralized transmission level flexibility; this makes it hard for distribution level DES, particularly community and aggregator owned systems, to access these markets. Wider regulatory reform is needed in terms of the development of multitier flexibility markets in which storage can participate in all levels of the system.

5.6.2 Mechanisms for Market Access and Participation

Although Nord Pool has one of the most open electricity markets in the world, its structure still favors large conventional actors. Minimum bid sizes and technical requirements often block small or distributed storage resources from balancing and reserve markets. Pilot initiatives such as the Swedish Enera program and flexibility platforms in Finland have demonstrated that aggregated small scale storage can deliver meaningful system services. Further scaling requires clear aggregator rights and standardized market entry rules.

Revenue opportunities can also be highly variable from one country to another. For example, Norway and Sweden compensate for ancillary services, but tariff structures for prosumers and aggregators are still under development in Finland. The investment incentives for DES therefore remain weak due to a lack of harmonized multi service remuneration frameworks

5.6.3 Interaction between Business Models and Policy Incentives

Clear policy is needed for the different DES business models. Aggregator driven and community energy models need regulations that enable local trading and peer-to-peer exchanges, as well as settlement mechanisms that are transparent. The experience of Finland with P2P pilots has been that local flexibility markets increase community participation and system efficiency, but wider replication suffers from a lack of standardized procedures.

Hybrid municipal private models, such as the FED Project in Sweden, illustrate that enabling incentives, such as exemption from grid fees, data transparency, and digitalization, make DES more profitable. Stringent Norwegian grid codes make shared or community storage less desirable. The most robust business models are those corresponding to strong policy signals whereby services like flexibility, reliability, and energy efficiency are rewarded, not the mere ownership of assets.

5.6.4 Cross Border Policy Coordination Despite strong regional interconnection.

DES participation in cross border flexibility remains limited. Wholesale electricity and reserve markets are considered the main core areas for Nordic market coordination, while distributed flexibility continues governed at a national level. Enhanced alignment with EU balancing network codes and clearer roles for TSOs, DSOs, and aggregators can further unleash regional values. According to Nordic Energy Research (2024), a better integration of renewables could be attained through coordinated stabilising and harmonized resilience markets, reducing operational costs up to as much as 20%.

5.7 Development of Future Distributed Energy Storage

This thesis shows how successful expansion in the DES within the Nordic region rests on progress at all four levels, technological development, regulatory adaptation, the evolution of business models, and social inclusion. Even though technologies are already mature, DES does not reach full multilevel value creation due to the presence of fragmented policy frameworks, uneven market access, and little community participation.

5.7.1 Technological Advancement and System Integration

In fact, wider DES adoption will require more standardization and interoperability of the digital systems across the Nordics. Differences in communication protocols and data management platforms create barriers both for the aggregators and small scale resources. Shared digital standards including transparent data architectures will underpin EU digital energy initiatives and greatly facilitate integration. Another priority currently emerging is sustainable battery lifecycle management. Nordic recycling and second life initiatives should be aligned with the planning of DES while aiming at the incorporation of environmental sustainability into future projects. Sector coupling, meaning the interlinkage of electricity storage with heating, transport, and industry, offers considerable flexibility dividends. System resilience, especially in cold climates with pronounced seasonal variations, will be enhanced by combining battery, thermal, and hydrogen storage.

5.7.2 Policy and Regulatory Adaptation

Consequently, the future policy framework should move away from asset-based regulation to service based regulation. DES should be remunerated for flexibility, balancing, and congestion management instead of being categorized either as generation or consumption. This requires a transparent and standardized local flexibility market in which DSOs can procure flexibility from aggregators and communities. There is also a need to pursue harmonization of regulation at a Nordic level. With shared transmission infrastructure and integrated operation through Nord Pool, there should be harmonization in fees regarding connection, tariffs, and rules concerning data sharing for storage. A Nordic Energy Storage Cooperation Framework can provide institutional grounds for such coordination.

5.7.3 Business and Market Model Evolution

Business models for DES must evolve with the multifunctional value of storage. Future deployments will have to be designed to capture multiple value streams at the same time, such as grid services, self consumption, carbon reduction, and/or local market participation. Energy as a Service models suppress consumer risk by shifting the investment away from ownership, while aggregator models support pooled participation in ancillary markets. Regulatory support remains key. Incentives based on performance, easier licensing, and wider market access to flexibility platforms would further solidify commercial viability for DES systems. Smart Otaniemi and cross-sector business models of the FED project show how such hybrid governance, a combination of public infrastructure with private innovation-can accelerate the technology adoption cycle.

5.7.4 Social Inclusion, Governance, and Knowledge Development

Long term DES uptake requires social acceptance, fair participation, and well defined governance structures. Community based storage, shared ownership, and local flexibility markets increase trust and participation but also raise novel challenges in terms of benefit sharing, privacy protection, and open operation rules. Capacity

building work by universities, municipalities, and energy agencies should support informed participation and innovation. In addition, institutional coordination must be strengthened in the future. Currently, technology policy and market regulation are organized separately. A Nordic DES Governance Council should be established with close links to policymakers, industry, and academia in order to better align strategies for the long term and enhance innovation ecosystems.

6 Global context and comparative review of DES implementation.

This section furnishes an internationally comparative review of the implementation of DES, concentrating on mature and emerging markets, comprising the United States, Germany, the United Kingdom, Japan, and Australia. Within these countries, different policy pathways and regulatory innovations have been adopted to accelerate storage technologies. By setting these experiences in contrast, this chapter sets out lessons for the Nordic region, where DES integration is technologically advanced but where policy and market frameworks are in a stage of evolution.

This analysis is organized around three dimensions drawn from the conceptual framework developed in Chapter 3.

Technology and Infrastructure Readiness
Market and Business Model Evolution
Policy and Regulatory Environment

The best practices, barriers, and insights developed within this comparative perspective are highlighted in the chapter, informing the subsequent analysis of the Nordic context presented in Chapter 4.

6.1 The United States - Market Driven Flexibility and Policy Incentives

The United States represents one of the most dynamic markets for distributed energy storage, in that significant drivers are found mainly at the state level, supplemented by market based innovation. DES deployment has been rapidly growing because of programs such as California's Self Generation Incentive Program (SGIP) (California Public Utilities Commission, 2023), New York's Reforming the Energy Vision (REV) initiative (NYPSC, 2022), and federal tax incentives under the Investment Tax Credit (ITC)

Technological and Infrastructure Readiness

The U.S. market has a wide spectrum of technological integration: from the dominance of lithium-ion batteries to newer players such as long duration flow batteries and vehicle to grid storage (DOE, 2023). Interconnection with distributed solar has catalyzed widespread deployment of residential scale installations spanning California, Arizona, and Texas.

Market and Business Model Evolution

Business models in the US have been optimized by means of the country's deregulated electricity markets, which enable independent aggregators and energy service companies to monetize distributed flexibility (FERC, 2020). Companies like Sunrun, Tesla Energy, and Stem Inc. initiated VPPs, pooling residential batteries resources for grid service provision (Wood Mackenzie, 2023). Revenue stacking pooling self consumption, time of use optimization, and ancillary service participation are nowadays a standard practices in various markets.

Policy and Regulatory Environment

Federal initiatives under FERC Order 841 and FERC Order 2222 have changed DES participation by requiring that energy storage resources be allowed to compete in wholesale markets. These regulatory actions have linked the gap between distribution level assets and system level market operations. Persistent challenges include policy fragmentation between states and limited standardization of data protocols (DOE, 2022). The United States shows how policy shaped market structures can promote large scale DES diffusion while keeping innovation through private sector involvement.

6.2 Germany - Grid Integration and Energy Communities.

The Energiewende policy has led to the role of Germany in leading the incorporation of renewable energy, making it one of the advance DES markets in Europe. Storage deloypment at both residential and commercial levels are driven by an emphasis on energy

autonomy, grid stability, and community contribution (BMWK, 2023; Agora Energiewende, 2022).

Infrastructure and Technological Readiness

Germany holds the best basis in decentralized renewable generation, which is mainly solar PV. Today, the integration of photovoltaics and battery storage systems has develop into mainstream, with more than 1.2 million residential systems installed by the year 2025 (Fraunhofer ISE, 2023). Technological focus is on smart control systems, optimizing self consumption and grid interaction (BNEF, 2023).

Market and Business Model Evolution

Prosumer oriented business models characterize the market in Germany. Energy cooperatives and community energy schemes form part of the country's landscape, whereby locals collectively invest jointly in solar plus storage projects (German Energy Agency–DENA, 2022). One such company, Sonnen GmbH, firmly instituted virtual communities spanning the country that allow prosumers to trade surplus energy (Sonnen, 2023). Aggregators also incorporated in FCR markets through decentralized resources (BNetzA, 2023).

Policy and Regulatory Environment

The core of the German regulation consists of two acts, the Renewable Energy Sources Act and the Energy Industry Act. In the same way they stimulate investment by granting subsidies or feed in tariffs, they limit double remuneration and grid charges. Recent reforms favour sector coupling and a grid friendly operation of storage systems (Agora Energiewende, 2023). DES can thus contribute to frequency stability and congestion management. The German involvement shows that a DES ecosystem can be balanced with policy alignment, consumer empowerment, and digitalization. The economic constraints endure with fluctuating tariff structures and diminishing subsidies (Fraunhofer ISE, 2023).

6.3 The United Kingdom - Aggregation and Market Flexibility.

The UK has placed energy storage as a strategic enabler for its net zero target set for 2050. While early advancements were dominated by large scale battery projects, distributed storage and flexibility services are now fast developing due to market reforms and digital innovation (UK Department for Energy Security & Net Zero, 2022, National Grid ESO, 2023).

Technological and Infrastructure Readiness

The UK has experienced a hastened deployment of distributed batteries, electric vehicles, and community microgrids in its electricity grid. Digital platforms like Piclo Flex, combined with open data frameworks, reinforce distributed energy resources that are progressively depended upon for system balancing and congestion management by grid operators (Piclo, 2023, Ofgem, 2023).

Market and Business Model Evolution

Aggregator participation has driven business innovation in the UK. In a virtual power plant model, companies like Octopus Energy, Moixa, and Limejump are aggregating storage at household and commercial levels to sell services back to the National Grid.The local flexibility markets are allowing distributed assets to participate in capacity auctions, a principal catalyst for integrating DES into mainstream market operations.

Policy and Regulatory Environment

The UK government has developed a wide ranging approach through the Smart Systems and Flexibility Plan and the Energy Security Bill 2023, both provide a clear legal definition of energy storage and enable DES assets to avoid double charging (BEIS & Ofgem, 2021, UK Parliament, 2023). Innovation is also facilitated through sandbox mechanisms by Ofgem, enabling new business models to function in regulated regulatory relaxation. The UK case shows how the combination of market deregulation, regulatory flexibility, and digital infrastructure can enable the increase of DES.

6.4 Japan - Technology Led Grid Resilience and Policy Coordination

Geographical susceptibility and a shortage of natural resources have been persistent concerns for Japan's energy security and resilience. The 2011 Great East Japan Earthquake and the nuclear accident at Fukushima galvanized the country's commitment both to renewables and updating the grid (METI, 2021, IEA, 2022). In this context, the Distributed Energy Storage model has become an integral factor in Japan's energy transition.

Technological and Infrastructure Readiness

Japan is at the major edge of battery technology innovation, backed by several significant industrial actors like Panasonic, Toshiba, and Hitachi (BloombergNEF, 2023). Residential storage has been heavily promoted in concert with rooftop solar under FIT and FIP programs, driving a cumulative installed total of over 500,000 household systems by 2024 Reinforcing lithium-ion batteries, Japan has also initiated hydrogen based storage, vehicle to grid integration, and hybrid energy systems incorporating both heat and electricity storage (METI, 2023).

Market and Business Model Evolution

The Japanese market supports technology driven and vertically integrated business models. Utilities like Tokyo Electric Power Company and Kansai Electric Power Company have allied with technology companies to offer "smart energy services" that integrate home storage, energy management, and grid support (TEPCO, 2023, KEPCO, 2023). Business models are usually utility coordinated, with end users as participants by way of contracted service programs rather than as independent market players.

Policy and Regulatory Environment

The Japanese Strategic Energy Plan 2021 directly indicates storage as one of the key flexibility resources required to reach carbon neutrality by 2050 (METI, 2021). The government subsidizes Distributed Energy Storage directly, boosts R&D programs, and reinforces regional energy management systems(ANRE, 2023). Market liberalization is

partial, the retail side opens up, with transmission and distribution staying tightly regulated. In Japan, innovation and coordinated policies have maintained system resilience even within the strict bounds of the centralized market model. However, there is still limited local participation and only modest market incentives for independent aggregators to diversify DES business models (BloombergNEF, 2023).

6.5 Australia - Market Reform and Distributed Participation

Australia has become an international frontrunner in distributed solar energy with battery storage deployment, with over 3 million rooftop PV systems and an increasing residential batteries uptake (Clean Energy Regulator, 2023, AEMO, 2023).

Technological and Infrastructure Readiness

The deployment of distributed storage in Australia is directly linked with the residential solar boom. House batteries such as Tesla Powerwall, SonnenBatterie, and Redflow have built up substantial decentralized capacity (BloombergNEF, 2023). The South Australian Virtual Power Plant project clustering a substantial number of home batteries into a single reliably dispatchable unit, constitutes one of the world's largest operational VPPs (South Australian Government, 2022).

Market and Business Model Evolution

The DES business ecosystem in Australia is powered by energy retailers and aggregators that allow households to monetize their energy storage by dynamic pricing and wholesale market participation (AEMC, 2022). The mix of consumer ownership with market participation heralds a hybrid business model that can achieve a balance of local value creation and broader system benefits (AEMO, 2023).

Policy and Regulatory Environment

Changes have been instituted by the Australian Energy Market Commission and the Australian Renewable Energy Agency to accommodate DER and DES in the context of market frameworks (AEMC, 2023; ARENA, 2023). The Energy Security Board's Post-

2025 Market Design positions distributed resources as active participants in the market. State-led initiatives, such as the South Australian Home Battery Scheme and the Victorian Renewable Energy Target, have also helped to increase uptake (SA Government 2022; Victorian Government 2023). Despite this, challenges remain on how to standardize technical protocols, manage data privacy, and impartially provide grid access. Australia is the perfect example of how policy driven market reform can unlock distributed storage potential by combining consumer participation, digital innovation, and system integration (AEMC, 2023).

6.6 Comparative Discussion and Lessons for the Nordic Market

The comparative review of global DES implementation indicates several inclusive trends that can help draw valuable lessons for the Nordic region. Yet, despite circumstantial differences, successful deployment across those countries rests on three core pillars, policy clarity, market access, and technology integration.

Policy and Regulation

Globally, DES growth is facilitated when policy frameworks directly recognize storage as a distinct system asset, distinct from generation or consumption. The US and UK have set clear former occurrences through removing double charging and enabling wholesale market participation - FERC Orders 841 and 2222,UK Energy Security Bill. More centralized systems such as Japan and Germany also illustrate well how coordinated policies and subsidies can accelerate DES deployment at scale. For the Nordics, this means the rules on storage ownership, data sharing, and market participation need to be aligned, in particular for smaller scale and community assets.

Market and Business Models

Successful DES markets combine flexibility services with value stacking opportunities. US and Australian models indicate that aggregator based frameworks and VPPs can link distributed assets to wholesale market clearing. In contrast, Japan's structurally integrated model presents resilience but lower competition. The community based

German approach has illustrated how local ownership builds social acceptance and adds to fair value distribution, a model quite relevant for Nordic cooperative traditions.

Technological Integration

Technical maturity does not mean creation of value by itself. All the reviewed countries are highly technically ready, but digital interoperability and data governance are still crucial challenges. The Nordic region, with its advanced ICT infrastructure, is well positioned to leverage data driven storage management systems, provided cross border standards under NordREG and ENTSO-E cooperation frameworks align.

Institutional and Cultural Factors

Institutional culture also molds DES diffusion. In this line, Germany and Denmark have been favored by greater local energy communities, while Japan's centralized coordination ensures resilience. Nordic countries can coordinate both employing community participation along with utility and aggregator collaboration to ensure inclusivity and scalability.

6.7 Global DES Frameworks and Lessons for the Nordic Region (Summary table)

Country	Key Characteristics	Business Model Orientation	Regulatory Framework Highlights	Transferable Lessons for Nordic Region
United States	Market driven, innovation led, strong aggregator participation	Aggregator based VPPs, service-oriented markets	FERC Orders 841 & 2222 enabling storage access to wholesale markets	Enable storage participation in all markets, remove double charging, strengthen aggregator role
Germany	Decentralized, community driven, subsidy supported	Community energy, prosumer ownership, peer trading	EEG & EnWG reforms, sector coupling initiatives	Foster community storage, encourage value stacking, expand citizen energy models
United Kingdom	Liberalized market, advanced digitalization	Aggregator-led flexibility markets, Energy as a Service	Smart Systems & Flexibility Plan, Ofgem sandbox	Promote regulatory experimentation and innovation-friendly markets
Japan	Technology driven, utility integrated	Utility managed storage, service contracts	Strategic Energy Plan, REMS programs	Build utility technology partnerships and DER coordination frameworks
Australia	Solar + storage dominance, hybrid participation	Consumer owned storage, VPPs	Post 2025 Market Design, state battery schemes	Integrate household flexibility into grid markets, strengthen DER orchestration
South Korea	Government-driven large scale storage rollout	Utility + industrial storage	National ESS Promotion Policies	Consider state led long duration storage support
China	Rapid industrial scaling, cost driven deployment	Provincial storage mandates, grid storage	NEA Storage Policy 2023	Leverage scale for cost reduction, promote hybrid configurations
Canada	Remote community storage, renewable integration	Utility led microgrids	Smart Grid Fund Initiatives	Expand storage for rural + remote energy resilience

Netherlands	Advanced digital trading, high RES penetration	Peer-to-peer trading pilots, energy communities	Energy Market Reform Agenda	Support digital interoperability and open energy data
Singapore	Urban storage deployment, grid optimization	Commercial + utility scale storage	Energy Storage Programme	Explore storage as infrastructure models

Table 3 -Summary of International DES Characteristics, Regulatory Approaches, and Insights Applicable to the Nordic Context.

6.8 Synthesis and Implications

Global experiences show that distributed storage systems develop when policy, market, and technology frameworks develop in concert. Some of the key strategic directions that the Nordic region can learn from mature DES markets are as follows. Establish common rules for market access consistent with aggregator participation and classification of storage assets according to Nordic standards.

- Promote hybrid ownership models - Favor cooperative and community energy systems, with a significant contribution of commercial organizers.
- Advance Digital Infrastructure - Implement data coordination standards to permit cross border DES operations.
- Coordinate Policy and Market timelines - Ensure that regulatory reforms progress in step with technological advancement and pilot project impacts.

7 Result

This chapter highlights the key empirical findings from the analyses of the Nordic DES pilot projects, policy frameworks, and market structures. The results will focus on aspects such as technological performance, social and community level outcomes, regulatory conditions, and multilevel value creation. Evidence from literature and pilot project documentation is synthesized with the purpose of highlighting how DES works in real life, what barriers persist, and what opportunities exist for wider Nordic-wide diffusion.

7.1 Technological Advancement and Integration of DES in the Nordic

Findings strongly support the high technological maturity of Nordic DES development, enabled by advanced digital infrastructure and also extensive pilot activities. Demonstrations like Smart Otaniemi in Finland and EnergyLab Nordhavn in Denmark have illustrated that distributed batteries are today capable of:

- Providing frequency regulation
- peak shaving function
- Support demand-side flexibility
- Integrating with local renewable generation

It is evident that DES integration enhances local reliability and system level flexibility, principally owing to the rapid response capability of lithium-ion systems. In this respect, technological development remains quite uneven among countries, mainly in terms of interoperability, data standards, and grid connection requirements. Variations in metering rules, asset classification, and communication protocols impede cross border coordination. DES is moving from the pilot stage to early commercialization, but full integration is restricted by regulatory and cost structure inconsistencies.

Pilot Project	Country	Demonstrated Technical Functions	Key Finding
Smart Otaniemi	Finland	Frequency regulation, sector coupling, V2G testing	High digital readiness enables scalable DES models
EnergyLab Nordhavn	Denmark	Local flexibility markets, PV+BESS optimisation	Strong integration with community energy models
NorFlex	Norway	Congestion management, local flexibility	Offers real-time adjustments but limited by regulatory fragmentation
Upplands Energi Community Storage	Sweden	Peak-shaving, energy sharing	High social acceptance but cost recovery unclear

Table 4 - Evidence from Nordic Pilot Projects on DES technological performance.

7.2 DES in Community and Local Energy Models

Thus, distributed energy storage is increasingly key to local energy autonomy, community balancing, and the smooth integration of distributed renewables across Nordic towns and cities. In other words, community batteries and neighborhood scale storage help households and small businesses ride demand waves together, maximize self consumption, and shave peak loads.

Projects like FED in Gothenburg, Smart Otaniemi in Finland, and NorFlex in Norway demonstrate that community oriented DES models are able to:

- balance solar PV and heat pumps at the local level
- ease congestion in distribution grids
- Improve load management and run municipal energy systems more efficiently.
- increase community involvement and awareness regarding energy consumption

Some pilots also linked DES to local energy trading functionalities, including small scale peer-to-peer trading. None of these trading features is central, however, their on the ground impact is slight compared with the wider benefits from local flexibility, reliability, and community empowerment. Social acceptance plays a huge role. Communities with clear governance, easy participation, and transparent cost sharing tend to invest more and engage more. On the other hand, municipalities with murky metering rules, cumbersome taxation, or low digital literacy often tend to be less confident in adopting DES.

Case / Pilot	Main Contribution	Secondary Features	Barriers
FED (Sweden)	Local balancing, load control	Some local trading functionality	Complicated tariffs
Smart Otaniemi (Finland)	Community flexibility & energy awareness	Minor P2P testing	Regulatory uncertainty
NorFlex (Norway)	Municipal flexibility services	Limited community trading pilots	Aggregator rules unclear
Small-scale municipal batteries (Sweden)	Peak shaving, cost reduction	–	Awareness + governance challenges

Table 5 - Evidence from community level DES pilots

7.3 Business models stay narrow and are dominated by single service revenue streams.

Among all the Nordic pilots reviewed, most of the storage systems operate with few monetization channels. Smart Otaniemi and EnergyLab Nordhavn use DES mainly for frequency control and grid support, while NorFlex does so for distribution level flexibility and congestion relief, and community batteries in Sweden for load shifting and tariff reduction.

Despite these technical capabilities, value stacking remains underdeveloped. Across pilots, DES typically earns revenue from only one or two services (e.g., FCR + peak shaving), rather than a full portfolio such as arbitrage, reserve markets, and congestion management. This prevents profitable scaling and explains why most projects depend on R&D or EU funding rather than commercially sustained income.

2. Aggregators are emerging but face unclear qualification rules

The results show that aggregators play an essential role in pooling small distributed assets, but their market entry remains limited due to:

- Unclear licensing and verification procedures
- Inconsistent rules between Finland, Sweden, Denmark, and Norway
- Technical integration barriers with DSOs
- Absence of revenue certainty for small and medium aggregators

Only a few operational models, such as Fingrid's aggregator pilot and Elisa's VPP services, demonstrate early-stage commercial activity. However, these examples also show that:

- Aggregators can reliably deliver FCR and reserve services
- Residential and community batteries can be aggregated for commercial grid services
- Market access needs harmonisation for scaling across borders

Overall, aggregator driven services exist, but commercial viability is still restricted by policy fragmentation.

3. New business models-EaaS, community ownership, and hybrid models-continue to rise but remain in experimental mode.

Case studies identify a number of evolving business configurations:

Energy as a service (EaaS)

Companies in Finland and Denmark tested models where customers pay for services, such as flexibility, rather than buying the battery. This reduces upfront cost and improves adoption, but the regulation is still not fully supportive to service-based remuneration.

Community Owned Models

Municipal and cooperative batteries in Sweden and Norway show:

- Strong community acceptance
- Fair cost sharing
- Improved reliability

But they lack:

- Standardized taxation
- Simple metering regulations
- Financing instruments

Hybrid Utility Community Models

Found in Denmark and Finland, integrating:

- Utility technical management
- Community participation
- Shared cost benefit framework

While socially attractive, these models necessitate updated grid codes and transparent revenue mechanisms to scale.

4. Market design undervalues flexibility thus limiting DES profitability

In all Nordic countries, the market still values energy more than flexibility.

Pilot results show DES provides:

- Congestion mitigation
- Peak demand reduction
- Local balancing
- Reservation capacity
- Improved reliability

Yet these services often lack clear pricing. This was the most consistent barrier reported across analyses of the pilots.

7.4 Multilevel Value Creation Potential of DES

DES generates systemwide value among technical, economic, institutional, and social strata, but only when aligned with coherent policy and market design.

Key findings

Technical:

DES supports integration of intermittent renewables, reduces peak loads, and enhances system flexibility.

Economic:

Revenue opportunities exist with arbitrage, FCR, and congestion management, for example; most pilots currently operate in single value chains, constraining profitability. Lack of revenue-stacking mechanisms reduces the incentives for investors.

Institutional:

DES aligns with national climate goals, but institutional fragmentation (TSO–DSO cooperation gaps, lack of harmonised grid codes) weakens deployment potential.

Social:

Where governance is clear and inclusive, DES increases citizen engagement and trust. In municipalities that lack both digital skills and clear processes, skepticism is raised.

7.5 Synthesis of Overall Findings

The results indicate that:

The Nordic countries are technologically ready: they have advanced digital systems and successful pilots proving viability.

- Regulatory disaggregation is the main limiting factor, not technology.
- DES value is multilevel, extending from grid reliability to local empowerment.
- Cross border harmonization is imperative to unlock systemwide flexibility

  The results indicate that:

8 Conclusion

The present thesis explores the development of multilevel value streams and infrastructure to enable DES in the Nordic electricity market, considering issues related to technological readiness, policy frameworks, and market structures along with stakeholder participation. Based on a qualitative approach, this research integrates literature synthesis, policy review, and assessment of pilot projects to investigate how DES may contribute toward system flexibility, renewable integration, and decentralized energy participation.

8.1 Summary of Key Findings

The technological maturity in the Nordic region, supported by well developed digital infrastructure, has created an enabling environment for flexibility services. Smart Otaniemi, EnergyLab Nordhavn, and NorFlex are examples of pilot projects that demonstrate DES's capability to provide frequency regulation, peak shaving, sector coupling, and prosumer driven energy balancing. At the same time, however, the study shows that institutional and regulatory barriers have now overtaken technological limitations as a barrier to DES implementation.

Fragmented regulations, inconsistent tariff structures, unresolved double taxation, and ambiguous aggregator roles continue to result in limited DES investments and make the road to large scale adoption slow. Community level and peer-driven models also look promising, but their diffusion remains constrained by limited governance structures and insufficient interoperability standards. One key finding is that DES value creation happens across technical, economic, and social layers, each linked to policy, technology, and market mechanisms changing in harmony with one another. Small steps forward in some but not others will inevitably lead to inefficiency and "value leakage."

8.2 Final synthesis and interpretation

Three integrative conclusions emerge:

1. DES is a strategic enabler of a flexible, decentralized energy system - It enables renewable integration, improves grid reliability, and allows for local participation in energy markets.
2. The main barriers to DES scale up include regulatory and institutional gaps - While Nordic countries do share EU aligned goals, the significant differences in implementation mean that different investor and aggregator challenges are offered.
3. Future development of DES calls for multilevel coordination - Harmonization of policies, standardization of data protocols, and integration of market designs are necessary to unleash complete DES value both in the technical and social dimensions.

8.3 Contributions of the Study

The contribution of this study is to:

Theoretically, this would be done by framing DES within a multilevel value creation approach that integrates technology, market design, and governance. Empirically, by comparing real Nordic pilot projects and identifying cross country lessons. In practice, determining the policy and market conditions that will support DES adoption at scale, including clear aggregator roles, harmonized grid codes, and community centered models.

8.4 Limitations and Future Research

As the study is based on secondary qualitative data and DES technologies and policies are continuously evolving, there are a number of limitations that this study possesses. Future research should cover the following:

- Quantitative modeling of DES economic impacts.
- Real-time data about the operation from storage systems.
- Comparative studies across non Nordic markets.

- Social acceptance and behavioral research into prosumer participation.

8.5 Recommendations

Based on the findings of this study, targeted actions are recommended for large-scale and efficient integration of DES in the Nordic electricity market:

1. To establish a common Nordic regulatory environment. Define energy storage as an independent market asset class and remove double taxation. A prevalent Nordic framework via NordREG must align grid codes, metering rules, and data sharing prerequisites on open cross border flexibility.

2. Introduce service based remuneration mechanisms. Market design needs to value the flexibility services granted by DES, frequency response, congestion management, and peak shaving, among others, through clear remunerating structures. This would enhance investment security and widen participation.

3. Strengthen the role of aggregators. Also, aggregator entry requirements clear licensing rules, standardized qualification procedures, and transparent participation guidelines to allow distributed assets to compete in balancing markets.

4. Foster Energy as a Service and community ownership models - Community driven, cooperative, and subscription based business models mitigate consumer risk while escalating locally driven engagement. Municipalities and energy communities should be given incentives, coupled with simplified permitting procedures, to develop DES assets.

5. Improve interoperability, digital security, and integrated planning .Common communication standards and shared data platforms are vital for DES to function smoothly across the Nordic systems. Further, DSOs should incorporate DES into grid planning as an alternative to conventional reinforcement.

6. Invest in social inclusion and energy literacy. Where we undertake public awareness campaigns, clear communication, and diverse voices governance, the levels of trust, participation, and acceptance increase in relation to distributed storage systems.

7. Promote long duration storage and circular economy solutions Future policy efforts should support the development of hydrogen, flow batteries, and second life battery use to complement environmental sustainability with system flexibility.

8.6 Final Remarks

DES is at the crossroads of technological innovation and institutional transformation. The Nordic experience shows that to fully exploit the potential, advanced storage technologies need to go hand in hand with synchronized regulatory reforms, market innovation, and citizen engagement. In a world where the transition toward decentralized energy resources is gaining speed, insights from this thesis help to shape DES into a core building block for resilient and sustainable electricity systems of tomorrow.

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