Battery Energy Storage System in the Finnish Real Estate Sector

Assessing Potentials for Improving Flexibility in Property Electricity Consumption and Techno-Economic Analysis

HAMK
HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

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Khuong Nguyen

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

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Author Khuong Nguyen
Abstract
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Supervisors Kaisa Kontu, Jussi-Pekka Krankkala

This thesis investigates the role and impact of Battery Energy Storage Systems (BESS) in optimizing energy consumption in the Finnish real estate sector. The study delves into the use and storage of energy with BESS, their interplay with Fingrid's reserve market, Smart Readiness Indicator (SRI), and the economic evaluation of BESS.

A thorough literature review and two practical case studies of residential and commercial applications serve as the backbone of this research, presenting extensive insights into the operation, battery types, and business models of BESS in the real estate sector. The review investigates Lithium iron phosphate (LFP) batteries, identified as most suitable for real estate. The analysis also includes an examination of Fingrid's reserve market's effects on BESS within the Finnish real estate sector. The SRI is introduced as a framework for integrating BESS into real estate properties and assessing associated techno-economic benefits for property owners. The findings affirm BESS's crucial role in managing peak loads, boosting solar energy self-consumption, and participating in reserve power markets, consequently improving energy efficiency, flexibility, and grid stability. The interaction between Fingrid's reserve market, SRI, and BESS enhances consumption flexibility and optimizes electricity use in buildings. The economic value of BESS considers investment, maintenance costs, income from reserve markets, and energy savings. The case studies highlight BESS's financial potential in commercial properties, particularly with governmental subsidies. However, residential BESS installations face economic viability challenges due to high initial costs and maintenance expenses.

The study's limitations include the limited timeframe, the research gap on BESS and reserve markets' influence on SRI scores in Finland, and the lack of empirical studies. Future research should include a broader range of case studies and delve deeper into the relationship between BESS, reserve markets, and SRI. Additionally, an extensive financial analysis considering taxes and government incentives will enhance understanding of BESS's investment viability.

Keywords BESS, Finnish real estate sector, reserve market, SRI, economic value
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Content

1 INTRODUCTION 1

1.1 Thesis background 1

1.2 Research objectives 2

1.3 Outline of the thesis 3

2 RESEARCH METHODOLOGY 4

3 BATTERY FOUNDATION 5

3.1 Battery terminology 5

3.1.1 Cells 5

3.1.2 Nominal voltage and Capacity 6

3.1.3 C-rate 7

3.1.4 Peukert equations and plots 8

3.2 Battery energy storage system (BESS) 10

3.2.1 General Characteristics 10

3.2.2 Business Models 12

3.3 Electrochemical cells 14

3.3.1 Principle of operation 14

3.3.2 Materials 16

3.4 Lithium iron phosphate (LFP) 27

3.4.1 General Characteristics 27

3.4.2 Charge and Discharge Ratings 30

3.4.3 Battery Capacity 32

3.4.4 Low Temperature Effects 33

4 Electricity markets 35

4.1 Financial Markets 35

4.2 Physical Markets 36

4.3 Fingrid's Reserve Markets 37

4.4 Appropriateness evaluation of BESS in the electricity markets 42

4.5 Appropriateness evaluation of specific battery types within Fingrid's reserve markets 46

5 Smart Readiness Indicator (SRI) 49

5.1 Overview of SRI 49
5.2 Assessment Methodologies 51
5.3 Calculation Methodology 53
5.4 Weighting Factors 59
5.5 Roles of BESS in SRI 63
6 Economic Analysis of BESS: Case Studies and Findings 66
6.1 Economic Analysis 66
6.2 Case Study I: The economic viability of a progressive smart building system with power storage 69
6.3 Case Study II: Assessment of economic benefits of battery energy storage application for the PV-equipped households in Finland 72
7 Final discussion and conclusions 75
7.1 Summary of main findings 75
7.2 Current Limitations 78
7.3 Recommendations for Future Research 79
References 81

List of Figures

Figure 1. Electric cell versus Electric Battery.....6

Figure 2. Peukert plot at different temperatures and currents.....9

Figure 3. BESS architecture.....11

Figure 4. Discharging (a) and Charging (b) processes in a battery cell 15

Figure 5. Reserves used in the Nordic countries.....38

Figure 6. Fingrid's reserve product comparision.....42

Figure 7. Suitable technologies for Fingrid's reserve products.....44

Figure 8. Framework of SRI scheme.....50

Figure 9. Interrelations between the key functionalities and impact criteria 50

Figure 10. SRI Assessment Methods 52

Figure 11. Overview of SR score calculation methodology.....55

Figure 12. Weighting Scheme Overview 60

Figure 13. Proposed weighting factors of key functionalities and impact criteria 60

Figure 14. Different climate zones of EU 61

Figure 15. The significance of different domains in the context of residential real estate according to climatic zones 63

Figure 16. The significance of different domains in the context of non-residential real estate according to climatic zones 63

List of Tables

Table 1. Characteristics of few major battery systems 16

Table 2. Comparison of major battery systems.....24

Table 3. Pros and Cons of LFP battery compared to other lithium-ion batteries 29

Table 4. Suggested operating specifications for LFP prismatic cells 30

Table 5. Effects of discharging a LFP battery at a slower rated capacity 33

Table 6. Relations between the available capacity (C) of a LFP battery changes with temperature and the cut-off voltage 34

Table 7. Differences between the annual and hourly markets 39

Table 8. Pros and Cons of Yearly and Hourly Markets 40

Table 9. Comprehensive evaluation on the appropriateness of each battery type with respect to Fingrid's reserve markets 47

Table 10. Seven SRI Classes.....53

Table 11. Effects of BESS on impact criteria and technical domains.....64

Table 12. Examined system layouts 73

Table 13. The summarized results from the literature review 78

Appendices

Appendix 1. SRI Method B: Detailed Service Catalogue

Appendix 2. Reserve obligations and their respective sizes as stipulated by Fingrid

1 INTRODUCTION

1.1 Thesis background

The increasing demand for energy has led to a mounting apprehension regarding the environmental impact of energy generation, consumption, and management. In recent years, the widespread electrification of transportation, heating, and cooling systems in recent years has intensified the requirements for electricity, thereby aggravating the predicaments associated with managing peak and off-peak demands. The real estate sector plays a significant role in this context, as buildings account for a substantial proportion of global energy consumption. According to a study from the International Energy Agency - IEA (IEA, n.d.), in 2021 the operation of buildings accounted for nearly one third of global final energy consumption. Finland has been actively working towards implementing sustainable energy solutions to optimize energy use in properties, reduce greenhouse gas emissions, and contribute to a more sustainable energy system.

In recent years, Battery energy storage system (BESS) solution in the real estate sector has emerged as a promising technology for addressing these challenges. This system could store excess energy produced during off-peak hours and release it during peak hours, thus reducing the dependence on the grid and increasing the flexibility of property electricity consumption. However, as a relatively new technology, BESS faces several obstacles that need to be overcome for widespread adoption in Finland and beyond.

To advance the understanding of BESS and its potential to optimize energy consumption in properties in Finland, this thesis delves into various aspects of this technology, from its operating principles to its impact on the electrical grid. Additionally, the study explores the role of the Smart Readiness Indicator (SRI) and Fingrid's reserve market in shaping the integration and value proposition of electric real estate batteries.

1.2 Research objectives

The main objective of this thesis is to contribute to the comprehension of BESS in the use and storage of energy within Finnish real estate sector. To achieve this, the thesis has put emphasize on addressing the following research questions:

RQ1: What is the role of BESS in the use and storage of energy within Finnish Real Estate sector?

RQ2: What is the interrelationship between Fingrid's reserve market, SRI, and BESS and based on which how can batteries improve the flexibility of a Finnish real estate's electricity consumption?

RQ3: How can owners evaluate the economic value of BESS in Finland?

RQ1 aims to study the significance of BESS in the context of energy utilization and storage within Finnish real estate sector. This involves exploring the potential of the system in enhancing energy efficiency, reducing peak demand, and facilitating the integration of renewable energy sources within the property sector.

RQ2 seeks to examine the interplay between Fingrid's reserve market, SRI, and real estate battery systems. This analysis focuses on understanding how these elements interact and influence each other, particularly in terms of promoting the flexibility and adaptability of electricity consumption in properties.

RQ3 provides guidance for real estate owners on assessing the economic value of their BESSs. This involves identifying the key metrics and presenting a framework for evaluating their overall cost-effectiveness and financial viability.

By addressing these RQs, the thesis seeks to offer valuable insights and recommendations that support the development of sustainable, intelligent, and resilient energy systems within the real estate sector in Finland. Ultimately, this research aims to inform and guide stakeholders in their transition towards a more sustainable energy future.

1.3 Outline of the thesis

The thesis is divided into six chapters as follows.

Chapter one discusses the background of the problem, the author's motivation for solving the problem, and provides an overview of the research objectives and structure of the thesis.

Chapter two outlines the research methodology adopted in this thesis, including the data collection methods, analytical techniques, and models used in the study.

Chapter three provides a comprehensive review of the battery foundation. It initially delves into essential battery terminology and the definition of BESS and its available business models. The chapter, subsequently, analyses the fundamentals of electrochemical cells and their operational principles. The analysis continues with an in-depth evaluation of battery materials, from which Lithium iron phosphate (LFP) batteries are highlighted as possessing the most beneficial characteristics for use in real estate. This preference stems from the unique characteristics of LFP batteries, which are explored further in a comprehensive examination. The investigation encompasses the battery's charge and discharge characteristics, its capacity and performance under varying rates, and the impact of temperature.

Chapter four discusses the effects of Fingrid's reserve market on BESS within Finnish real estate, from which it determines the most suited reserve product and market for BESS in this sector.

Chapter 5 introduces SRI as a framework for examining the integration of BESS into real estate properties, and for evaluating the associated benefits and opportunities for property owners from a techno-economic standpoint. It highlights BESS could significantly contribute to the smart readiness of buildings by enhancing their energy efficiency, resilience, and adaptability to grid signals.

Chapter 6 further enriches the literature review with two practical case studies. These are discussed to analyse the implementation of BESS in residential and commercial applications in Finland. These case studies clearly demonstrate the significance of comprehending the

concepts of SRI and the reserve markets to make decisions regarding the deployment of BESS in Finnish real estate.

Chapter seven provides a discussion of the results and draws conclusions based on the findings. It discusses the implications of the study for the Finnish real estate sector, identifies the limitations of the research, and suggests directions for future research.

2 RESEARCH METHODOLOGY

To address the research questions and achieve the thesis objectives, a comprehensive literature review was conducted. This methodology allows for a thorough understanding of the existing body of knowledge related to real estate battery systems, energy use, storage, and efficiency in the property sector. Simultaneously, to enhance the concreteness of the RQs and provide practical insights into the application of BESS in the Finnish real estate sector, two case studies were studied. These case studies represent residential and commercial energy storage systems, thus offering valuable and context-specific insights. Moreover, these case studies provide specific, real-world examples of how BESS can be implemented in different types of properties, and thereby foster wider adoption of BESS in other types of real estate. The literature review adheres to guidelines defined by the University of Illinois (2021).

2.1 Search Strategy and Selection Criteria

The literature search was conducted using relevant databases and search engines, including Google Scholar, Scispace, ScienceDirect and other specialized databases in the field of energy and sustainability. A combination of keywords and phrases related to real estate battery systems, Fingrid's reserve market, SRI, energy use, storage, and efficiency was used to identify relevant publications. The selection criteria for including articles in the review was based on their relevance to the research questions, the quality of the research, and the date of publication, with a focus on more recent studies.

2.2 Data Extraction and Analysis

When the relevant articles had been identified and collected, a systematic approach was employed to extract and analyse the data. This involved categorizing the literature based on the research questions and identifying common themes, patterns, and trends. The extracted data was synthesized and critically analysed to draw conclusions and provide insights relevant to the research questions.

2.3 Synthesis and Reporting

The findings from the literature review were synthesized and presented in a structured manner, addressing each research question separately. The synthesis highlights the key findings, discuss the implications of the results, and identify any gaps or limitations in the existing literature. The conclusions drawn from the literature review have informed the recommendations and contributed to the overall thesis objectives.

By employing a literature review methodology supplemented by practical case studies, this research has provided a comprehensive understanding of the role of real estate battery systems in the property sector, the interrelationship between Fingrid's reserve market, SRI, and real estate battery systems, and the evaluation of the economic value of these systems. This approach has allowed the identification of valuable insights and the development of recommendations to support the advancement of sustainable, intelligent, and resilient energy systems in the Finnish real estate sector.

3 BATTERY FOUNDATION

3.1 Battery terminology

3.1.1 Cells

A cell is s the most diminutive unit capable of providing an electrical potential difference that can be harnessed to energize a load. The magnitude of this potential difference is contingent

upon the chemical composition employed in the construction of the cell. There are various types of cells, each with its own unique chemistry, voltage, and capacity. Certain cellular structures are engineered for single-use purposes and subsequently undergo recycling, whereas others are designed for rechargeability. Primary cells are denoted as single-use cells, while secondary cells are recognized as rechargeable cells. (*Battery Explained: Types of Batteries and Their Applications*, 2023)

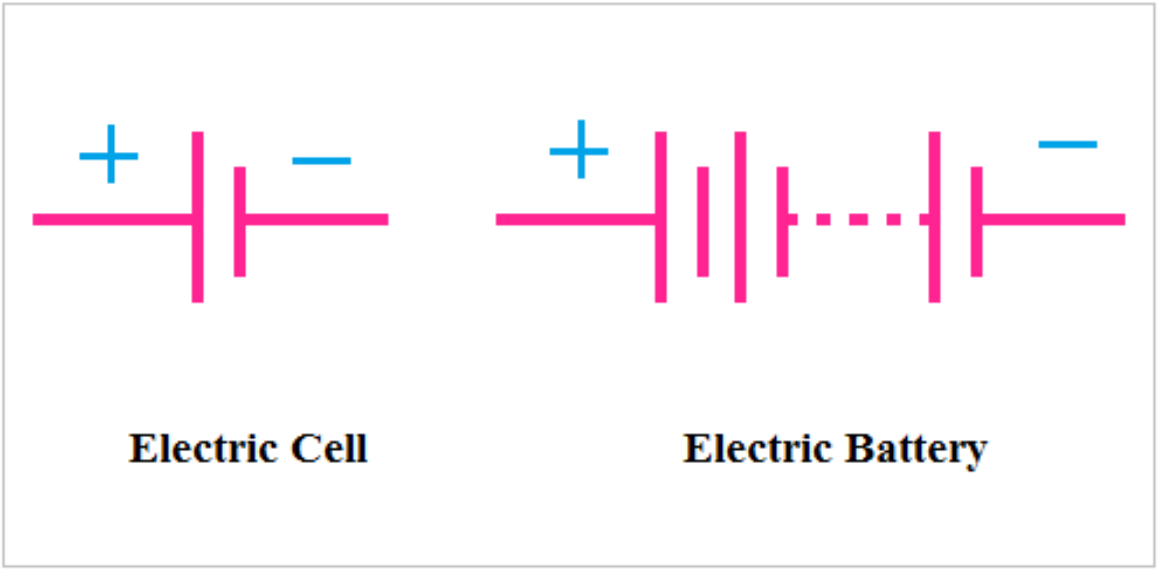


Figure 1. Electric cell versus Electric Battery (Difference Between Cell and Battery with Detailed Comparison - BYJU'S, n.d.)

It is important to distinguish between a cell and a battery. As illustrated in Figure 1, it is noteworthy that a "battery" is composed of multiple "cells" that are interconnected either in a series or parallel configuration. To put it simply, cells represent the elemental units that comprise the essential structure of a battery. In high-capacity battery packs, the number of connected individual cells could reach thousands, and they tend to be wired externally. Large bus bars or thick wires are used to connect the cells together so that they can carry the high electrical currents required for the specific application of the battery.

3.1.2 Nominal voltage and Capacity

The voltage output of a battery is based upon a mixture of active chemicals or materials (electrodes) that are housed within the cells. The electrical potential difference of a cell varies

based on its state of charge, ranging from complete discharge to full charge or any intermediate state. The nominal voltage of a battery is the mean voltage output observed during its discharge cycle. The nominal voltage of a cell may not be consistent with its actual voltage at a particular moment. The potential variation of the battery cell's state of charge is contingent upon its historical usage patterns. (Kumar, 2022)

Regarding the capacity, it is defined as a measure of the total amount of electrical energy a cell or a battery can store and deliver to a device or system. It is commonly measured in ampere-hours (Ah) or milliampere-hours (mAh), representing the amount of current a battery can deliver over a specific time. Essentially, battery capacity tells how long a battery can power a device before needing to be recharged or replaced. For example, a 2000mAh battery can theoretically provide a current of 2000 milliamperes (2 amperes) for one hour. However, the actual number may vary based on the load, battery chemistry, temperature, and age of the battery. A higher capacity generally means a longer runtime for a device or system, but it can also lead to an increase in size and weight of the battery. For a secondary battery cell, it is considered to reach its end when its capacity is only 70% of the original capacity.

3.1.3 C-rate

The C-rate is a measure representing the rate at which a battery is charged or discharged relative to its capacity. It is expressed as a multiple of the battery's capacity, typically in ampere-hours (Ah) or milliampere-hours (mAh). The C-rate helps to understand how quickly a battery can be charged or how fast it can deliver its stored energy. (*Battery Terms & Definitions*, n.d.)

For instance, a 1C discharge rate means that the battery will discharge its entire capacity in one hour. A 2C discharge rate would discharge the same battery in half an hour, while a 0.5C discharge rate would take two hours to discharge the battery fully. Similarly, a 1C charge rate means that the battery will be fully charged in one hour, whereas a 0.5C charge rate would take two hours to charge the battery completely.

A higher C-rate indicates a faster charging or discharging process. However, it is essential to consider the battery's chemistry, as different battery types have specific maximum C-rates they can handle without degrading their performance or causing safety concerns. Understanding C-rate is essential as it helps in selecting the most suitable battery for a specific application based on charge and discharge rate requirements and in managing the battery within its safe operating limits.

3.1.4 Peukert equations and plots

Peukert plots, also known as Peukert curves, are graphical representations of the Peukert equation in battery technology. The Peukert equation describes the relationship between a battery's capacity, discharge rate, and the time it takes to discharge (Omar et al., 2013).

As discussed in section 3.1.3, the capacity of a battery (Ah) is an indicator of the amount of charge a battery can store and deliver over time. It should be noticed that this capacity is not a constant, rather it is contingent upon the discharge rate, or how quickly the stored energy is being used. When energy is drawn faster from a battery with a larger load or higher current, the battery's effective capacity decreases. The reason for this decrease in capacity with higher loads is due to the voltage drop that occurs in the battery. As more current is drawn, the voltage across the battery's terminals decreases, which in turn reduces the battery's capacity to deliver energy. This voltage drop is more significant with higher loads; hence the capacity decrease is more pronounced.

This phenomenon is described by Peukert's Law, which states that the available capacity of a battery decreases as the rate of discharge increases. The Peukert equation is typically expressed as:

$I^n \times t = C$, where: t: the time (Hours) it takes for a battery to discharge

I: the current (or load) (A)

C: the battery's capacity (Ah) for a constant load of I (A).

n: Peukert’s constant

Peukert's constant (n) is a measure of how much the capacity decreases with increasing discharge rate. If n is close to 1, the battery's capacity is not greatly affected by the discharge rate. If n is greater than 1, the capacity decreases significantly as the discharge rate increases.

In a Peukert plot, the discharge time (T) is plotted on the vertical axis, and the discharge current (I) is plotted on the horizontal axis as shown in Figure 2. Multiple curves or lines can be plotted on the graph, each corresponding to a specific battery parameter or battery type.

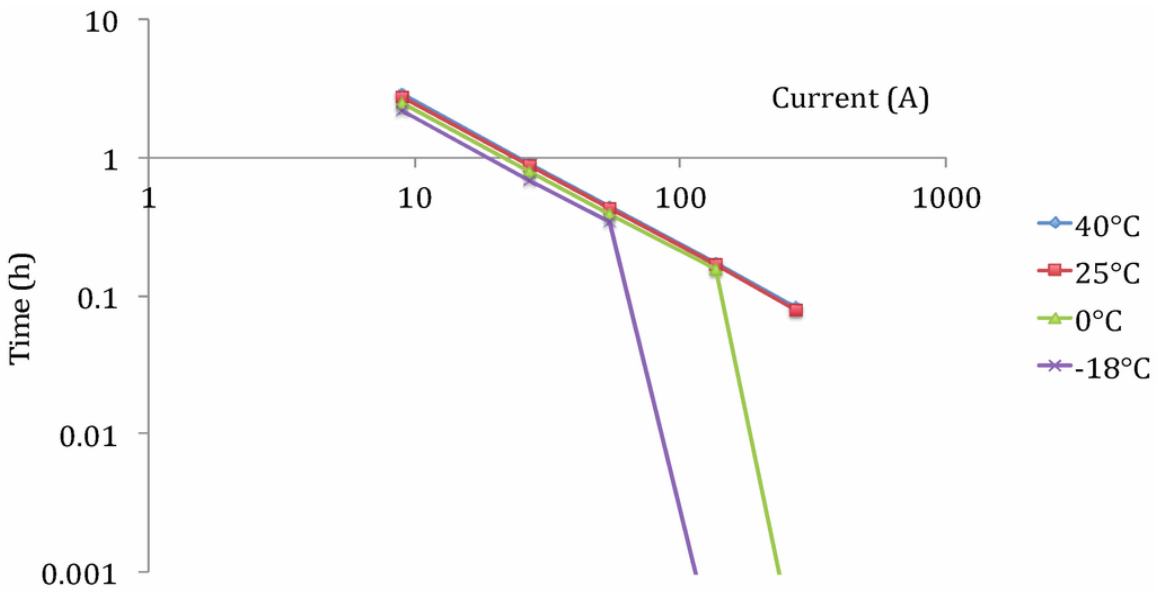


Figure 2. Peukert plot at different temperatures and currents (Omar et al., 2013)

Peukert plots are useful for battery analysis, design, and selection. They provide insights into a battery's performance under different discharge conditions and help estimate the battery's usable capacity at various discharge rates.

3.2 Battery energy storage system (BESS)

3.2.1 General Characteristics

According to Petrova (2021), BESS is an Energy Storage System (ESS) that acquires energy from diverse sources, aggregates it, and retains it in rechargeable batteries for subsequent utilization. In the event of necessity, the electrochemical energy stored in the battery is released and distributed to residential, automotive, and industrial or commercial establishments.

A BESS is a complex system that consists of both physical components and software at various levels of abstraction. The primary components of BESS comprise of a battery system, a battery management system (BMS, an inverter or a power conversion system (PCS), and an energy management system (EMS). The inclusion of various safety systems in a BESS is contingent upon its operational parameters and functionality. These safety systems may comprise a fire control system, smoke detector, temperature control system, as well as cooling, heating, ventilation, and air conditioning systems as shown in Figure 5. The monitoring and control units of safety systems ensure the safe operation of a BESS by overseeing its parameters and responding to any emergencies that may arise (Petrova, 2021).

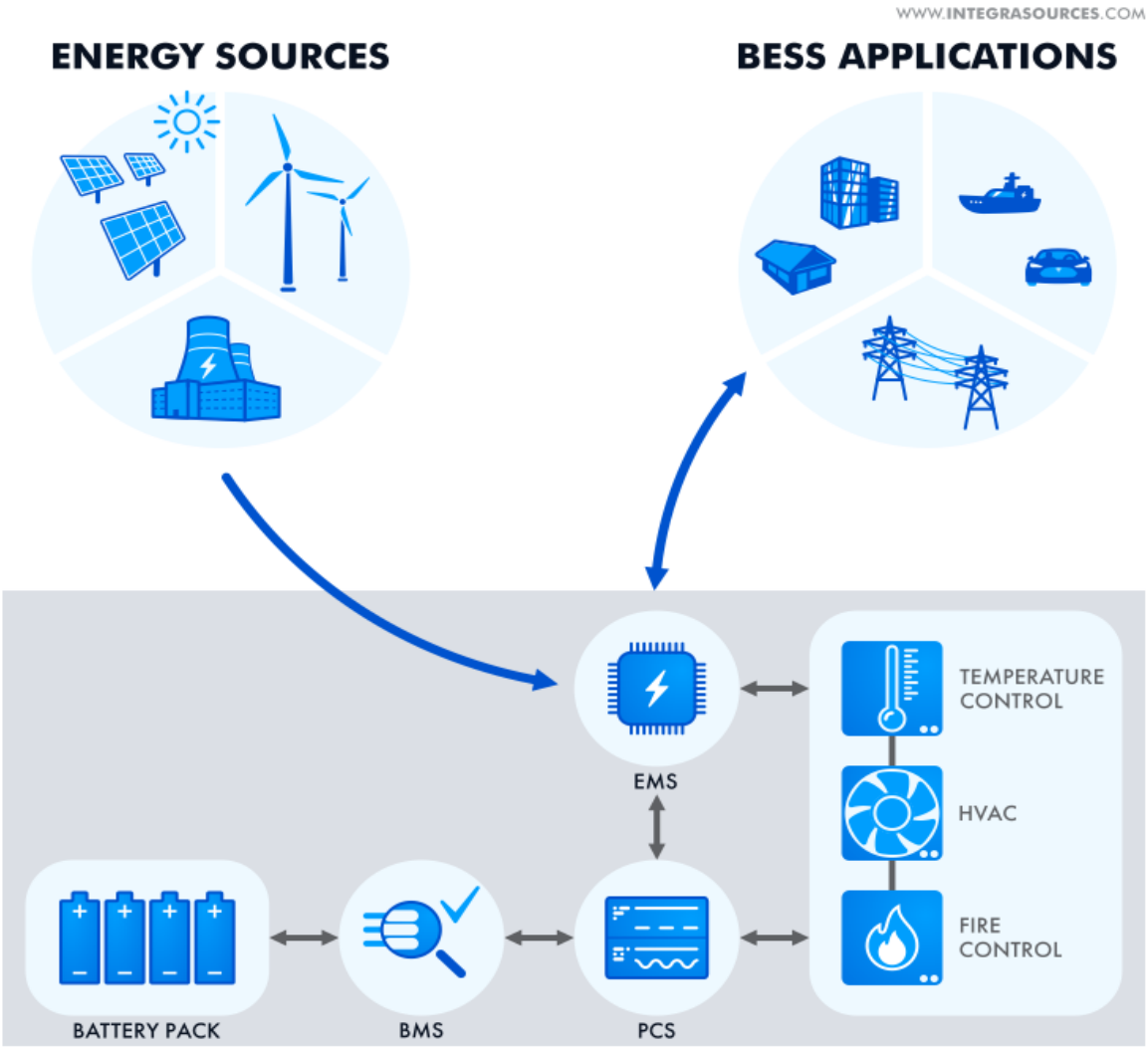


Figure 3. BESS architecture (Petrova, 2021)

Based on Figure 3, the operating principle of BESS could comprise of three phases namely Charging phase, Storage phase, and Discharging phase.

Regarding the Charging phase, the EMS monitors conditions of Energy sources (real-time grid conditions, energy prices, etc.) and the SoC of the battery. The decision to charge the battery is determined by the EMS based on the given inputs, taking into consideration the cost-effectiveness of the process. After determining cost-effectiveness, the EMS initiates the charging process by signalling the PCS. The PCS, in its role as a rectifier, converts incoming Alternating Current (AC) power from the grid to Direct Current (DC) power for charging the battery. As charging begins, the BMS continuously monitors battery parameters such as SoC, temperature, voltage, and current. If any parameter is out of the normal range, the BMS communicates with the EMS to modify or halt charging.

Once the battery is fully charged, the BMS signals the EMS, which then instructs the PCS to halt charging. This is the Storage phase. The battery, during this time, sits idle, storing energy until its utilisation is required. In this phase, the EMS coordinates with the HVAC systems to maintain the optimal environmental conditions for the BESS. The BMS continues to monitor battery parameters and the environment (temperature, humidity, etc.) to ensure safe storage conditions. If the BMS detects abnormal conditions, such as an increase in temperature, it may trigger the HVAC system to adjust the environment and may also activate fire control mechanisms if required.

Concerning the Discharging phase, when the EMS detects a need for power, either due to increased demand or higher grid prices, it triggers the discharge of the battery by signalling the PCS to start the discharging process. The PCS, acting as an inverter, converts the DC power stored in the battery to AC power for use in the building or grid. As discharging occurs, the BMS keeps monitoring the battery parameters and communicates with the EMS to manage the discharge rate based on the SoC, load requirements, and battery health.

Complex BESSs necessitate resilient software solutions. Contemporary systems employ machine learning algorithms to enhance energy management. Achieving precise estimations of battery states and characteristics necessitates dependable algorithms and mathematical models that are constructed within the software development of the BMS.

3.2.2 Business Models

According to Akhil et al. (2015, p. 20), BESS could be owned and operated by the Power Generation Company (PGC), the Retailer (acting typically also as Balance Responsible Company (BRC)), the Aggregator (AGG), and the Prosumer (PRO). These stakeholders could work together based on one of the following business models.

Direct Ownership: In this case, the Prosumer (PRO) – the building owner – purchases, installs, and operates the BESS directly. The PRO has full control over the system and reaps all the financial and operational benefits. The PRO could use the BESS to manage their own energy consumption, sell excess energy back to the grid (PGC or Retailer/BRC), or participate in

demand response or other grid services programs organized by the Retailer/BRC or Aggregator (AGG).

Lease: The PRO leases the BESS from a third-party provider, which could be any of the other stakeholders (PGC, Retailer/BRC, or AGG). The provider installs, maintains, and possibly operates the system, while the PRO pays a regular fee for using the system.

BESS as a Service (BESSaaS): A third-party provider installs, operates, and maintains the BESS, and the building owner (PRO) pays a fee for the service. The provider could be a specialized BESSaaS company or any of the other stakeholders (PGC, Retailer/BRC, or AGG). The provider also manages interactions with the grid and energy markets, potentially in coordination with the Retailer/BRC or Aggregator (AGG).

Power Purchase Agreement (PPA): This model is typically used in conjunction with a renewable energy system. The PPA provider, which could be a PGC, Retailer/BRC, or an independent developer, installs, operates, and maintains the BESS and renewable energy system. The building owner (PRO) agrees to purchase the electricity generated at a predetermined price.

Shared Savings / Performance Contracting: In this model, a third-party provider installs, operates, and maintains the BESS, and the financial benefits are shared with the building owner (PRO) based on the performance of the system. The provider could be a specialized energy services company or any of the other stakeholders (PGC, Retailer/BRC, or AGG). The Retailer/BRC might also be involved in verifying the system's performance and resulting savings.

Virtual Power Plant (VPP): In this model, the Aggregator (AGG) plays a key role. The AGG aggregates multiple BESS (owned by multiple PROs) into a single, controllable resource. Each PRO retains ownership of their individual BESS but allows the AGG to control the system in exchange for a fee or share of the profits. The PGC and Retailer/BRC might interact with the VPP as a single entity, buying and selling energy and ancillary services.

Each of these models involves different levels of collaboration and interaction between the stakeholders, and the specific roles and relationships can vary depending on the local regulatory and market environment. It should be noticed that these models are not mutually exclusive, and hybrid or combined models are possible.

3.3 Electrochemical cells

3.3.1 Principle of operation

The fundamental concept underlying an electrochemical cell involves the accumulation of electrical potential energy. When a cell undergoes charging, it experiences an increase in its potential energy. Subsequently, as the cell undergoes discharge, it experiences a reduction in its potential energy level. Ultimately, upon complete discharge, the cell reaches its minimum potential energy state, signifying that it cannot be discharged beyond this point.

Between the electrodes, there is an accumulating electrical pressure because of the electrochemical potential energy at each electrode seeking to be dissipated in order to perform work. This electrical pressure is called electrical potential. The potential difference between the two electrodes is called the cell voltage. Upon connection of the external load to the cell, the flow of electrons from the negative electrode through the circuit to the positive electrode results in the conversion of electrochemical potential energy into electrical energy, which can be utilised to perform work via the external load. (Brendan & Sims, 2017, pp. 7–8)

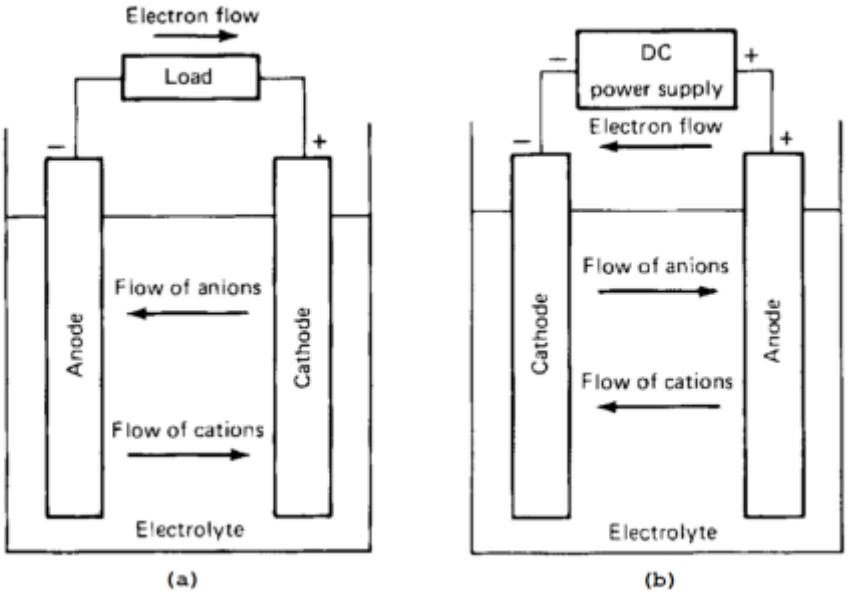


Figure 4. Discharging (a) and Charging (b) processes in a battery cell (Brendan & Sims, 2017, p. 7)

Figure 4 (a) illustrates a typical representation of the discharge process of a cell. When the cell is connected to an external load, electrons flow from the anode, which is oxidized, through the external load to the cathode, where the electrons are accepted, and the cathode material is reduced. The electric circuit is completed in the electrolyte by the flow of anions (negative ions) and cations (positive ions) to the anode and cathode, respectively.

An easy-to-understand illustration for the discharge reaction can be that between Zinc (Zn) as the anode material and chlorine gas (Cl_2) as cathode material:

Overall reaction (discharge): $Zn + Cl_2 \rightarrow Zn^{2+} + 2Cl^- \rightarrow ZnCl_2$.

Anodic reaction (oxidation, loss of electrons): $Zn \rightarrow Zn^{2+} + 2e$. At the anode, two electrons (2e) are removed from the metal, leaving behind positively charged Zn ions (Zn^{2+} cations) in the electrolyte. This creates an excess of positive charge at the anode. To balance this charge, negatively charged ions (anions) in the electrolyte move towards the anode.

Cathodic reaction (reduction, gain of electrons): $Cl_2 + 2e \rightarrow 2Cl^-$. At the cathode, each Cl atom accepts one electron from Zn^{2+} cations, resulting in an excess of negative charge at the cathode. To balance this charge, cations in the electrolyte move towards the cathode. These ion migrations allow the continuation in the flow of charge to complete the circuit.

Considering the charging process, the cell is now connected to a DC supply instead of a load to complete the circuit. In this case, the external voltage (the voltage of the DC supply) is higher than the cell voltage, which means there is a greater potential energy exterior to this cell than there is interior to this cell. Thus, energy is pumped back into the cell, and the current flow is reversed. Oxidation takes place at the positive electrode and reduction at the negative electrode, as shown in Figure 4 (b). As the anode is, by definition, the electrode at which oxidation occurs and the cathode is where reduction takes place, the positive electrode is now the anode, while the negative electrode is now the cathode.

3.3.2 Materials

Table 1 summarizes characteristics of few major battery systems based on their chemicals, while Table 2 provides a qualitive comparison of the mentioned systems. Collective data in Table 1 was retrieved from different sources namely Asian Development Bank (2018), Martha et al. (2003), Linden & Reddy (2001), Skyllas-Kazacos et al. (2009), and Zhao et al. (2006). Table 2 was deduced from data learned in Table 1.

Table 1. Characteristics of few major battery systems[1]

	Nickel-cadmium (Ni-Cd)	Lead-Acid	Lithium-ion (Li-ion)

[1] Values provided in Table 1 are approximate and can differ depending on the specific battery design and manufacturer.

Specific type			VLRA	LCO	LFP	NMC
Chemistry	Anode	Cd	Pb	Graphite (C)	Graphite (C)	Graphite (C)
	Cathode	NiOOH	PbO_2	$LiCoO_2$	$LiFePO_4$	$LiNiMnCoO_2$
	Electrolyte	KOH	H_2SO_4	Organic solvent	Organic solvent	Organic solvent
Cell Voltage (V)	Nominal	1.2	2.0	3.6 to 3.7	3.2	3.6 to 3.7
	Open circuit	1.29	2.1	4.2	3.65	4.2 (NMC111) 4.3 (newer NMC)
	Operating	1.0 to 1.25	1.8 to 2.0	3.0 to 4.2	2.5 to 3.65	2.8 to 4.2 Possibly 4.3 for high Nickel NMC chemistries
	End	1.0	1.75	3.0	2.5	2.8

Operating Temperature (°C)	-40 to 60	-20 to 50 (optimal 20 to 25)	-20 to 60[2]	-20 to 60[3]	-20 to 60[4]
Specific Energy at 20°C (Wh/kg)	40 to 60	10 to 20	150 to 200	90 to 160	150 to 220 (varies depending on Ni content)
Energy Density at 20°C (Wh/L)	40 to 80	30 to 50	400 to 600	250 to 350	350 to 600 (varies depending on Ni content)
Discharge Profile (Relative)	Moderately Sloping	Flat with a slight decline in voltage as it approaches full discharge	Steady voltage decreases with a **Flat** discharge curve at around 3.7 V	**Flat** discharge curve at around 3.2 V with a sudden voltage drop at the end of discharge	Steady voltage decreases with a **Flat** discharge curve at around 3.6-3.7 V

[2] a significant drop in performance when the temperature gets below 0°C.
[3] better performance in lower or higher temperature compared to two other Li-ion cells.
[4] a significant drop in performance when the temperature gets below 0°C.

Self-discharge rate at 20°C (% loss/month)	10 to 15	1 to 3	1 to 3	Less than 1	1 to 2
Charge acceptance rate (%)	80 to 95	70 to 85	95 to 98	90 to 95	95 to 98
Memory effect	Yes	No	No	No	No
Toxic material	Cadmium	Lead	Cobalt	None	Cobalt
Cycle life (cycles)	500 to 2000	300 to 1000	500 to 1000	2000 to 5000	1000 to 2000
Capital Expenditures (CapEx)	Moderate - High	Low	High	Moderate - High	High
Operating Expenditures (OpEx)	Moderate[5]	Moderate	Moderate[6]	Low	Moderate
Advantages	Low costs	Low costs	High Energy Density &	High thermal stability	High Energy Density &

[5] require regular maintenance, and disposal costs can be higher due to environmental concerns related to cadmium.
[6] short cycle life could cause high long-term replacement costs.

	Low maintenance Long cycle life Wide operating voltage, better performance in low or high temperature	Low maintenance	Specific Energy	High Power Density Longer life cycle compared to LCO and NMC Very low self-discharge rate Low OpEx and more affordable compared to other Li-ion batteries Environmentally friendly	Specific Energy Good balance between energy density, power output, and thermal stability
Limitations	Low energy density High self-discharge rate Suffer from memory effect	Low energy density Short cycle life Bulky size	Low thermal stability Short cycle life Cobalt content => High Cost & Environmental issues	Lower energy density compared to other Li-ion cells yet much higher than other cells namely Lead-Acid and Ni-Cd	Moderate thermal stability => a concern in high-power applications Moderate cycle life Cobalt content => High Cost & Environmental issues

		Sodium Sulfur (NaS)	Vanadium Redox Flow (VRFB)
Chemistry	Anode	Na	Liquid electrolyte solution containing vanadium ions in a low oxidation state, typically V(II) and V(III) ions
	Cathode	S	Liquid electrolyte solution containing vanadium ions, but in a high oxidation state, typically V(IV) and V(V) ions.
	Electrolyte	solid beta-alumina ceramic	aqueous solution of vanadium salts
Cell Voltage (V)	Nominal	2.0 to 2.1	1.0 to 1.4
	Open circuit	2.3 to 2.4	1.4 to 1.6
	Operating	1.8 to 2.3	0.8 to 1.4
	End	1.8	0.8

Operating Temperature (°C)	300 to 350 (original) 100 to 150 (new version)	-20 to 50
Specific Energy at 20°C (Wh/kg)	150 to 760[7]	25 to 35
Energy Density at 20°C (Wh/L)	300 to 500	15 to 25
Discharge Profile (Relative)	Flat with a noticeable decline in voltage as it approaches full discharge	**Exceptionally Flat** throughout the entire discharge process
Self-discharge rate at 20°C (% loss/month)	Less than 1	Less than 1
Charge acceptance rate (%)	85 to 95	70 to 90
Memory effect	No	No

[7] for high temperature version.

Toxic material	Potential[8]	Potential[9]
Cycle life (cycles)	2500 to 4500	10000 to more than 20000
Capital Expenditure (CapEx)	High	High
Operating Expenditures (OpEx)	Low[10]	Low
Advantages	High Energy Density Very low self-discharge rate Long cycle life	Very long cycle life Very flat discharge profile Very low self-discharge rate
Limitations	High operating temperature	Low energy density

[8] Na when contacts with water may cause fires or explosions. S presents environmental risks in the form of sulfur dioxide – SO_2 emissions.
[9] Vanadium compounds can be harmful to the environment and human health, particularly when inhaled or ingested.
[10] the high operating temperature requires additional infrastructure and maintenance to ensure proper functioning and safety, which can increase the overall operating costs.

	High CapEx Limited commercial availability Safety concern	High CapEx Bulky size Complex system design

Table 2. Comparison of major battery systems[11]

System	Weighting Constant[12]	Ni-Cd	VLRA	LCO	LFP	NMC	NaS	VRFB
Safety	8	4	3	2	5	3	2	4.5
Costs (CapEx + OpEx)[13]	7	3	5	2	3	2.5	3.5	2
Cycle life	6	2.5	2	2.5	4	3.5	4.5	5

[11] Rating on a scale of 5 with 5 being excellent.
[12] 1: least important, 8: most important
[13] 1: most expensive, 5: most affordable.

Low-Temperature Operation	5	4	3	2.5	4	2.5	1	4
Energy Density	4	2	2	4.5	3.5	5	3	1
Specific Energy	3	2	1.5	4.5	4	5	3	1
Charge retention (ability to hold a charge over time)	2	3	4	4.5	5	4.5	4.5	5
Charge acceptance (ability to receive a charge quickly)	2	4	3	4	3.5	4	3.5	2
Flatness of Discharge Profile	1	4	3	4.5	4.5	4.5	3.5	5
Overall		120	115.5	110.5	152.5	131.5	113	126

Table 2 suggests nine important factors to consider when selecting a battery as a means of storing energy for commercial buildings. The selected factors are referred from BSLBATT (2022). The prioritization of significance in Table 2 was illustrated via "Weighting Constant". This constant is used to assign a weight to each criterion, reflecting its relative importance in the decision-making process. The overall score for each battery type is the sum of the scores for each attribute, multiplied by the weighting constant for that attribute. This weighted scoring provides a more nuanced comparison, as it considers the varying significance of each attribute.

From a holistic perspective, it is evident that the Lithium Iron Phosphate (LFP) battery system scores the highest overall. It is the most balanced system, scoring high on safety (5), cycle life (4), charge retention (5), and flatness of discharge profile (4.5). It also offers reasonable performance in specific energy, energy density, and low-temperature operation, which are crucial for large energy storage applications in Finland's cold climate. The system's only significant drawback is its average cost score (3) and charge acceptance (3.5), which means it may be more expensive to implement and may not receive charge as quickly as some other systems. NMC battery system comes second, largely due to its high scores in specific energy and energy density. However, its lower scores in safety and low-temperature operation - both highly important attributes - make it less suitable than LFP for the Finnish climate. Other li-ion battery system – LCO receives lowest overall score due to its low performance in safety (2), costs (2), and low-temperature operation (2.5), which are critical criteria for the considered application in this thesis.

Ni-Cd perform well in safety, low-temperature operation, and charge acceptance. However, it scores lower in costs, cycle life, energy density, specific energy, and charge retention. Ni-Cd may be suitable for applications that prioritize safety and low-temperature performance, but its limitations in the other attributes may restrict its effectiveness for large real estate energy storage in Finland. VLRA scores highest in costs and charge retention but performs moderately in safety, low-temperature operation, charge acceptance, and flatness of discharge profile. Its low scores in cycle life, energy density, and specific energy suggest that it may not be the best option for large-scale energy storage in Finland. Regarding the NaS, it performs well in cycle life and charge retention but has a low score in low-temperature operation, which is a

significant concern for Finland's climate. It also has average scores in safety, costs, energy density, specific energy, and flatness of discharge profile. The low-temperature performance and safety concerns may limit the suitability of NaS batteries for the Finnish market.

Lastly, concerning VRFB, it performs exceptionally well in cycle life, charge retention, and flatness of discharge profile. It also has good scores in safety and low-temperature operation. However, it scores lower in costs, energy density, specific energy, and charge acceptance. Despite these limitations, the VRFB system's strengths in the most critical attributes (in the context of Finland) make it a competitive option for large real estate energy storage.

Based on the above analysation, ensuing sections delve into an in-depth analysis of LFP.

3.4 Lithium iron phosphate (LFP)

3.4.1 General Characteristics

The Lithium Iron Phosphate (LFP) batteries have gained significant recognition for their utilization in renewable energy storage, electric vehicles, and portable electronics since their inception in the late 1990s. Lithium Iron Phosphate (LFP) batteries have gained recognition for their efficient and economical charging capabilities, leading to a transformation in the battery and electric vehicle (EV) industries across Europe and North America. (Clemens, 2023)

LFP batteries are noted for their durability, superior thermal stability, and extensive cycle life, largely attributable to the usage of iron phosphate in the cathode material. As a safer alternative to conventional lithium-ion batteries, LFP technology harnesses lithium iron phosphate $LiFePO_4$ as the cathode, mitigating the risk of severe issues such as thermal runaway, which are commonly associated with traditional lithium-ion batteries as analysed in section 3.3.2. The primary determinant of LFP batteries' capacity is the amount of cathode material, unlike other lithium-ion batteries where it is largely the electrolyte. This configuration allows for redox reactions during charging and discharging to take place chiefly at the cathode, with lithium ions migrating between the cathode and anode. Consequently, this results in high stability, extended cycle life, and exceptional thermal performance.

LFP batteries are typically available in prismatic or cylindrical forms. The prismatic form is generally more space-efficient and easier to assemble into battery packs, while the cylindrical form can be more durable and better at dissipating heat. Both designs make use of a liquid electrolyte, allowing for fast ion transport and efficient charge/discharge processes. LFP batteries, in their cylindrical form, are commonly chosen for small energy storage power battery packs (portable electronic devices, power tools, electric bikes, and small-scale solar energy storage systems, which have a capacity in the range of a few Wh to a few kWh). One of the rationales could be the cylindrical design allows for easy combination and flexible structuring. The cylindrical form factor allows for various configurations and arrangements, making it easier to create custom battery packs that fit the specific dimensions and energy requirements of a variety of small devices and applications. In addition, as mentioned above, it allows for better heat dissipation compared to other form factors. The inherent gaps between the cells in a pack allow for more efficient airflow and cooling, which can significantly improve the longevity and safety of the battery pack, particularly in high-drain devices like power tools and electric bikes. (Brava Batteries, n.d.)

Conversely, medium and large energy storage power battery packs often implement prismatic LFP batteries. Medium energy storage systems are applications such as electric vehicles, larger solar energy storage systems, and small-scale stationary energy storage (for instance, residential energy storage systems). Their capacity tends to range from several kWh to a few hundred kWh. Large energy storage power battery packs commonly refer to applications such as grid energy storage, large industrial backup power systems, and utility-scale renewable energy storage. They have capacities that are typically in the MWh range, sometimes even reaching GWh for very large installations. Further analysis in terms of the prismatic LFP battery performance characteristics is covered from section 3.4.2 to section 3.4.4 since this thesis is concerned with medium energy storage power battery packs for energy storage in real estate. The primary advantage of employing prismatic batteries is that they possess larger capacities. When creating a large LFP battery pack, fewer battery cells are needed, resulting in improved consistency throughout the battery pack, simplifying the design and potentially lowering costs. Prismatic cells are generally more space-efficient than cylindrical cells, as they can be packed more closely together without leaving any wasted space. This can be particularly important in medium and large energy storage applications where space might be at a

premium. Furthermore, prismatic LFP batteries exhibit excellent scalability characteristics, providing a high degree of flexibility for larger energy storage systems. They can be arranged and connected in a multitude of configurations, thereby accommodating specific voltage and capacity requirements. This ability to be easily tailored to the specific needs of a medium or large energy storage system greatly enhances their appeal for these applications. (Brava Batteries, n.d.).

While LFP technology yields several merits, it could not be devoid of limitations. The energy density of LFP batteries is usually lower than other lithium-ion chemistries, like lithium cobalt oxide, making LFP batteries heavier and larger for an equivalent capacity. Extreme temperatures can also affect their performance, despite a wide operating temperature range. The advantages and drawbacks of LFP technology compared to other lithium-ion technologies are comprehensively presented in Table 3 deduced by the author from the analysis made in section 3.3.2.

Table 3. Pros and Cons of LFP battery compared to other lithium-ion batteries

Pros	**Cons**
Long Cycle Life: LFP batteries typically offer a longer cycle life compared to other lithium-ion chemistries as discussed in section 3.3.2. This provides superior longevity and dependability in applications that require frequent charging and discharging. **High Thermal Stability:** LFP batteries maintain their performance across a wider temperature range compared to other lithium-ion batteries. They can operate safely even in high-temperature conditions. **Safety**: The thermal and chemical stability of the LFP cathode material minimizes the risk of battery failure, fire, and explosion. Unlike	**Energy Density:** Given that space can be a limiting factor, especially in urban areas, the lower energy density of LFP batteries could require more space for the same storage capacity compared to other lithium-ion technologies. However, this must be balanced against the safety benefits of LFP technology.

other lithium-ion technologies, LFP batteries are much less prone to thermal runaway. **Environmental Impact:** The key materials in LFP batteries (iron and phosphate) are non-toxic and abundant, making these batteries a more environmentally friendly option. In contrast, other lithium-ion chemistries often use scarce or hazardous materials.	

3.4.2 Charge and Discharge Ratings

According to Bretscher (2015), prismatic LFP cells were previously rated for charge at up to 1-2C and discharge up to 3C, implying a theoretical charging duration of 30 minutes and discharging duration of 20 minutes. However, high current throughput for extended periods, particularly during charging, can accelerate wear and damage, especially at lower temperatures. Long-term, sustainable operation usually requires a charge and discharge rate of around 0.3C. Certain new-generation LFP batteries, encased in aluminum, could offer a rating of 0.5C, allowing for a minimal sustainable charging time of approximately 2.5 hours when absorption is included. Consequently, it may be necessary to limit charging currents to avoid oversizing alternators or chargers. Table 4 shows suggested operating specifications for $LiFePO_4$ prismatic cells as per Bretscher (2015).

Table 4. Suggested operating specifications for LFP prismatic cells (Bretscher, 2015)

Charging	Max. charge voltage(V)	3.65
	Suggested charge current (C)	0.3
	Max. charge current (C)	1 – 2

	Cut-off current (C)	0.033
	Charging temperature range (^{o}C)	0 – 45
Discharging	Min. discharge voltage (V)	2.5
	Suggested discharge current (C)	0.3
	Max. discharge current (C)	2 – 3
	Discharge temperature range (^{o}C)	-20 – 55
State Of Charge (SOC)	Suggested operating window	10 – 90% SOC

As detailed in Table 4, the upper limit for charge voltage in LFP batteries is suggested to be 3.65V, any beyond which could pose a risk of being overcharged, potentially causing a reduction in the cell's operational lifespan or even safety issues. The rate at which these cells should ideally be charged is termed as the charge current, recommended at 0.3C. This suggests that the charging current should be 30% of the cell's rated capacity to promote health and longevity. Although it is possible to charge at a higher rate, with the maximum charge current defined as 1-2C, it's generally discouraged as higher charge rates can cause increased stress on the battery cells, thereby affecting their longevity and reliability. An equally important aspect is the cut-off current, which has been specified as 0.033C. This value is the

threshold at which the battery is considered fully charged during the constant voltage phase of charging. The charging process should be terminated at this point to avoid overcharging. Another factor to consider is the charging temperature range spanning from 0°C to 45°C. Charging within this range is critical as charging at temperatures outside this range could cause the battery to malfunction or lead to permanent damage. In the context of discharging, the minimum discharge voltage for these cells is 2.5V. In addition, a recommended discharge current of 0.3C is specified, suggesting that discharging at a rate of 30% of the cell's capacity is ideal for optimal battery life. Although the maximum discharge current is given as 2-3C, it is advisable to avoid regularly discharging at this high rate to prevent undue stress on the battery. The operational temperature range for discharging is wider than that for charging, spanning from -20°C to 55°C. Operating within this temperature range is necessary to ensure the safe and efficient discharge of the battery. Regarding SoC, it is recommended to keep the LFP battery within a 10-90% SoC window to significantly extend the battery's lifespan. Constantly charging to 100% SoC or discharging to 0% could strain the battery and shorten its useful life.

3.4.3 Battery Capacity

According to Bretscher (2015), in terms of LiFePO4 batteries, Peukert's effect becomes increasingly noticeable when temperatures drop below 15°C, manifesting as reduced available capacity. In practical applications with LFP batteries, the Peukert's constant (n) is experimented to have a value of 1.04 at moderate temperatures. As discussed in section 3.1.4, if n is close to 1, the battery's capacity is not greatly affected by the discharge rate. However, the accuracy of this calculation could be impacted by temperature variations, as the calculation does not consider them. Large temperature swings, such as those experienced from winter to summer, could significantly affect the calculation. In addition, it should be noticed that Peukert's Law was initially designed for Lead Acid battery, so there could be inconsistencies due to the variable nature of the n constant with lithium-ion chemistry. LFP batteries and lead-acid batteries are rated differently in terms of their capacity. For LFP batteries, their capacity is often measured at higher discharge rates, such as over 2 hours (0.5C) or over about 3 hours (0.3C). On the other hand, the capacity of lead-acid batteries is usually measured over 20 hours (C/20). This means that if a LFP battery is discharged at a

slower rate than it is rated for, it will exceed its rated capacity. Table 5 illustrates effects of discharging a LFP battery at a slower rate than it is typically rated for, as a consequence of Peukert's Law.

Table 5. Effects of discharging a LFP battery at a slower rated capacity (Bretscher, 2015)

Rated capacity at 0.5C	**Discharge current at C/20**	**Effectively available capacity**
100Ah	5A	109.6Ah
200Ah	10A	219.2Ah
300Ah	15A	328.8Ah
400Ah	20A	438.4Ah

It is evident in Table 5 that there is an obvious enhance in capacity of the battery when being discharged at slower rate. A 100Ah battery at a C/20 discharge rate would provide an effective capacity of 109.6Ah. This increased effective capacity can have a significant impact, especially when large battery systems are utilized.

3.4.4 Low Temperature Effects

As analysed in above sections, LFP batteries provide less capacity as temperatures drop. This is due to lithium ions have difficulty moving out of the graphite in the cold, effectively locking some of the capacity inside. Lower temperatures also mean the battery reaches its discharge cut-off voltage sooner, leaving a portion of the capacity unused. The cut-off voltage is

essentially the point at which the battery is considered "empty" and should stop discharging to prevent damage. Table 6 shows the available capacity (C) of a LFP battery changes with temperature and the cut-off voltage.

Table 6. Relations between the available capacity (C) of a LFP battery changes with temperature and the cut-off voltage (Bretscher, 2015)

Temperature	**Cut-off voltage = 2.5V**	**Cut-off voltage = 2V**
25°C	C = 100%	
15°C	C = 98%	
0°C	C = 90%	
-10°C	C = 74.5%	C = 87%
-20°C	C = 56%	C = 72%

From Table 6, it is evident that as the temperature decreases, the available capacity of the battery also decreases. However, by using a lower cut-off voltage, some of the capacity lost due to the cold temperature could be regained. This is because at lower temperatures, the battery's voltage experiences a steeper decline. Consequently, by lowering the cut-off voltage, a greater proportion of the battery's capacity can be utilized prior to reaching the "empty" point. This, however, comes with a caveat that it may lead to deeper discharges, which can potentially impact the long-term health and lifespan of the battery.

During charging processes, cold temperatures exert deleterious effects on LFP batteries. When these batteries are being charged and the temperature drops below a certain level, they can lose their capacity to hold a charge more quickly. This temperature limit is usually considered to be 0^{o}C, but it can vary depending on different factors. In cold environment, lithium ions may fail to enter the graphite, causing them to build up on the surface of the graphite. This build-up is called lithium plating and it leads to a permanent loss of lithium ions, which reduces the overall capacity of the battery. This problem becomes even more serious when the battery is being charged quickly. Fast charging speeds up the movement of lithium ions, but in cold temperatures where the intercalation process is already impaired, the lithium ions are more likely to get stuck and not enter the graphite, resulting in more lithium plating. Therefore, it is believed that fast charging and low temperatures together can cause more damage to LFP batteries, leading to a loss of capacity and a shorter lifespan for the battery.

4 Electricity markets

Before BESS could be used in the Finnish power system, a determination must be made regarding the optimal segment of the Nordic electricity market in which to deploy it. Nordic electricity market is an open and neutral marketplace where electricity prices are determined by supply and demand. The market is classified into three segments, aptly referred as Financial Market, Physical Market, and Reserve Market.

4.1 Financial Markets

These markets deal with something called derivatives. Derivatives are financial contracts, whose valuation derives from an underlying entity (in this case, electricity prices). These contracts are traded on the Nasdaq OMX Commodities financial markets. Remarkably, there is no physical exchange of electricity within these markets. Rather, participants engage in the buying and selling of contracts representing the electricity. When these contracts are settled, monetary transactions occur without any corresponding delivery of electricity. This type of market serves two main purposes:

Risk Management: The purchase and sale of these contracts provide an effective mechanism for individuals to manage the financial risk associated with fluctuations in electricity prices.

Price Hedging: People can protect themselves from potential future changes in electricity prices. For instance, if there is an anticipation of a price surge, a contract can be procured at the present rate allowing for the acquisition of electricity at the current price, irrespective of any future escalation in the actual price.

The contracts transacted within these markets can span diverse time frames, ranging from as short as a day to as long as six years. They can be designed to cover various durations including a day, a week, a month, a quarter, or a year. The price used for these contracts is based on the Elspot system price from the physical market of Nord Pool, which is an actual market for electricity in the Nordic region.

4.2 Physical Markets

These markets facilitate actual trading and delivering of electricity. In the Nordic region, the trading transpires via Nord Pool, which is owned by the Nordic TSOs. Nord Pool has two trading mechanisms: the day-ahead market known as Elspot, and the intraday market referred to as Elbas (Partanen et al., 2014).

Day-Ahead Market (Elspot): This is where contracts are made for the delivery of electricity for the next day. It is called "day-ahead" because the contracts are made a day before the actual delivery of electricity.

Intraday Market (Elbas): This is a market where electricity is traded on the same day it is delivered. It is used for making adjustments if there are sudden changes in electricity demand or supply after the day-ahead market has closed.

Both these markets have different demands, prices, and technical requirements, which vary depending on what the electricity producers are trying to achieve.

4.3 Fingrid's Reserve Markets

Electricity is exchanged primarily via the physical markets, yet they alone could not always regulate and maintain grid frequency around 50 Hz. This is where "reserve markets" come in. Reserve markets are designed to manage the small, rapid fluctuations in electricity supply and demand that occur constantly throughout the day. They exist to ensure that the balance of supply and demand is maintained, and that the frequency of the power grid remains stable at its target level (50 Hz).

As per System Operation Agreement established by the joint Nordic power system, each country's TSO is responsible for maintaining and balancing their reserves. TSO is a company that operates the high-voltage electricity grid in a country or a region. In Finland, Fingrid is the only entity authorized to function as a TSO (*Reserves and Balancing Power*, n.d.). The reserve obligations as stipulated by Fingrid can be referred to in Appendix 2.

According to Fingrid (2023, p. 4), reserve markets are classified into three distinct categories namely Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR), and Replacement Reserve (RR), as shown in Figure 5. However, it should be noticed that the RR is not implemented in the Nordic power system, and consequently, it is not a subject of consideration in this thesis.

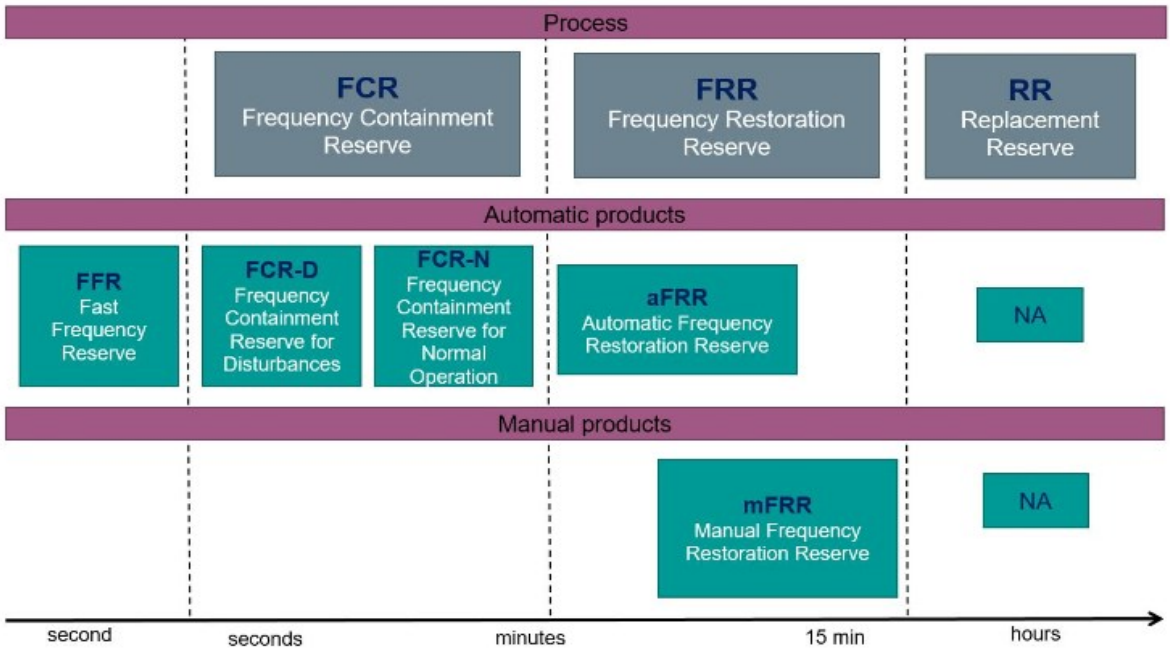


Figure 5. Reserves used in the Nordic countries (Fingrid, 2023, p. 4)

Regarding FFR, it is primarily needed to address disturbances in low inertia situations, which typically occur during spring, summer, and autumn. Specifically, there is increased demand for FFR during weekends and night-time periods. In addition, according to Fingrid (2023, p. 7), the need for FFR is strongly influenced by the hydrological situation in the Nordics. This suggests that the availability and capacity requirements of FFR may vary based on the water levels and conditions in hydroelectric power systems.

FFR requires a very fast response in case of a large underfrequency event. The response time is specified as 1.3 seconds at a frequency of 49.7 Hz, 1.0 second at 49.6 Hz, or 0.7 seconds at 49.5 Hz. These response times highlight the need for immediate action to restore grid frequency. The minimum duration of FFR activation is specified as 5 seconds if the deactivation speed is within a maximum of 20% of the FFR capacity per second. If the deactivation speed exceeds this threshold, the minimum duration is extended to 30 seconds. This requirement ensures the stability and reliability of the grid during FFR operations. (Fingrid, 2023, p. 7)

FFR is procured on a daily basis through the national hourly market, taking into account the forecasted inertia. Capacity payments are based on the availability of FFR. The price level for FFR in the market is stated to be in the range of dozens of euros per megawatt-hour (€/MWh). When participating in the FFR procurement process, the minimum bid size is specified as 1 megawatt (MW). This indicates that participants must offer a minimum capacity of 1 MW when bidding for FFR contracts. (Fingrid, 2023, p. 7)

Fingrid procures two separate markets for FCR-N and FCR-D. In each market, long-term (yearly) and short-term (hourly) agreements are possible. Participation in the hourly market is independent of participation in the yearly market and can take place in the middle of the calendar year, while participating in the yearly market is not possible in the middle of the year. Table 7 outlines the primary differences between the yearly and hourly markets. Table 8 was derived by the author from the data presented in Table 7, with the aim of analysing the advantages and disadvantages of each market.

Table 7. Differences between the annual and hourly markets (Fingrid, 2023, p. 11)

Yearly market	Hourly market
Bidding competition organised once a year (autumn).	A reserve provider can participate in the hourly market by making a separate agreement with Fingrid. This does not require making a yearly agreement.
In the middle of a contractual period, it is not possible to enter by making a yearly agreement for reserve maintenance.	Possible to enter the hourly market even in the middle of the year.
The amount based on reserve plans is bought in total.	TSO buys only required amount of reserve.
Reserve plans must be submitted the previous day by 6 pm (EET).	Bids for the hours in the following 24-hour period must be submitted by 6.30 pm (EET).
The reserve provider is obliged to maintain the reserve it sells to the yearly market within the framework of its free capacity after day-ahead market.	Reserve providers may submit daily offers for their reserve capacity. A provider that has a yearly agreement may participate in the hourly market only if it has supplied the reserve amount specified in the yearly agreement in full.
Fixed price is valid throughout the year. This is set based on the most expensive bid approved for the yearly market.	Payment is set based on the most expensive bid used separately for each hour.

Table 8. Pros and Cons of Yearly and Hourly Markets

	Pros	Cons
Yearly Market	**Stability:** Participants in the yearly market can secure contracts for the entire year, providing stability and assurance of revenue. **Long-Term Planning:** Providers can plan their reserve capacity availability and resources well in advance based on the contracted volumes. **Fixed Price:** The fixed price established in the yearly market provides price certainty for the contracted reserve capacity.	**Limited Flexibility:** Once providers have committed their capacity to the yearly market, they cannot offer it in the hourly market, limiting their flexibility to respond to changing market conditions. **Contract Duration:** Providers are locked into contracts for the entire year, which may not align with their operational or strategic preferences. **Potential Overcommitment:** Providers may face challenges if they overcommit their capacity in the yearly market and are unable to meet other market demands or operational requirements.
Hourly Market	**Flexibility:** Participants in the hourly market have the flexibility to enter and offer their reserve capacity at any time during the year, allowing them to respond to dynamic market conditions. **Real-Time Demand:** Providers can offer reserve capacity based on real-time market demand, ensuring their capacity is utilized when needed. **Price Variability:** Hourly market prices can vary based on the highest accepted bid for each specific hour, potentially	**Uncertain Demand:** Providers in the hourly market may face uncertainty regarding the actual procurement of their reserve capacity, as purchases are made based on system needs and availability. **Operational Challenges:** Providers need to actively monitor the market and submit bids on a daily basis, which may require additional resources and operational attention. **Price Fluctuations:** Hourly market prices can be more volatile compared to the fixed price in the yearly market,

	providing opportunities for higher prices during periods of high demand.	potentially leading to lower revenue or less predictable income.

Concerning FCR-D, it activates linearly in response to larger frequency deviations. The activation speed is specified as 50% within 5 seconds and 100% within 30 seconds. This means that the reserve gradually ramps up its response to match the severity of the frequency deviation. FCR-D is divided into two products: FCR-D up and FCR-D down. FCR-D up involves power plants increasing production and loads reducing consumption to help raise the frequency back to the desired level. On the other hand, FCR-D down involves power plants decreasing production and loads increasing consumption to lower the frequency. The activation of FCR-D is based on local frequency measurements. When the local frequency deviates significantly, the automatic control system triggers the appropriate response in the FCR-D reserves. When participating in the FCR-D procurement process, the minimum bid size is specified as 1 MW. This means that participants must offer a minimum capacity of 1 MW when bidding for FCR-D contracts. (Fingrid, 2023, p. 8)

While FCR-D addresses disturbances and larger frequency deviations with separate upregulation and downregulation products, FCR-N focuses on maintaining grid stability during normal operations. FCR-N continuously activates within the standard frequency range, which means it remains operational to maintain grid stability during normal operations. The activation speed is specified as 100% within 3 minutes, indicating that the reserve power ramps up or down fully within this timeframe to address any frequency deviations. FCR-N is a symmetrical product, meaning it must be capable of both increasing and decreasing power output. This flexibility allows it to respond to frequency deviations in either direction to help maintain grid stability. FCR-N is automatically controlled based on local frequency measurements. When the local frequency deviates from the standard range, the automatic control system triggers the necessary adjustments in the FCR-N reserves. When participating in the FCR-N procurement process, the minimum bid size is specified as 0.1 MW. This means that participants must offer a minimum capacity of 0.1 MW when bidding for FCR-N contracts. This lower minimum bid size allows for more flexibility and participation from smaller-scale energy resources. (Fingrid, 2023, p. 9)

In summary, Figure 6 provides a consolidated view of the diverse reserve products, their respective capacities, and activation times within both Finnish and Nordic power systems. It emphasizes the variations in activation rates and usage scenarios to determine the distinct roles of each reserve type. This data is vital in assessing the appropriate reserve products for the deployment of BESS, which is further discussed in the ensuing section.

Figure 6. Fingrid's reserve product comparision (Fingrid, 2023, p. 5)

4.4 Appropriateness evaluation of BESS in the electricity markets

Regarding the financial markets, BESS do not play a direct role in them. This is primarily because these markets focus on financial transactions associated with electricity prices, rather than the tangible supply and demand of electricity, an area where batteries play a pivotal role.

Regarding physical markets, BESS may encounter challenges in achieving profitability in these markets due to the following factors.

Price Competition: The fierce competition usually experienced in these markets can sustain relatively low prices.

Hierarchy of Generation Costs: The sequence of energy sources utilized is typically dictated by production costs, with the most cost-effective sources employed first. BESS may not compete effectively in terms of cost with other sources, like wind, nuclear, and Combined Heat and Power (CHP) electricity, which underpin the physical power markets.

Price Volatility: The price discrepancy between periods of low and high demand might not be substantial enough to make the trading process profitable for a BESS.

Size Limitations: The significant volumes of energy typically traded in physical markets may surpass the storage capacity of batteries.

Nevertheless, BESS could be more suitable for reserve markets, wherein they provide a power reserve which could be quickly dispatched when necessary. The more demanding the operational requirements, the fewer reserve units capable of meeting them, and thus, the higher the potential compensation.

As per Fingrid (2023), BESS is particularly suited to offer reserves requiring rapid response times albeit for limited activation durations. This aspect aligns well with the needs of FFR and FCR-D, both of which demand rapid activation—in a second and in seconds, respectively. In terms of FFR, BESS can rapidly adjust its output in response to significant frequency deviations and low inertia situations, enabling it to handle rapid changes in grid conditions. Meanwhile, for FCR-D, BESS could also quickly respond to significant frequency deviations, thus aiding in maintaining the stability of the power grid. FCR-N can also be a viable market for BESS, yet its suitability hinges upon the sufficiency of the energy reservoir. Given that FCR-N is used all the time and thus may demand prolonged periods of energy supply, the limited energy storage capacity of BESS could pose a challenge. Hence, energy sufficiency, particularly the battery's state of charge, becomes a critical consideration for this reserve type.

The slower response times of aFRR and mFRR, along with their less frequent usage compared to FCR-N, may make them less suited for BESS. Specifically, aFRR and mFRR require activation in five and fifteen minutes, respectively, which is relatively longer compared to the fast response times that BESS is known for. Moreover, aFRR and mFRR are not used continuously, but rather, they are activated if necessary. This intermittent usage may not align well with the

operational characteristics of BESS, which can deliver the most value when its fast response times are fully utilized.

In summary, Figure 7 suggests appropriate technologies for each reserve products. The suggestions were made by Fingrid (2023).

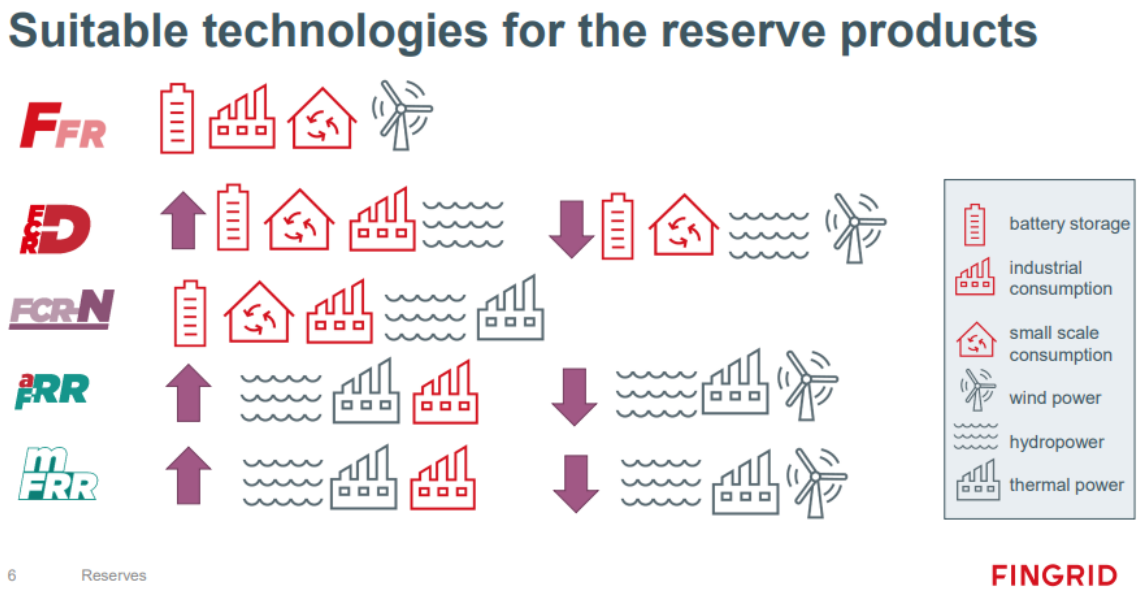


Figure 7. Suitable technologies for Fingrid's reserve products (Fingrid, 2023, p. 6)

To have a full picture about the most beneficial reserve product for BESS operations, a quantitative comparison was conducted. The comparison compares FCR-N, FCR-D, and FFR based on measurable quantities such as price (€/MW), volume (MW), and received bids (MW).

From the data provided by Fingrid. (n.d.), it could be noticed that FCR-N consistently commands a higher price per MW,h as compared to FCR-D up. This price differential means the BESS would potentially earn more revenue providing FCR-N, assuming it can meet the activation speed and usage requirements. The FCR-D down market also has a significant price, but the data is only available for 2022 and 2023. It is higher than FCR-D up but less than FCR-N. Concerning the volume facet, FCR-D up generally has a larger volume (greater demand) than FCR-N, implying that there could be more opportunities for the BESS to be utilized. However, FCR-N has also shown increasing volume demand over the years, suggesting a

growing market. The price and volume for FCR-N seem to be less volatile compared to FCR-D up, which might be preferable for a stable return-on-investment calculation for a BESS. FCR-N is utilized all the time, whereas FCR-D is activated in large frequency deviations. This means the BESS might experience more wear and tear if used for FCR-N, impacting its lifespan. However, the higher price per MW,h for FCR-N might compensate for this aspect. Considering these points, it seems that FCR-N could be a more beneficial option compared to FCR-D for a BESS in real estate due to higher prices per MW,h and relatively stable demand.

Given the established significance of FCR-N, it would be equally important to ascertain whether the FCR-N yearly or the FCR-N hourly market is more advantageous. Data from Fingrid. (n.d.) suggests that the average price in the FCR-N hourly market (€41.09/MW) is considerably higher than the average price in the FCR-N yearly market (ranging from €9.97/MW,h to €19.10/MW,h, with a maximum in 2023 at €19.10/MW,h). This indicates that if the BESS can capture this average price, it could potentially earn more in the hourly market. The average volume of frequency-controlled normal reserve in the hourly market is 30 MW, less than the volume range in the yearly market (67.7 MW to 105.8 MW), suggesting that there could be more opportunities to sell reserves in the yearly market. However, the BESS may not always be able to fully utilize the higher volume in the yearly market due to capacity or other constraints. Furthermore, The FCR-N hourly market has periods where the volume is 0 MW, meaning the BESS might not be used during these times. While this would result in fewer earnings, it could also mean less wear and tear on the BESS, potentially prolonging its useful life. In contrast, in the yearly market, the BESS might be used more frequently or even constantly, leading to higher wear and tear. Given these factors, if the primary aim is to maximize revenue and the BESS has a robust construction and sufficient energy reservoir to handle regular use, the FCR-N hourly market could be more beneficial due to the higher average prices. However, if the goal is to balance earnings with the longevity of the BESS, the FCR-N yearly market might be more appropriate due to its relatively stable demand and potentially less intensive usage pattern.

Lastly, by considering the data from Fingrid. (n.d.), it could be concluded whether the FFR market holds more potential benefits than the FCR-N hourly market. The average price in the FFR market is €29/MW, which is less than the average price in the FCR-N hourly market

(€41.09/MW). This indicates that from a price perspective, the FCR-N hourly market might be more beneficial. In terms of procured volume, the FFR market averages at 3 MW, a figure significantly lower than the average volume of frequency-controlled normal reserve in the FCR-N hourly market (30 MW). This suggests there might be fewer opportunities for reserve provision in the FFR market compared to the FCR-N hourly market. The average received bids in the FFR market is 23 MW, which is less than the received bids in the FCR-N hourly market (93 MW). This might imply less competition in the FFR market, but again, it also signifies less volume of demand. Based on these comparisons, it appears that the FCR-N hourly market might provide better profitability opportunities for a BESS in real estate compared to the FFR market. The higher average prices and volumes in the FCR-N hourly market make it more attractive for BESS.

In conclusion, within Fingrid's offered reserve products, the FCR-N hourly market best encapsulates the strengths of battery technology and presents the most promising prospects for BESS in the real estate sector.

4.5 Appropriateness evaluation of specific battery types within Fingrid's reserve markets

This section extends the previous discussion in section 4.4 by focusing on the appropriateness of specific battery types within Fingrid's reserve markets. The unique characteristics of each battery, as investigated in section 3.3.2, determine its suitability for various markets. For example, the section 4.4 noted that FCR-N hourly market might be beneficial for a BESS due to higher average prices and volumes and the BESS's fast response times. For instance, from the analysation in section 3.3.2, it could be deduced that lithium-ion (LFP, NMC, and LCO) batteries, which are known for their quick response times, could potentially excel in the FCR-N hourly market. On the other hand, batteries such as Ni-Cd, which have a lower energy density, might struggle in FCR-D and FFR due to their energy limitations. Comprehensive evaluation on the appropriateness of each battery type with respect to Fingrid's reserve markets is shown in Table 9. The author derived this table from the data discussed in sections 3.3.2 and 4.3.

Table 9. Comprehensive evaluation on the appropriateness of each battery type with respect to Fingrid's reserve markets[14]

	FCR-N	FCR-D & FCR-D down	FFR	Remarks
Lithium-ion (LFP, NMC, LCO)	5	5	5	Good energy density, power, safety, and life cycle. Their rapid response time and ability to handle high power loads makes them highly suitable for all reserve markets.
VRFB	3	3	4	Excellent cycle life and steady power delivery, but their low energy density and slower charge acceptance rate compared to other types of batteries may limit their suitability, especially for markets requiring fast charging or high energy capacity. They are more suitable for FFR as it does not require a high energy density
Ni-Cd	3	3	3	Long life span, good charge acceptance, and reliable performance even in cold conditions. However, they have lower energy density compared to lithium-ion batteries, which may limit their suitability in markets requiring high energy capacity. Ni-Cd batteries are susceptible to the "memory effect", which can limit their

[14] Rating on a scale of 5 with 5 being excellent.

				performance over time if not managed properly.
NaS	3	3	3	High energy density and can provide power for extended periods, but the high operating temperatures limit their applicability, especially in Finland
VRLA	2	2	3	Lack the cycling capabilities, charge/discharge rates, and energy density. Fingrid's FCR-N and FCR-D markets may require frequent charge-discharge cycles, the limited cycling capability of VRLA batteries might make them less suitable for these markets. Struggle to meet the requirements of the FCR-N and FCR-D markets, which require rapid and sustained responses to power demand changes. The FFR market usually requires a faster response but for a shorter duration compared to the FCR markets. Since VRLA batteries can provide high surge currents, they could meet the fast response requirements of the FFR market.

5 Smart Readiness Indicator (SRI)

5.1 Overview of SRI

The Smart Readiness Indicator (SRI) first appeared in the 2018 revision of the Energy Performance of Buildings Directive - EPBD (European Parliament and Council of the European Union, 2018), marking an effort to unify the approach of EU countries towards evaluating the smart readiness of their real estate sector. It could be said that SRI was introduced to encourage the adoption of smart energy-efficient technologies and to stimulate building renovation investments in Europe. (European Commission, 2022, p. 5)

SRI is a framework designed to assess a building's capacity for optimal energy efficiency and performance, adaptability to grid signals (energy flexibility), and responsiveness to owners' needs (European Commission, 2022, p. 5). The overall structure of SRI scheme includes nine domains, seven impact criterion, three SRI key functionalities as illustrated in Figure 8.

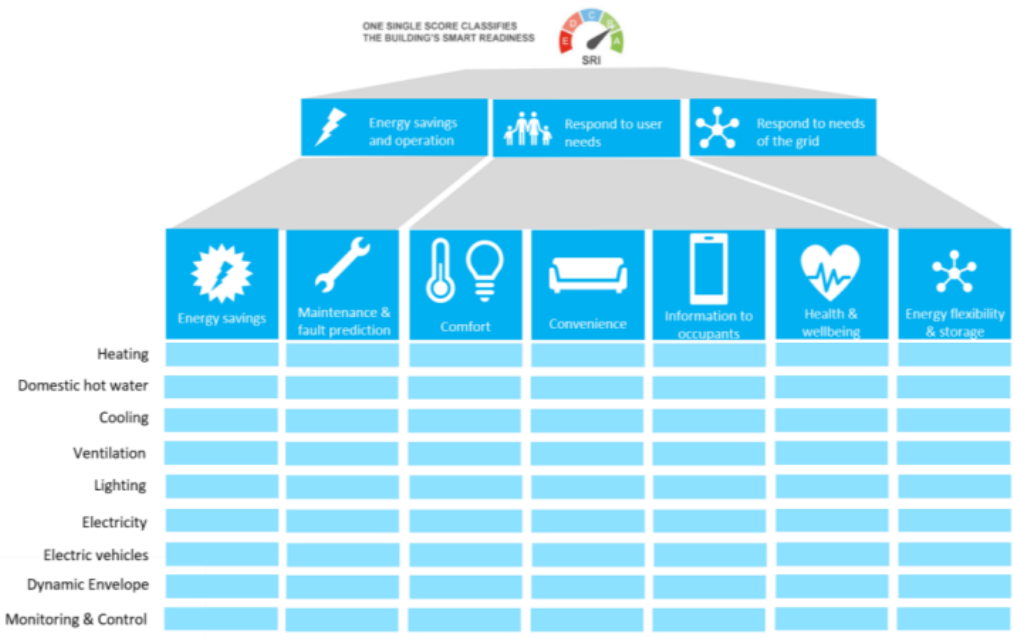
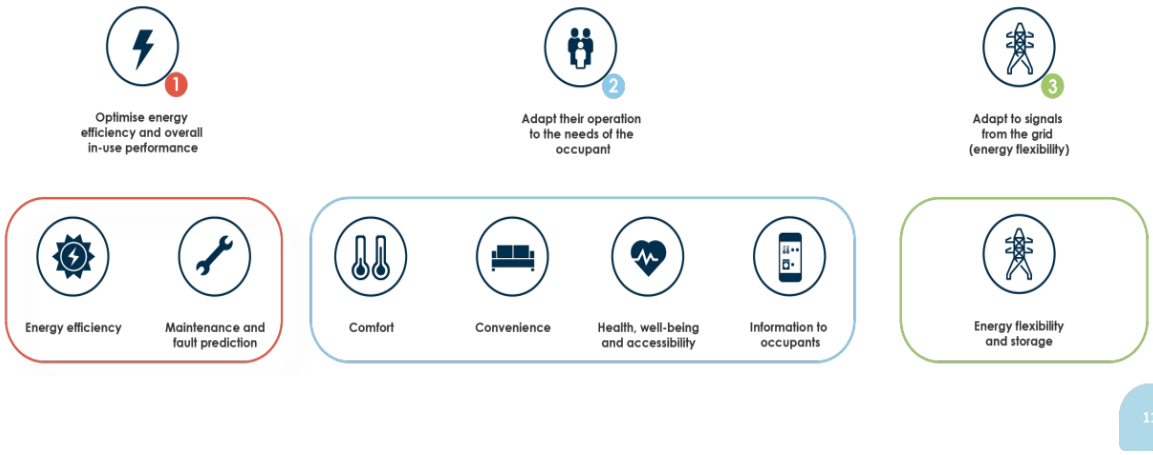


Figure 8. Framework of SRI scheme (Verbeke, Aerts, Reynders, Ma, & Waide, 2020, p. 20)

As shown in Figure 8, on the top level, SRI revolves around three key functionalities, which could be further encompass seven impact criteria. Figure 9 depicts the interrelations between the key functionalities and impact criteria as stated by the European Commission (2022, p. 11).

Figure 9. Interrelations between the key functionalities and impact criteria (European Commission, 2022, p. 11)



Energy savings and maintenance: The building's ability to maintain energy performance by adjusting energy consumption. This functionality correlates to “Energy Savings” and “Maintenance and fault prediction”. The impact criterion “Energy Savings” means the service's capability to save energy, for instance, through better control of room temperature settings, while “Maintenance and fault prediction” refers the potential of the service to improve the operation of the technical building systems.

Comfort, ease & wellbeing: The capacity to sustain healthy indoor conditions, by adapting operational modes based on the occupants' needs and providing reports on energy usage. This functionality is associated with "Comfort", "Convenience", "Health and well-being", and "Information to occupants". "Comfort" implies conscious and unconscious perception of the physical environment, including thermal, acoustic, and visual comfort. “Convenience” indicates services that simplify life for the occupant, such

as systems that require fewer manual interactions. “Health and well-being” determine smarter controls that improve indoor air quality compared to traditional controls. Lastly, “Information to occupants” pertains to the provisions of information about the operation of the building.

Grid flexibility: The capability to adjust the building's overall electricity demand to accommodate fluctuations in the power grid. This functionality ties to "Grid flexibility and storage" criterion. The criterion indicates a building's potential to flexibly use and store energy in relation to the power grid such as electricity grids or district heating.

These impact criteria impact a total of 54 smart-ready services within nine technical domains: heating, domestic hot water (DHW), cooling, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control. Details of the 54 services are shown in Appendix 1. Each service can exhibit varying degrees of smartness or "functionality levels" (0 to 4). A higher functionality level signifies a smarter implementation of the service, which yields more beneficial impacts for the building. For each functionality level, an “impact score” is assigned to quantify potential impacts on the building across each impact criterion. The impact score typically ranges from 0 to 3, where a higher score represents a greater positive impact. While most impact scores are positive indicating beneficial outcomes, some could also be negative if the functionality level has potential downsides. For example, uncontrolled charging of batteries might have a negative impact on the grid flexibility criterion.

5.2 Assessment Methodologies

The time required for a SRI assessment is closely tied to the complexity of the SRI definition, which reflects the complexity and diversity of the smart services present in the building. To cater to this diversity and different user requirements, three broad types of SRI assessments were suggested by Verbeke, Aerts, Reynders, Ma, & Waide (2020, p. 15) as illustrated in Figure 10.

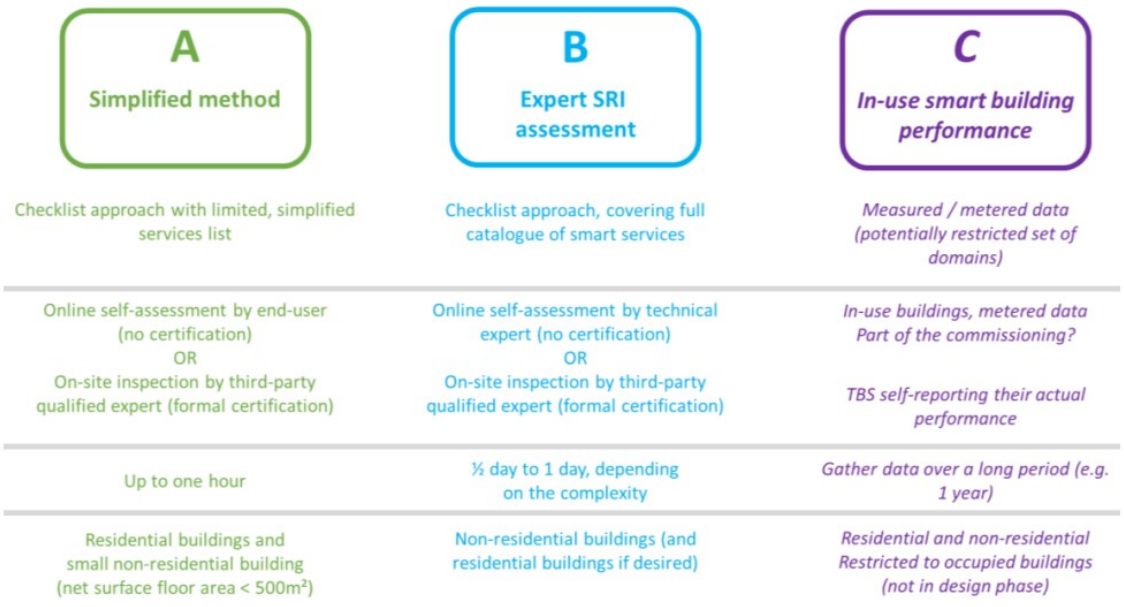


Figure 10. SRI Assessment Methods (Verbeke, Aerts, Reynders, Ma, & Waide, 2020, p. 15)

Method A is basically a simplified version of Method B. This method is particularly suited to residential buildings and small non-residential buildings. It utilizes a checklist approach and assesses a limited or simplified list of services. As a result, it is rather fast - typically, an assessment of a single-family home could be completed in under an hour. To further reduce cost and increase accessibility, this method allows for self-assessment, in addition to formal assessment by a third-party expert. However, please note that only assessments carried out by a third-party expert would result in a formal certification.

The detailed version, Method B, targets non-residential buildings and is more comprehensive. The assessment could take half a day to a full day, depending on the building size and complexity. Typically, this method would necessitate an on-site inspection by a third-party qualified expert, leading to a more accurate SR score. However, self-assessment could also be possible, for example, by a facility manager.

Besides these two versions, there is a third potential method - Method C, which aims to base the SRI on actual performance data of in-use buildings. Over time, it is possible that Technical Building Systems (TBS) and Building Automation and Control Systems (BACS)

could potentially autonomously report their levels of functionality, thereby supporting both Method A and Method B. This would require benchmarking to assess the real impact of smart technologies in terms of energy savings, increased flexibility, comfort improvements, etc. While this method holds significant promise, it also poses many practical and legal challenges that need to be addressed before it can be fully implemented. Consequently, in this thesis, Method C is just deemed a potential of SRI.

5.3 Calculation Methodology

Smart readiness score (SR score) of a building is represented as a percentage indicating the degree of proximity to the maximum level of smart readiness. The degree of smartness of a building is directly proportional to the percentage value it possesses. It is possible to transform the percentage into an alternative measure, such as seven SRI classes shown in Table 10. (Verbeke et al., 2020, p. 152)

Table 10. Seven SRI Classes (Verbeke et al., 2020, p. 152)

SRI Class (A-G)	SR Score (%)
A	> 90%
B	80% - 90%
C	65% - 80%
D	50% - 65%

E	35% - 50%
F	20 – 35%
G	< 20%

In the simplest terms, SR score is basically a weighted sum of the seven total impact scores. The total impact scores could be calculated by implementing seven steps as suggested by Verbeke et al. (2020, pp. 129–132). To gain a comprehensive understanding of the above outlined calculation methodology, Figure 11 could be reviewed for a visual depiction.

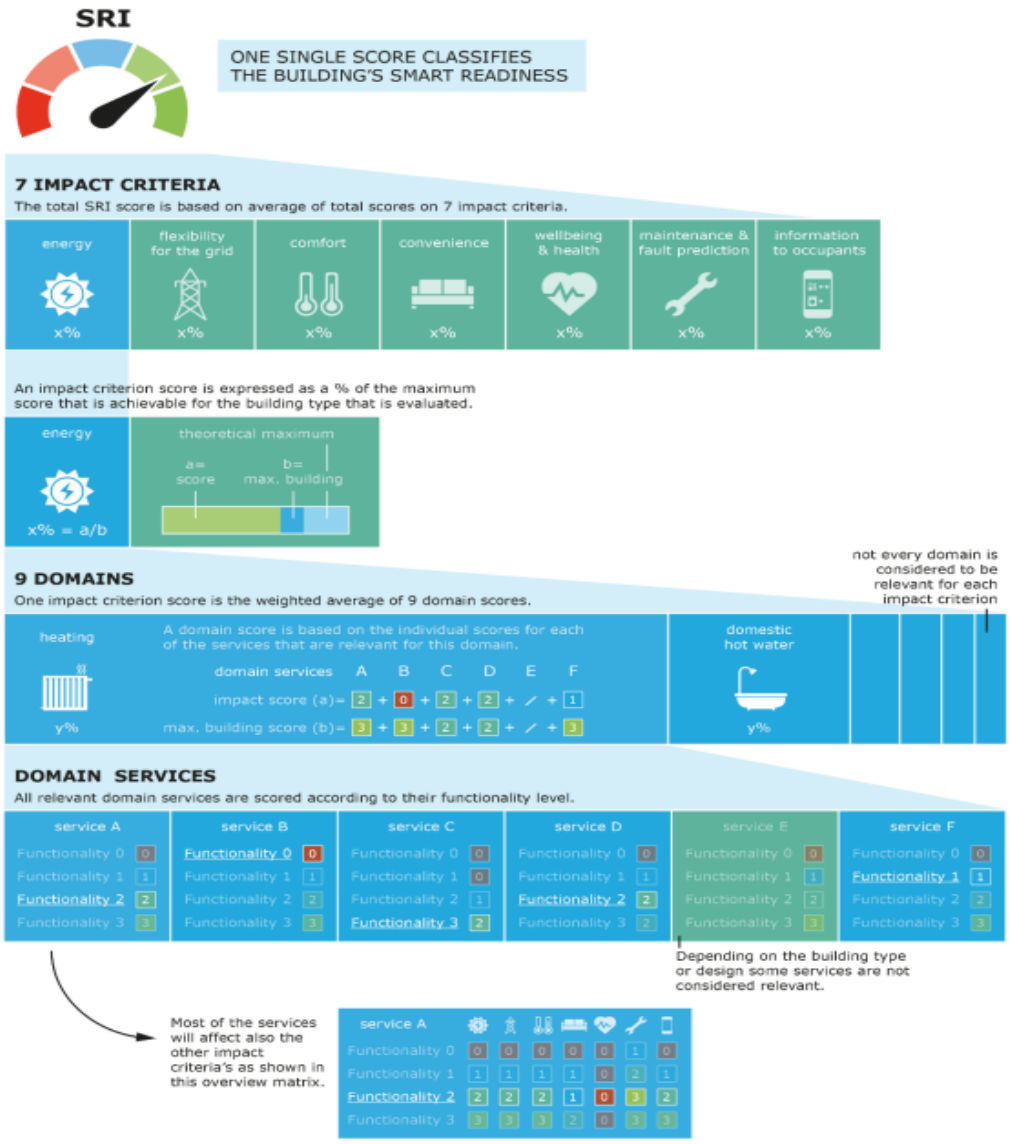


Figure 11. Overview of SR score calculation methodology (Verbeke et al., 2020, p. 26)

(1) Triangle process: involves the evaluation and documentation of the current smart services within nine domains. This step is necessary to account for the fact that not all smart-ready services are applicable or relevant for every building. There are various reasons why certain services might not be relevant or desirable for a specific building. These could be due to local and site-specific factors, such as the absence of certain technical building systems, geographical location, the type of building (residential or non-residential), or the current state of the building (new construction, retrofit, existing building). In cases where a service is not relevant or not present, that service does not need to be scored,

and the maximum attainable score for the building is reduced. This renormalisation process ensures that buildings are not unfairly penalised for lacking a service or domain that is not relevant or feasible for them. Some services might be mutually exclusive. For instance, a building might not have both district heating and CHP. The triage process avoids scoring services which are not present in the building. Lastly, some services might be absent but nonetheless desirable from a policy perspective. The triangle process could provide inputs to give incentives for upgrading existing buildings with additional smart services. It should be noticed that this process could be time consuming, particularly when dealing with large and complex buildings. However, it is of paramount importance in guiding subsequent steps and influencing the final SR score of the building.

(2) Functionality level evaluation: The assessment of the functionality level of smart-ready services in a building or building unit is conducted for each relevant service. This may involve a visual inspection or retrieval of technical documentation. This step is depicted in the bottom sections of Figure 11.

(3) Calculate the impact criterion scores: The impact criterion score for each technical domain is calculated as follows for each of the seven impact criteria:

$I(d, ic) = \sum_{i=1}^{Nd} Iic(FL(Si, d))$, where

d: number of the technical domain ($d \in \mathrm{N}$),
ic: number of the impact criterion ($ic \in \mathrm{N}$),
Nd: total number of services in technical domain d ($Nd \in \mathrm{N}$),
Si,d: service i of technical domain d ($i \in \mathrm{N}$, $1 \leq i \leq NSd$),
$FL(Si,d)$: functionality level of service Si,d in the building or building unit,
$Iic(FL(Si,d))$: impact criterion score of service Si,d for impact criterion number ic, according to the service's functionality level, $Iic(FL(Si,d)) \in \mathrm{N}$,
$I(d, ic)$: impact criterion score of domain number d for impact criterion number ic, $I(d, ic) \in \mathrm{N}$.

If a smart-ready service is deployed at multiple functional levels $FL(Si,d)$ across a building or building unit, the impact criteria score $Iic(FL(Si,d))$ of service Si,d may be computed as a weighted average.

(4) Calculate maximum impact scores: The maximum impact criteria score for each technical domain for each impact criterion is calculated in line with the catalogue of smart-ready services, as follows.

$Imax\ (d,\ ic) = \sum_{i=1}^{Nd} Iic(FLmax(Si,d))$, where:

$FLmax(Si,d)$: highest functionality level that service Si,d could have according to the smart-ready service catalogue,
$Iic(FLmax(Si,d))$: impact criterion score of service Si,d for its highest functionality level, which means the maximum impact criterion score of service Si,d for impact criterion number ic,
$Imax(d,\ ic)$: maximum impact criterion score of domain number d for impact criterion number ic.

(5) **Calculate SR score per impact criterion:** For each impact criterion, the SR score can be determined by dividing the weighted sum obtained in step 3 by the maximum weighted sum calculated in step 4. The derivation of weighting factors is based on the relative significance of each technical domain with respect to the impact criterion. Further elaboration on this topic can be found in section 5.4.

$\mathrm{SRic} = \frac{\sum_{d=1}^{N} Wd,ic \times \mathrm{I(d,ic)}}{\sum_{d=1}^{N} Wd,ic \times \mathrm{Imax(d,ic)}} \times 100$, where:

d: number of the technical domain,
N: total number of technical domains,
$Wd,\ ic$: the weighting factor (%) of technical domain number d for impact criterion number ic,
$SRic$: SR score (%) for impact criterion number ic.

(6) Calculate SR score per key functionality: For each key functionality, the SR score could be indicated as below.

$\mathrm{SRf} = \sum_{ic=1}^{M} \mathrm{Wf(ic)} \times \mathrm{SRic}$, where:

SRc: SR score for key functionality f,
M: total number of impact criteria, $M \in \mathrm{N}$,
$Wc(ic)$: weighting factor (%) of impact criterion number ic for key functionality f,
$SRic$ is the smart readiness score of impact criterion number ic.

(7) Total SR score for a real estate: the Total SR score of a real estate could be indicated by weighing the three SR score per key functionality as below.

$SR = \sum \frac{1}{3} \times \mathrm{SRf}$, where

SR is the total SR score,
$SR\mathrm{f}$ is the SR score of key capability f.

(8) (Optional) Calculate SR score per technical domain:

$$\mathrm{SRd,ic} = \frac{\mathrm{I(d,ic)}}{\mathrm{Imax(d,ic)}} \times 100$$

As noticed in the calculations, the total SR score is composed of several sub-scores, each of which represents a specific domain or impact category within the building (SR score per impact criterion, SR score per technical domain, SR score per key functionality). The benefit of evaluating these sub-scores is that they allow for a more detailed assessment of a building's smartness. While the overall SRI score provides a broad picture, the sub-scores allow you to see which specific areas of the building are particularly smart or could use improvement. For example, a building might have a high overall SRI score, but the sub-scores could reveal that its energy efficiency is excellent while its automation systems could be improved.

5.4 Weighting Factors

According to Verbeke et al. (2020, p. 21), theoretically, methods for obtaining weighting factors at the domain and service levels are based on three primary approaches: equal weighting, predicted impact approach, and energy balance approach. The objective is to fairly reflect the diverse impacts and considerations of different domains in the SRI for buildings. The equal weighting approach assigns equal weight to all domains, thereby ensuring every domain's relevance and influence in the overall scoring. The predicted impact approach considers the estimated influence of a domain in cases where an energy balance link could not be made. For instance, domains such as "monitoring & control" and "dynamic building envelope" might not directly correlate with energy balance but still hold importance. In such scenarios, a weight is assigned based on the predicted or estimated impact of that domain. Regarding the energy balance approach, it bases the weights on the relative importance of domains in an energy balance, which can reflect regional differences. This means that the weightings can vary depending on the regional energy needs. For instance, in Northern Europe, the heating domain may be assigned more weight due to the colder climate, while in Southern Europe, the cooling domain might be more relevant due to the warmer climate.

In reality, the approaches of equal weighting, predicted impact, and energy balance are not used in isolation. Rather, they are mixed to form a comprehensive and efficient weighting scheme, as proposed by Verbeke et al. (2020, p. 21). This proposed scheme blends fixed weights, equal weights, and energy balance weights, contingent upon the domain in question and its potential impact. The scheme takes into account different building types, namely non-residential and residential buildings, to cater to their unique requirements. Furthermore, it also factors in geographical variances by considering different climate zones including Northern Europe, Western Europe, North-Eastern Europe, South-Eastern Europe, and Southern Europe. This tailoring helps the scheme to accurately reflect the distinct attributes and needs of various building types across different locations. A detailed visualization of the scheme is illustrated in Figure 12 and Figure 13. Figure 14 outlines the specific countries that fall into each climate zone.

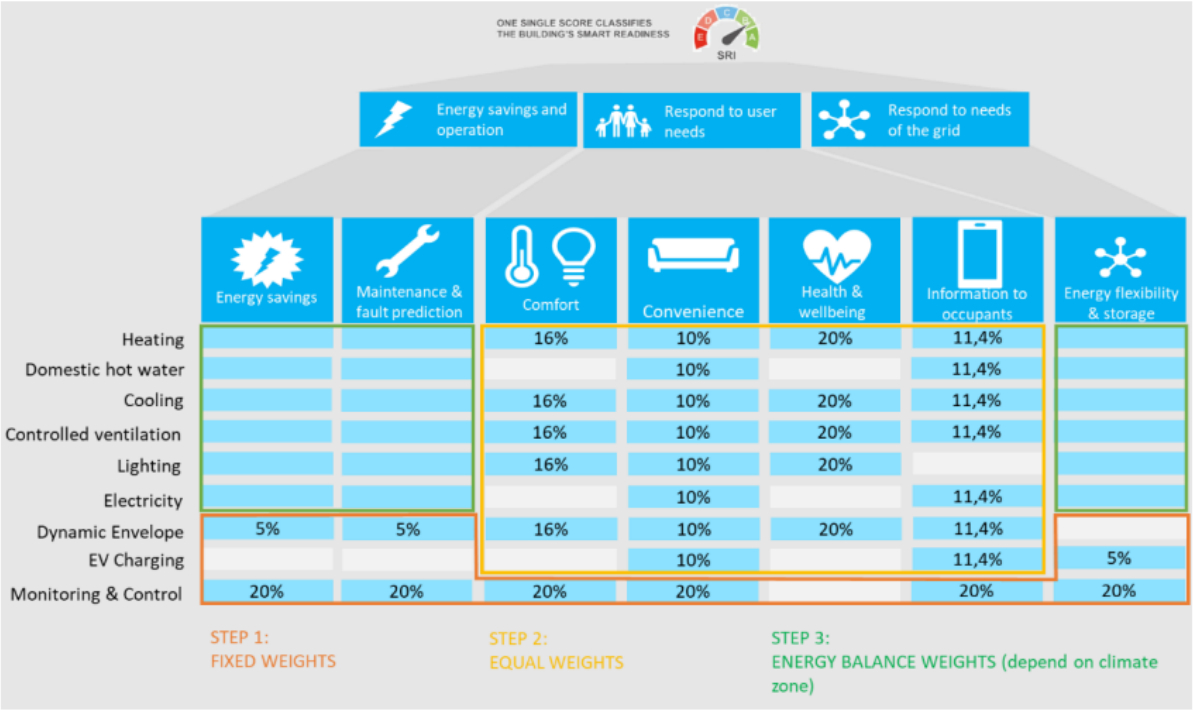


Figure 12. Weighting Scheme Overview (Verbeke et al., 2020, p. 22)

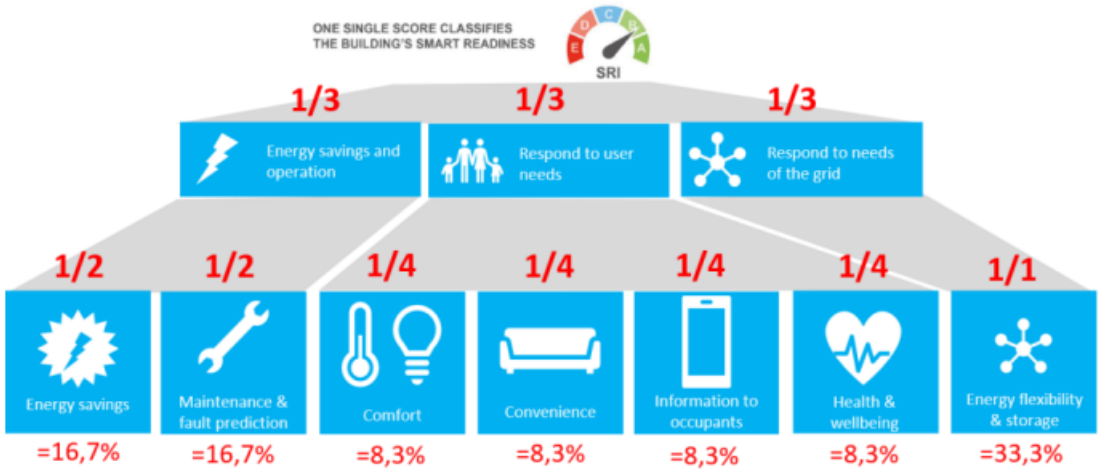


Figure 13. Proposed weighting factors of key functionalities and impact criteria (Verbeke et al., 2020, p. 22)

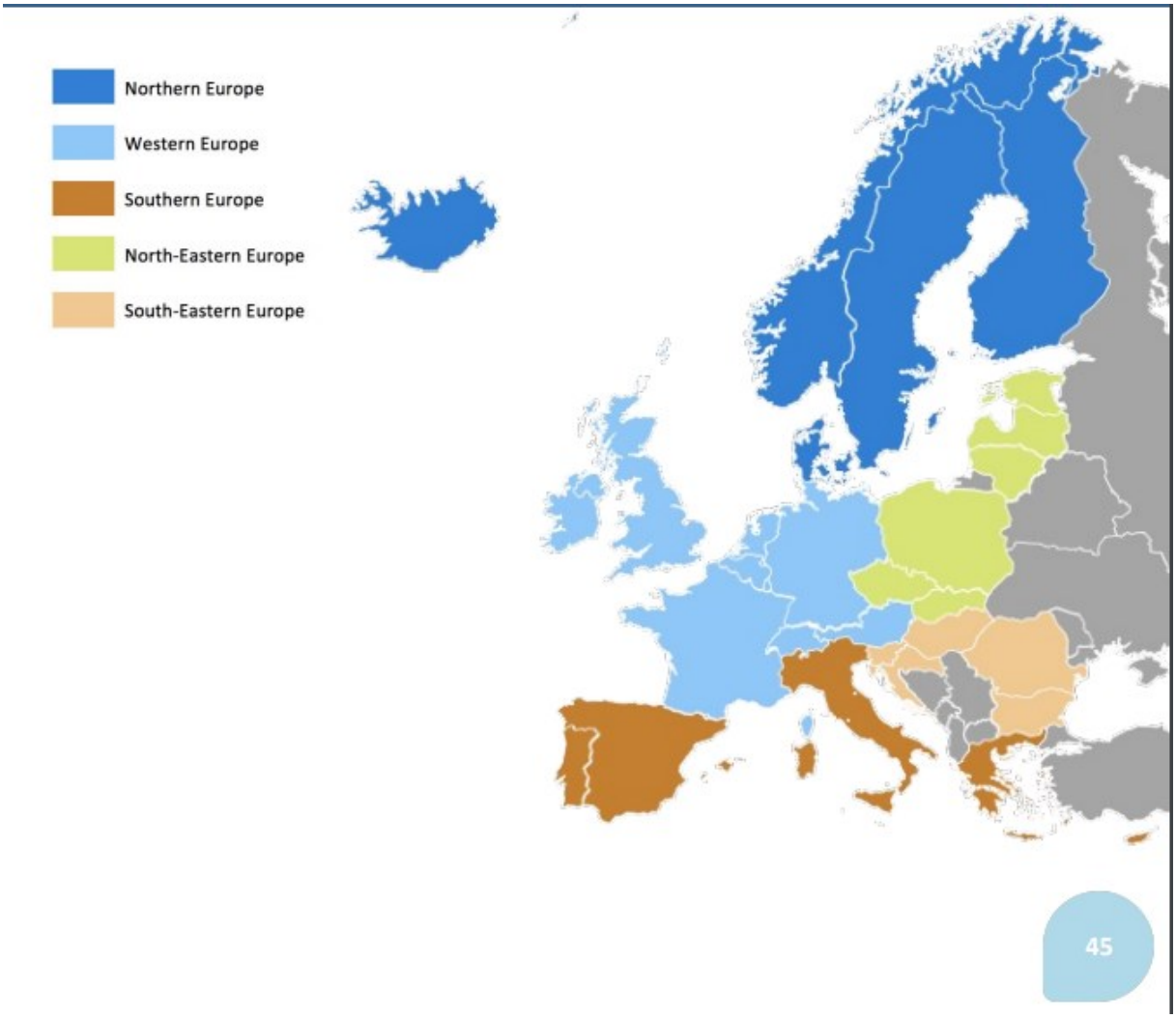


Figure 14. Different climate zones of EU (European Commission, 2022, p. 45)

The followings delineate steps to define weighting scheme depicted in Figure 26.

(1) **Defining Fixed Weights:** A fixed weight of 20% is allocated to all impact criteria for the domain "Monitoring and control". "Electric vehicle charging" and "Dynamic building envelope" get a fixed weight of 5% for the impact criteria "Energy savings", "Maintenance and fault prediction", and "Energy flexibility and storage". If a domain does not have any impact scores, its value is set to zero. These weights are constant, independent of the climate zone or building type, and could not be altered when using an alternative energy balance.

(2) **Defining Equal Weights:** "Comfort", "Convenience", "Health and wellbeing", and "Information to occupants" are assigned equal weights. The value of the weighting factor is determined by dividing the residual weight for the given impact criterion (100% minus the sum of fixed weights) by the number of domains relevant for that impact criterion. These values (the fixed weights) are not dependent on the climate zone or building type, and they can't be altered when using an alternative energy balance.

Example:

$f_{HEAT,comfortable} = (1 - f_{MC,comfortable}) \,/\, number\ of\ relevant\ domains$
$=> f_{HEAT,comfortable} = (1 - 0.20) \,/\, 5$
$=> f_{HEAT,comfortable} = 0.16$

where $f_{DOMAIN,impactCriterion}$: weighting factor for a given domain and impact criterion

(3) **Defining Energy Balance Weights:** Energy balance weights are assigned to the impact criteria "energy savings", "maintenance and fault prediction", and "energy flexibility and storage". The weighting factor's value is found by multiplying the remaining weight for the given impact criterion (100% minus the sum of fixed weights) by the relative importance of the domain in the energy balance. These values depend on the climate zone and building type, and they could be modified when using an alternative energy balance.

Example: for non-residential buildings in Northern Europe, the weighting factor for the “Heating” on “Energy savings” could be found as below:

$f_{HEAT,energySavings} = (1 - (f_{DYNAMIC\_ENVELOPE,energySavings} + f_{MC,energySavings})) \times aHEAT$
$=> f_{HEAT,energySavings} = (1 - (0.05 + 0.20)) * 0.418$
$=> f_{HEAT,energySavings} = 0.31$

where: $f_{DOMAIN,\ impactCriterion}$: weighting factor for a given domain and impact criterion,

$\alpha DOMAIN$: relative importance of a domain in the energy balance, values of which could be retrieved from either Figure 15 or Figure 16).

RESIDENTIAL BUILDINGS

WEIGHTINGS	North	West	South	North-East	South-East
Heating	39.9	45.3	42.2	40.5	27.5
DHW	12.4	10.2	13.3	18.6	7.7
Cooling	0.0	4.1	9.2	0.0	19.5
Ventilation	25.0	23.8	12.3	25.4	14.4
Lighting	4.9	2.0	3.6	0.8	1.2
Electricity	17.8	14.8	19.5	14.7	29.6

Figure 15. The significance of different domains in the context of residential real estate according to climatic zones (Verbeke et al., 2020, p. 121)

NON-RESIDENTIAL BUILDINGS

WEIGHTINGS	North	West	South	North-East	South-East
Heating	41.8	36.4	40.3	39.0	38.3
DHW	7.2	11.0	14.3	12.5	15.4
Cooling	12.5	16.9	15.7	11.2	9.9
Ventilation	26.2	19.1	11.7	24.4	20.1
Lighting	10.4	13.8	16.0	9.7	11.9
Electricity	2.0	2.8	2.1	3.1	4.4

Figure 16. The significance of different domains in the context of non-residential real estate according to climatic zones (Verbeke et al., 2020, p. 121)

5.5 Roles of BESS in SRI

Smart Readiness Technologies (SRT) are the technologies that allow a building to increase its Smart Readiness Indicator score. These technologies can include things such as smart thermostats, smart meters, energy management systems, demand response capabilities, and BESS (Verbeke et al., 2020, p. 1). BESS can be considered a Smart

Readiness Technology (SRT) based on several factors aligned with the three key characteristics, seven impact criteria, and nine technical domains defined above.

Energy Performance and Operation: A BESS contributes to this capability by optimizing the use of locally produced renewable energy, reducing the reliance on the grid, and lowering the overall energy consumption. By storing excess energy generated during off-peak hours for use during peak demand periods, it enhances the building's energy performance and operational efficiency. Advanced BESS could even provide alerts for maintenance needs and potentially predict faults based on performance data, helping to prevent system failures and improve the lifespan of the system.

Response to the Needs of the Occupants: A BESS can be tailored to respond to the unique energy needs of the occupants. By providing a reliable source of power during outages or in off-grid scenarios, it enhances convenience and comfort for occupants.

Energy Flexibility: One of the key functionalities of a BESS is to provide energy flexibility. It allows for load shifting, meaning it stores energy when demand is low (and energy is cheap) and releases it when demand is high (and energy is expensive). This feature is essential for managing fluctuating energy needs and for participating in demand response programs with the grid.

For an in-depth review of the effects of BESS on impact criteria and technical domains, Table 11, which was concluded by the author of this thesis, could be referred to.

Table 11. Effects of BESS on impact criteria and technical domains

Impact Criteria	
Energy Efficiency	A BESS boosts energy efficiency by effectively storing surplus power generated during peak production times and releasing it when production is low. This can considerably reduce the dependence on the grid, leading to lower energy costs and greener power consumption. Moreover, the BESS can be configured to only draw

	power during off-peak times when energy prices are low, thus promoting energy efficiency.
Maintenance & Fault Prediction	BESS, when paired with advanced analytics and monitoring systems, could provide predictive maintenance capabilities. They can alert the system operators about potential faults or inefficiencies based on real-time and historical performance data. Predictive analytics can identify patterns that may signal upcoming system failures, allowing for preventative measures to be taken, improving overall system reliability.
Comfort (Indirect)	A BESS indirectly contributes to comfort by ensuring a reliable, continuous power supply. In the event of grid outages, a BESS can seamlessly provide power, ensuring that systems contributing to occupant comfort (like HVAC, lighting, etc.) continue to function unimpeded.
Convenience (Indirect)	Power disruptions can cause inconvenience and disruption in both homes and businesses. A BESS ensures a reliable power source during outages, mitigating the impact of power disruptions, and thereby enhancing convenience.
Health & Wellbeing (Indirect)	BESS indirectly contribute to health and wellbeing. For example, HVAC systems, which help maintain good indoor air quality, depend on a reliable power supply, which a BESS can provide.
Information to Occupants	Modern BESS often incorporate smart technologies that monitor system performance and energy usage. These data can be made accessible to occupants, helping them understand their energy usage patterns and make informed decisions to optimize energy use.

Energy Flexibility and Storage	A BESS provides a significant boost in energy flexibility and storage. The ability to store and use energy when required enables a building to manage its energy demands more effectively, contributing to grid stability. In addition, it also enables participation in, for example, Fingrid's reserve market.
Technical Domains	
Electricity	A BESS is an integral part of the technical domain of electricity in smart readiness. It provides a means to store electrical energy and dispatch it as needed, contributing to energy flexibility, efficiency, and reliability. Storage of locally generated electricity is actually one of smart-ready services in both SRI assessment method A (simplified version) and method B (detailed version).
Monitoring & Control	Advanced BESS come with intelligent monitoring and control systems that enable effective energy management. Real-time monitoring allows operators to track the BESS's performance, efficiency, and health. In addition, they can be integrated with building management systems, enabling automated control based on the building's energy needs and the state of the grid, thereby enhancing a building's smart readiness.

6 Economic Analysis of BESS: Case Studies and Findings

6.1 Economic Analysis

This section discusses the investment metrics and property valuation methods to evaluate the financial viability of BESS in the real estate sector. According to Berk & DeMarzo (2007, p. 15), conventionally, the assessment of the economic value of an investment can be conducted through the utilisation of metrics such as Payback Period, Return on Investment (ROI), and Internal Rate of Return (IRR).

The payback period represents the timeframe over which an investment's costs are recovered. For BESS, this is calculated by dividing the initial investment cost by the annual net cash inflow (savings on energy bills and income from energy markets). Variables such as electricity price volatility, grid fees, and the scale of renewable energy integration are key factors impacting the payback period. Generally, the higher these factors, the higher the cash flow, and the shorter the payback period. It should be noticed that this metric does not consider the time value of money or cash flows after the payback period.

$\text{Payback Period} = \frac{\text{Investment costs}}{CF}$, where:

Investment Costs: total cost of the investment initially,
CF: Annual Net Cash Inflow - total annual financial gain from the employed BESS, which could include savings on energy costs due to the BESS (since it allows energy being stored when prices are low and used when prices are high) and income from joining Fingrid's reserve market.

Regarding ROI, it is useful for understanding the profitability of an investment relative to its cost. For instance, if the initial cost of a BESS was €100K, and it generates net operating income of €10K a year, the ROI would be 10%. While it is helpful in comparing different investments, it does not consider the holding period of the investment, which could be a downside.

$\text{ROI} = \frac{NOI}{Investment\ Costs}$, where:

NOI: Net Operating Income. In real estate, NOI refers to the annual income generated by a property after subtracting operating expenses but before subtracting taxes and interest payments. Operating expenses can include costs like maintenance, repairs, management fees, and utilities. NOI = Gross Income - Operating Expenses

IRR calculates the discount rate at which the net present value (NPV) of the investment's cash flows equals zero. The IRR is a more sophisticated measure as it considers the time value of money and could be used for comparing potential investments over time. Finding IRR typically

involves using iterative trial-and-error calculations to determine the right rate, but the basic concept is as follow.

$\text{NPV} = \sum_{t=0}^{n} \frac{CFt}{(1+IRR)\hat{}n} = 0$, where:

CFt: Similar to the annual cash inflow, but for a specific time frame (n), such as a month or quarter. This could vary based on energy usage and energy prices during different times of the year.

According to Janhunen (2023, p. 15), the traditional metrics (Payback Period, ROI, or IRR) focus primarily on direct financial returns, so they could not capture additional benefits influencing property value, such as energy resilience, grid independence, or contribution to environmental sustainability. Professional real estate owners, for instance, might rely on income-generating property valuation methods. These methods take into account not only the initial investment costs but also a range of other factors such as the property's gross income, operating expenses, and property yield. A primary goal is to enhance and sustain the NOI from the property to manage investment risk. In this context, Direct Capitalization and Discounted Cash Flow (DCF) method could offer a more comprehensive approach to evaluate income-generating investments like BESS.

Direct Capitalization method estimates the property's value based on the income it generates. The property value, in this case, is the estimated monetary worth of the real estate property after the inclusion of the BESS. The Direct Capitalization method utilized NOI, which includes the cost savings and potential income from the BESS (such as selling excess power back to the grid, reducing peak demand charges, participating in demand response programs, etc.). The formula for finding the property's value is as below.

$\text{Property Value} = \frac{NOI}{Cap\ Rate}$, where:

Cap Rate (Capitalization Rate): a percentage that reflects the risk associated with the NOI. For a BESS, this could be influenced by factors like the volatility of energy prices, the

reliability and lifespan of the battery system, the regulatory environment, and other market and technical risks.

It is worth noticing that Direct Capitalization provides a snapshot based on one year of income and expenses and assumes that these amounts will remain constant over time. As a result, it may not fully capture the long-term value and potential fluctuations in income and expenses of an investment like BESS, which is where methods like DCF could provide a more detailed and dynamic valuation.

The DCF method calculate the present value (PV) of the future financial benefits of a BESS investment, considering the time value of money and the risks and opportunity costs associated with the investment. In financial terms, PV is a concept stating an amount of money today is worth more than the same amount in the future. The PV of property could be calculated as follow.

$\mathrm{PV} = \sum_{t=0}^{n} \frac{NOIt}{(1 + Discount\ Rate)\hat{}t}$,where:

NOIt: Net Operating Income for period (t)
Discount Rate: This is the rate used in a DCF analysis to bring future cash flows from the BESS back to their present value. In simpler terms, suppose that an individual is anticipated to generate a revenue of €100 from the battery in the upcoming year. Assuming a discount rate of 1.5%, the current worth of that €100 is diminished in the subsequent manner: €100 / (1 + 0.015) = €98.52. The Discount Rate reflects the time value of money and the risk associated with future cash flows from the BESS, which could be influenced by factors such as changes in energy prices, demand for energy, and the performance and lifespan of the BESS.

6.2 Case Study I: The economic viability of a progressive smart building system with power storage

Case Study I discusses a study titled “The Economic Viability of a Progressive Smart Building System with Power Storage” by Janhunen, Leskinen, and Junnila, from the Department of Built

Environment at Aalto University. It was published on the 25th of July 2020. The paper delves into the role smartness plays in the built environment in fostering climate change mitigation through energy conservation, efficient utilization of renewable energy, and reduction of greenhouse gas emissions. The researchers designed a case study with a primary focus on understanding the cash flows and economic viability associated with a real-life smart system investment in a building. A three-fold data collection process was employed, including an estimation of a case building's level of (energy) smartness, semi-structured interviews with building owners to understand their motivation for smart investments, and an analysis of the investment's profitability.

The subject of the case study was a commercial building in Southern Finland, which is renowned for the systematic implementation of smart technologies into the built environment. The building, with a total area of 100,000 m², was the first European shopping center to receive LEED Platinum certification for existing buildings in 2015. A substantial smart energy system, consisting of energy storage, software development, and energy conservation technologies, was implemented in the building, with a total investment cost of approximately €6M.

The study investigates the total investment in a smart energy system, which amounts to approximately €6M. The investment is supported by a €2M government subsidy. The system includes several technologies, such as a rooftop photovoltaic (PV) system, energy storage, and system integration with advanced demand management capabilities. The total cost for the battery system amounts to €2M, which is a third of the total investment. According to the assumptions used in the study, the expected life cycle of the battery is approximately 20 years, after which the owner would need to reinvest in a new battery. The financial analysis is based on 10 months of operation, with the savings and new income generated by the smart energy system factored in. The savings stem from improvements in energy efficiency, while the new income is generated from the reserve power markets, enabled predominantly by the battery system. The maintenance costs of the smart system, which are often a significant consideration in the investments, are not explicitly available due to confidentiality reasons. However, these were estimated based on Finnish data and the relationship between technical property maintenance costs and investment costs. In this case, maintenance costs were

calculated to be about 1% of the investment costs, which includes insurance and repair costs. The annual savings from the entire system is estimated to be around €180K, while the new income generated is around €480K. Significantly, the battery system itself is responsible for generating the entirety of the new income due to its ability to participate in the reserve power markets. This makes it a critical aspect of the overall investment's economic viability.

The paper found that the subject building exhibited a high degree of smart technology integration, as its SRI score reached 92%. Interestingly, the case building scored 100% in 30 (out of 39) smart ready services on the SRI rating scheme, showcasing a highly efficient integration of smart technologies. Investor interviews revealed that the most crucial decision-making factor for this investment was its profitability. Two profitability scenarios were formulated for the investment: one without the €2M government subsidy and one with it. According to the financial analysis, without the subsidy, the project's ROI was 10%, with an IRR of 5%, and a payback period of 10 years. However, with the subsidy included, the ROI increased to 15%, the IRR to 11%, and the payback period decreased to 6.7 years. This clearly highlights the significant positive impact of the government subsidy on the project's profitability.

The battery system plays a crucial role in the profitability analysis, contributing significantly to the new income generated. This is evident in the sensitivity analysis. There, one scenario assumes that the battery would generate 80% of the estimated income (low-income scenario), and another scenario assumes 20% higher than estimated income (high-income scenario). The IRR fluctuates from 8% to 13% based on these battery income scenarios, indicating a direct and significant correlation between the performance of the battery system and the project's overall profitability.

The results of the study show that the battery system, along with other smart technologies, can generate substantial income for the investment. This is most evident in the sensitivity analysis, where various income scenarios for the battery show the direct impact on the project's IRR. However, it is crucial to acknowledge the risks associated with such an investment. The performance of the battery system can affect the overall profitability of the project, as in the sensitivity analysis. If the battery underperforms, it could result in lower-

than-expected returns. Moreover, the maintenance costs of the system can also impact profitability. As seen in the sensitivity analysis, higher than estimated maintenance costs can decrease the expected property value increase and the IRR. Another critical factor to consider is the uncertainty related to electricity price growth rates. Electricity prices directly impact the savings generated by the battery system, and hence the overall returns from the investment. A sudden drop in electricity prices, for example, could lower the cost savings and, consequently, the returns from the investment.

Overall, it is of paramount importance to carefully consider these factors when investing in a battery system in a smart building, particularly when participating in Fingrid's reserve markets. While such investments can indeed be highly profitable, as this case study demonstrates, they also come with certain risks that must be adequately mitigated to ensure sustained profitability. Investors must take a holistic view of the project, considering not only the potential income from the battery system and other smart technologies but also potential risks and costs. This includes the costs and reliability of the technologies, the stability of electricity prices, the reliability of income from reserve markets, and the possible impacts of policy or regulatory changes.

6.3 Case Study II: Assessment of economic benefits of battery energy storage application for the PV-equipped households in Finland

Case Study II discusses a research study, first published on 05/07/2019, by a team of scholars - Kuleshov, Peltoniemi, Kosonen, Nuutinen, Huoman, Lana, Paakkonen, and Malinen. Their paper, titled "Assessment of economic benefits of battery energy storage application for the PV-equipped households in Finland", is an in-depth techno-economic exploration of the LFP-based battery storage's integration with residential rooftop PV installations in Finland.

The study's primary objective is to evaluate the operational performance and assess both the current and future economic viability of using LFP batteries alongside household PV systems in Finland. This objective was largely driven by the motivation to reduce battery costs, currently needing to overcome a grid storage cost of 6–10 cent/kWh, depending on the location. The researchers were especially interested in identifying the threshold at which

future Finnish retail market prices and storage costs would ensure a profitable return on investment within the battery's expected lifespan.

To fulfil this objective, the team devised a detailed techno-economic model of the LFP-based BESS operating in combination with typical household rooftop PV systems in Finland. This model, based on active power flows, replicates many of the crucial characteristics of actual battery and PV systems. It employs actual power production data from a 15,000 W inverter of a rooftop PV installation located in Tampere, Finland, and a load profile from a single-family household with an annual consumption of 10,000 kWh. The model also utilizes estimates of battery costs based on current retail prices for LFP battery modules, which in 2018, varied between €329.2 and €754.9/kWh.

The paper delves into several hypothetical scenarios of household load, PV installation, and battery storage size. These scenarios are derived from the cases of both a small household with a total annual consumption of 10,308 kWh and a larger household equipped with a domestic water electric heater (DHW). In each scenario, the researchers examined the changes in operational and economic outcomes upon the integration of 5.3 and 10.6 kWh battery storage systems as shown in Table 12. The assumption was a 5kW DC/DC converter size in all cases, and investment calculations considered a 15-year depreciation period with a discount rate of 1% applied for net present value (NPV) calculations.

Table 12. Examined system layouts (Kuleshov et al., 2019, p. 4929)

Load	Building without electric DHW		Building with electric DHW	
PV	5.4 kWp		10.8 kWp	
BESS	5.3kWh	10.6kWh	5.3kWh	10.6kWh

Scenario	S1	S2	L1	L2

The study found that implementing a BESS in a household increases self-consumption of PV-produced energy (the energy used directly, instead of selling back to the grid), reducing dependence on the grid. This increase leads to significant savings on electricity bills: €65 per year for the 5.3 kWh battery and €100.9 per year for the 10.6 kWh battery (based on scenarios S1 and S2). However, the marginal benefits decrease with larger storage systems, indicating a diminishing return on investment as the battery size increases. Households with larger PV installations (10.8 kWp) realize higher savings on their electricity bill (€73.4 for 5.3 kWh battery and €110.7 for 10.6 kWh battery in scenarios L1 and L2 respectively) compared to households with smaller installations - 5.4 kWp. This is due to higher energy production and hence greater utilization rates of the storage capacity. Regarding the battery durability, the estimated battery lifespan, based on cycling rates, exceeds 15 years in all scenarios, which means that the battery's calendar life may be longer than its cycling life, depending on usage and conditions. Lastly, the NPV, which measures the profitability of an investment, remains negative in all scenarios, when considering the maximum battery cost. This implies that the savings generated from the BESS are insufficient to offset the high upfront costs within the given period. The situation improves slightly with the use of less expensive batteries, but profitability remains elusive unless the cost of grid electricity increases significantly, and battery costs decrease.

The analysis has several implications for the adoption of residential BESS in conjunction with PV installations. Although the deployment of these systems can lead to energy cost savings and greater energy independence, the financial viability of these investments remains a significant hurdle, especially given the current high costs of battery storage technology. This implies that, at present, the primary benefits of residential BESS are not strictly financial, but rather relate to energy resilience, a reduced carbon footprint, and the opportunity to use more of the green energy produced by PV installations.

In the future, there are two potential factors that may contribute to an increased financial feasibility for residential BESS.

Rising Energy Prices: Higher grid electricity prices increase the cost savings resulting from self-consumption of PV-produced energy, improving the financial returns of BESS investments.

Falling Battery Costs: Advances in battery technology, increased production scale, and greater competition are expected to lead to lower battery costs in the future. This would decrease the initial investment required for a BESS, improving the NPV of these investments.

Considering these patterns, it is plausible that the economic viability of residential BESS will improve in the upcoming decades, especially if complementary policy interventions are implemented.

7 Final discussion and conclusions

7.1 Summary of main findings

The thesis aims to contribute to the comprehension of real estate battery systems in terms of energy use, storage, and efficiency in Finnish property sector. Three research questions (RQ1, RQ2, and RQ3) were established to study the main aims from different perspectives.

RQ1 aims to study the significance of BESS utilized in Finnish real estate in the context of energy utilization and storage. The analysis reveals the pivotal role that BESS can play in boosting energy efficiency, moderating peak demand, and facilitating the seamless integration of renewable energy sources. The theoretical study compared various battery technologies with LFP outperformed the rest for BESS implementation in the Finnish context. For LFP, a performance analysis has been thoroughly conducted, with focuses on charge and discharge characteristics, capacity and performance at different rates, and the temperature effects. Further studies on Fingrid's reserve market, the utilization of SRI, and the financial implications of BESS implementation has highlighted the significant roles BESS could play not only in

improving energy efficiency, but also in enhancing system flexibility, creating new financial opportunities, and fulfilling sustainability targets.

RQ2 seeks to examine the interplay between Fingrid's reserve market, SRI, and BESS in Finnish real estate sector. A study of Fingrid's different reserve products indicated BESS's value in markets demanding rapid response times, especially in the FCR-N context. The high power and fast response of BESS can quickly balance short-term frequency fluctuations and can be instrumental in reducing the need for more expensive and less environmentally friendly peaking power plants. Additionally, in scenarios of large power imbalances as catered to by FCR-D and FFR, BESS can decisively influence grid stability through its quick energy injection or absorption capabilities. By participating in these reserve markets, Finnish real estate can not only stabilize their energy expenses but also significantly contribute to broader grid stability. Regarding SRI, it could further add to this intricate relationship by rating a building's capacity to improve its operation and energy consumption based on the efficiency of its utilized smart technologies. With BESS integrated with a smart energy management system, a building's SRI rating can be significantly enhanced. An intelligently optimized BESS setup enables smart load shifting, utilization of off-peak power, and participation in the reserve markets. This flexibility has directly enhanced a building's SRI score. However, BESS's effectiveness is currently limited in the aFRR and mFRR markets that demand longer-term storage capacity and slower response times, which do not align with BESS's present capabilities. These markets are generally better suited to larger-scale resources with slower response times, such as hydroelectric dams or demand-side management of large consumers. Overall, the dynamic relationship between Fingrid's reserve market, SRI, and BESS holds substantial potential to enhance the flexibility of Finnish real estate's electricity consumption. By strategically leveraging the rapid response capabilities of BESS and aligning it with SRI objectives, Finnish real estate could optimize their energy use, engage in ancillary services markets, and amplify their contribution to overall grid stability.

RQ3 was built upon RQ1 and RQ2 providing guidance for real estate owners on assessing the economic value of their real estate battery systems. This involves employing traditional financial metrics, namely Payback Period, ROI, and IRR to provide crucial insights into the direct financial returns. In addition, property valuation methods like Direct Capitalization and

Discounted Cash Flow (DCF) were applied to capture additional benefits influencing property value (energy resilience, grid independence, or contribution to environmental sustainability).

To make these RQs more tangible and relatable, the thesis explored two real-life case studies, specifically chosen to represent small-scale (residential) and medium-scale (commercial) energy storage applications in the real estate sector. By studying these cases, the thesis was able to offer several valuable insights into the economic value of BESS for property owners in Finland. Overall, from the case studies, BESS in commercial buildings shows financial promise, particularly when complemented by governmental subsidies. Participation in reserve power markets presents a valuable income stream, highlighting the potential of BESS as an economic asset. Conversely, the residential case study proved that the current economic viability of small-scale BESS installations is challenged by high initial costs and maintenance expenses.

The case studies have confirmed the need for a comprehensive approach to assess the economic value of BESS for property owners in Finland, beyond traditional financial metrics. The DCF methods, which factor in gross income, operating expenses, and property yield, has proven to be effective in assessing the potential for long-term cost savings and income generation. Additionally, this approach accounts for external factors such as government subsidies, fluctuations in electricity prices, and advancements in technology that may impact the value of BESS over time. Policy interventions can have a significant impact on the economic viability of BESS investments. Incentives such as government subsidies can reduce the initial investment burden and enhance the financial attractiveness of BESS installations. On the other hand, regulatory changes could affect energy prices or the ability to participate in reserve power markets, which could also influence the economic value of BESS installations. Therefore, it is crucial for property owners and investors to monitor policy developments related to energy and climate change.

In conclusion, the findings extracted from the extensive literature review are organized according to the three RQs, and these insights are further elucidated through two case studies as shown in Table 13. Table 13 was concluded by the author of this thesis after the in-depth review of the subject matter.

Table 13. The summarized results from the literature review

	Case Study I (Commercial Building)	**Case Study II** (Residential Buildings)
RQ1: What is the role of BESS in the use and storage of energy within Finnish Real Estate sector?	The BESS plays a crucial role in energy management, enabling the building to manage peak loads and participate in the reserve power market.	The BESS aids in increasing the self-consumption of solar energy, reducing reliance on the power grid, and aiding in the management of peak power loads.
RQ2: What is the interrelationship between Fingrid's reserve market, SRI, and BESS and based on which how can batteries improve the flexibility of a Finnish real estate's electricity consumption?	Participation in Fingrid's reserve market with the help of BESS improves the building's SRI rating and generates income. The BESS provides flexibility in power consumption by allowing peak load shifting.	The BESS, coupled with the SRI framework, enables residential buildings to become more energy independent and reduce grid reliance. This results in enhanced consumption flexibility and contributes to improved SRI.
RQ3: How can owners evaluate the economic value of the BESS in Finland?	The economic value is evaluated by considering the initial investment, maintenance costs, the income from participating in the reserve market, and energy savings due to efficient load management.	The economic value is evaluated by a detailed techno-economic model considering PV production, household energy consumption, BESS costs, and potential energy savings.

7.2 Current Limitations

This thesis acknowledges certain limitations that are a consequence of the study's context and the inherent restrictions of the research design. A two-month timeframe for the conduct of

this research restricted the scope of investigation, enabling only two case studies to be thoroughly examined. This time constraint, while promoting a focused investigation, limited the capacity to explore a wider array of scenarios and contexts. Additionally, the literature review unveiled a notable gap in existing research papers. The scarcity of comprehensive studies that scrutinize the impact of BESS and reserve market on the SRI score in Finland was a significant limitation. A detailed analysis of this specific aspect could have enriched the insights derived from the study and better guided the understanding of BESS, the reserve market, and SRI interactions.

Furthermore, the geographical distance and remote nature of the research hindered the application of empirical methodologies that could have strengthened the validity of the thesis. For instance, the execution of a hands-on experiment at HAMK campus might have translated the theoretical constructs from the literature review into a tangible practice. This practical exercise could have been a powerful method to validate the theoretical assumptions drawn from the literature review.

Lastly, while the financial analysis attempted to be thorough and robust, there remains potential for refinement. A more extensive exploration of related tax implications and incentives provided by the Finnish government could have provided a more nuanced understanding of the financial viability of BESS implementations. Acknowledging these limitations, this thesis views them not as impediments, but as avenues for future research and inquiry to advance the understanding of real estate battery systems.

7.3 Recommendations for Future Research

Given the limitations identified, a roadmap for future research is recommended to deepen our understanding of BESS and its role within the Finnish real estate sector, supporting the broader aim of fostering sustainable, intelligent, and resilient energy systems.

Firstly, future studies with an extended timeframe could engage in more diverse and in-depth case studies. This wider exploration of the Finnish real estate landscape would provide invaluable insights into BESS applicability in different property scenarios and contribute to the

body of knowledge guiding the energy transition in the sector. The observed research gap concerning the influence of BESS and the reserve market on SRI scores in Finland presents a crucial focus for future inquiry. A dedicated investigation of this association may uncover tactics for real estate stakeholders to optimize their SRI scores via BESS utilization, which could promote sustainable and energy-efficient approaches.

Bridging theoretical understanding with empirical practices is another critical area for future exploration. Practical experiments, such as implementing a small-scale BESS project on HAMK campus, could serve as tangible testbeds to corroborate the theoretical deductions made in this thesis. The learnings from these hands-on experiences would inform stakeholders about the real-world implications of adopting BESS, facilitating better informed and pragmatic decision-making.

Lastly, a more in-depth financial analysis that considers the taxes and Finnish government incentives related to BESS could offer a more precise understanding of the investment viability. This information would be a valuable resource for potential investors, enhancing their ability to assess the financial implications and strategize accordingly. Incorporating these recommendations in future research will substantially enhance our understanding of BESS in the Finnish real estate sector. The gained insights would serve as a catalyst for stakeholders to confidently navigate the path towards a more sustainable energy future.

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Appendix 1. SRI Method B: Detailed Service Catalogue

The catalogue was retrieved from “Final report on the technical support to the development of a smart readiness indicator for buildings” (Verbeke et al., 2020, pp. 399-409).

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Heating	Heat emission control	No automatic control	Central automatic control (e.g. central thermostat)	Individual room control (e.g. thermostatic valves, or electronic controller)	Individual room control with communication between controllers and to BACS	Individual room control with communication and occupancy detection
Heating	Emission control for TABS (heating mode)	No automatic control	Central automatic control	Advanced central automatic control	Advanced central automatic control with intermittent operation and/or room temperature feedback control	
Heating	Control of distribution fluid temperature (supply or return air flow or water flow) - Similar function can be applied to the control of direct electric heating networks	No automatic control	Outside temperature compensated control	Demand based control		
Heating	Control of distribution pumps in networks	No automatic control	On off control	Multi-Stage control	Variable speed pump control (pump unit (internal) estimations)	Variable speed pump control (external demand signal)
Heating	Thermal Energy Storage (TES) for building heating (excluding TABS)	Continuous storage operation	Time-scheduled storage operation	Load prediction based storage operation	Heat storage capable of flexible control through grid signals (e.g. DSM)	

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Heating	Heat generator control (all except heat pumps)	Constant temperature control	Variable temperature control depending on outdoor temperature	Variable temperature control depending on the load (e.g. depending on supply water temperature set point)		
Heating	Heat generator control (for heat pumps)	On/Off-control of heat generator	Multi-stage control of heat generator capacity depending on the load or demand (e.g. on/off of several compressors)	Variable control of heat generator capacity depending on the load or demand (e.g. hot gas bypass, inverter frequency control)	Variable control of heat generator capacity depending on the load AND external signals from grid	
Heating	Sequencing in case of different heat generators	Priorities only based on running time	Control according to fixed priority list: e.g. based on rated energy efficiency	Control according to dynamic priority list (based on current energy efficiency, carbon emissions and capacity of generators, e.g. solar, geothermal heat, cogeneration plant, fossil fuels)	Control according to dynamic priority list (based on current AND predicted load, energy efficiency, carbon emissions and capacity of generators)	Control according to dynamic priority list (based on current AND predicted load, energy efficiency, carbon emissions, capacity of generators AND external signals from grid)
Heating	Report information regarding HEATING system performance	None	Central or remote reporting of current performance KPIs (e.g. temperatures, submetering energy usage)	Central or remote reporting of current performance KPIs and historical data	Central or remote reporting of performance evaluation including forecasting and/or benchmarking	Central or remote reporting of performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
Heating	Flexibility and grid interaction	No automatic control	Scheduled operation of heating system	Self-learning optimal control of heating system	Heating system capable of flexible control through grid signals (e.g. DSM)	Optimized control of heating system based on local predictions and grid signals (e.g. through

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
						model predictive control)
Domestic hot water	Control of DHW storage charging (with direct electric heating or integrated electric heat pump)	Automatic control on / off	Automatic control on / off and scheduled charging enable	Automatic control on / off and scheduled charging enable and multi-sensor storage management	Automatic charging control based on local availability of renewables or information from electricity grid (DR, DSM)	
Domestic hot water	Control of DHW storage charging (using hot water generation)	Automatic control on / off	Automatic control on / off and scheduled charging enable	Automatic on/off control, scheduled charging enable and demand-based supply temperature control or multi-sensor storage management	DHW production system capable of automatic charging control based on external signals (e.g. from district heating grid)	
Domestic hot water	Control of DHW storage charging (with solar collector and supplymentary heat generation)	Manual selected control of solar energy or heat generation	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge and demand-oriented supply or multi-sensor storage management	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge, demand-oriented supply and return temperature control and multi-sensor storage management	
Domestic hot water	Sequencing in case of different DHW generators	Priorities only based on running time	Control according to fixed priority list: e.g. based on rated energy efficiency	Control according to dynamic priority list (based on current energy efficiency, carbon emissions and capacity of generators, e.g. solar, geothermal heat, cogeneration plant, fossil fuels)	Control according to dynamic priority list (based on current AND predicted load, energy efficiency, carbon emissions and capacity of generators)	Control according to dynamic priority list (based on current AND predicted load, energy efficiency, carbon emissions, capacity of generators AND external signals from grid)

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Domestic hot water	Report information regarding domestic hot water performance	None	Indication of actual values (e.g. temperatures, submetering energy usage)	Actual values and historical data	Performance evaluation including forecasting and/or benchmarking	Performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
Cooling	Cooling emission control	No automatic control	Central automatic control	Individual room control	Individual room control with communication between controllers and to BACS	Individual room control with communication and occupancy detection
Cooling	Emission control for TABS (cooling mode)	No automatic control	Central automatic control	Advanced central automatic control	Advanced central automatic control with intermittent operation and/or room temperature feedback control	
Cooling	Control of distribution network chilled water temperature (supply or return)	Constant temperature control	Outside temperature compensated control	Demand based control		
Cooling	Control of distribution pumps in networks	No automatic control	On off control	Multi-Stage control	Variable speed pump control (pump unit (internal) estimations)	Variable speed pump control (external demand signal)
Cooling	Interlock: avoiding simultaneous heating and cooling in the same room	No interlock	Partial interlock (minimising risk of simultanieus heating and cooling e.g. by sliding setpoints)	Total interlock (control system ensures no simultaneous heating and cooling can take place)		
Cooling	Control of Thermal Energy Storage (TES) operation	Continuous storage operation	Time-scheduled storage operation	Load prediction based storage operation	Cold storage capable of flexible control through grid signals (e.g. DSM)	

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Cooling	Generator control for cooling	On/Off-control of cooling production	Multi-stage control of cooling production capacity depending on the load or demand (e.g. on/off of several compressors)	Variable control of cooling production capacity depending on the load or demand (e.g. hot gas bypass, inverter frequency control)	Variable control of cooling production capacity depending on the load AND external signals from grid	
Cooling	Sequencing of different cooling generators	Priorities only based on running times	Fixed sequencing based on loads only: e.g. depending on the generators characteristics such as absorption chiller vs. centrifugal chiller	Dynamic priorities based on generator efficiency and characteristics (e.g. availability of free cooling)	Load prediction based sequencing: the sequence is based on e.g. COP and available power of a device and the predicted required power	Sequencing based on dynamic priority list, including external signals from grid
Cooling	Report information regarding cooling system performance	None	Central or remote reporting of current performance KPIs (e.g. temperatures, submetering energy usage)	Central or remote reporting of current performance KPIs and historical data	Central or remote reporting of performance evaluation including forecasting and/or benchmarking	Central or remote reporting of performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
Cooling	Flexibility and grid interaction	No automatic control	Scheduled operation of cooling system	Self-learning optimal control of cooling system	Cooling system capable of flexible control through grid signals (e.g. DSM)	Optimized control of cooling system based on local predictions and grid signals (e.g. through model predictive control)
Controlled ventilation	Supply air flow control at the room level	No ventilation system or manual control	Clock control	Occupancy detection control	Central Demand Control based on air quality sensors (CO2, VOC, humidity, ...)	Local Demand Control based on air quality sensors (CO2, VOC,...) with local flow from/to the zone regulated by dampers

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Controlled ventilation	Air flow or pressure control at the air handler level	No automatic control: Continuously supplies of air flow for a maximum load of all rooms	On off time control: Continuously supplies of air flow for a maximum load of all rooms during nominal occupancy time	Multi-stage control: To reduce the auxiliary energy demand of the fan	Automatic flow or pressure control without pressure reset: Load dependent supplies of air flow for the demand of all connected rooms.	Automatic flow or pressure control with pressure reset: Load dependent supplies of air flow for the demand of all connected rooms (for variable air volume systems with VFD).
Controlled ventilation	Heat recovery control: prevention of overheating	Without overheating control	Modulate or bypass heat recovery based on sensors in air exhaust	Modulate or bypass heat recovery based on multiple room temperature sensors or predictive control		
Controlled ventilation	Supply air temperature control at the air handling unit level	No automatic control	Constant setpoint: A control loop enables to control the supply air temperature, the setpoint is constant and can only be modified by a manual action	Variable set point with outdoor temperature compensation	Variable set point with load dependant compensation. A control loop enables to control the supply air temperature. The setpoint is defined as a function of the loads in the room	
Controlled ventilation	Free cooling with mechanical ventilation system	No automatic control	Night cooling	Free cooling: air flows modulated during all periods of time to minimize the amount of mechanical cooling	H,x- directed control: The amount of outside air and recirculation air are modulated during all periods of time to minimize the amount of mechanical cooling. Calculation is performed on the basis of temperatures and humidity (enthalpy).	

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Controlled ventilation	Reporting information regarding IAQ	None	Air quality sensors (e.g. CO2) and real time autonomous monitoring	Real time monitoring & historical information of IAQ available to occupants	Real time monitoring & historical information of IAQ available to occupants + warning on maintenance needs or occupant actions (e.g. window opening)	
Lighting	Occupancy control for indoor lighting	Manual on/off switch	Manual on/off switch + additional sweeping extinction signal	Automatic detection (auto on / dimmed or auto off)	Automatic detection (manual on / dimmed or auto off)	
Lighting	Control artificial lighting power based on daylight levels	Manual (central)	Manual (per room / zone)	Automatic switching	Automatic dimming	Automatic dimming including scene-based light control (during time intervals, dynamic and adapted lighting scenes are set, for example, in terms of illuminance level, different correlated colour temperature (CCT) and the possibility to change the light distribution within the space according to e. g. design, human needs, visual tasks)
Dynamic building envelope	Window solar shading control	No sun shading or only manual operation	Motorized operation with manual control	Motorized operation with automatic control based on sensor data	Combined light/blind/HVAC control	Predictive blind control (e.g. based on weather forecast)
Dynamic building envelope	Window open/closed control,	Manual operation or	Open/closed detection to shut down	Level 1 + Automised mechanical window opening	Level 2 + Centralized coordination of operable	

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
	combined with HVAC system	only fixed windows	heating or cooling systems	based on room sensor data	windows, e.g. to control free natural night cooling	
Dynamic building envelope	Reporting information regarding performance of dynamic building envelope systems	No reporting	Position of each product & fault detection	Position of each product, fault detection & predictive maintenance	Position of each product, fault detection, predictive maintenance, real-time sensor data (wind, lux, temperature…)	Position of each product, fault detection, predictive maintenance, real-time & historical sensor data (wind, lux, temperature…)
Electricity	Reporting information regarding local electricity generation	None	Current generation data available	Actual values and historical data	Performance evaluation including forecasting and/or benchmarking	Performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
	Storage of (locally generated) electricity	None	On site storage of electricity (e.g. electric battery)	On site storage of energy (e.g. electric battery or thermal storage) with controller based on grid signals	On site storage of energy (e.g. electric battery or thermal storage) with controller optimising the use of locally generated electricity	On site storage of energy (e.g. electric battery or thermal storage) with controller optimising the use of locally generated electricity and possibility to feed back into the grid
Electricity	Optimizing self-consumption of locally generated electricity	None	Scheduling electricity consumption (plug loads, white goods, etc.)	Automated management of local electricity consumption based on current renewable energy availability	Automated management of local electricity consumption based on current and predicted energy needs and renewable energy availability	
Electricity	Control of combined heat and power plant (CHP)	CHP control based on scheduled runtime management and/or current heat energy demand	CHP runtime control influenced by the fluctuating availability of RES; overproduction will be fed into the grid	CHP runtime control influenced by the fluctuating availability of RES and grid signals; dynamic charging and runtime control		

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
				to optimise self-consumption of renewables		
Electricity	Support of (micro)grid operation modes	None	Automated management of (building-level) electricity consumption based on grid signals	Automated management of (building-level) electricity consumption and electricity supply to neighbouring buildings (microgrid) or grid	Automated management of (building-level) electricity consumption and supply, with potential to continue limited off-grid operation (island mode)	
Electricity	Reporting information regarding energy storage	None	Current state of charge (SOC) data available	Actual values and historical data	Performance evaluation including forecasting and/or benchmarking	Performance evaluation including forecasting and/or benchmarking; also including predictive management and fault detection
Electricity	Reporting information regarding electricity consumption	None	reporting on current electricity consumption on building level	real-time feedback or benchmarking on building level	real-time feedback or benchmarking on appliance level	real-time feedback or benchmarking on appliance level with automated personalized recommendations
Electric vehicle charging	EV Charging Capacity	not present	ducting (or simple power plug) available	0-9% of parking spaces has recharging points	10-50% or parking spaces has recharging point	>50% of parking spaces has recharging point
Electric vehicle charging	EV Charging Grid balancing	Not present (uncontrolled charging)	1-way controlled charging (e.g. including desired departure time and grid signals for optimization)	2-way controlled charging (e.g. including desired departure time and grid signals for optimization)		

Domain	Smart ready service	Functionality level 0 (as non-smart default)	Functionality level 1	Functionality level 2	Functionality level 3	Functionality level 4
Electric vehicle charging	EV charging information and connectivity	No information available	Reporting information on EV charging status to occupant	Reporting information on EV charging status to occupant AND automatic identification and authorizition of the driver to the charging station (ISO 15118 compliant)		
Monitoring and control	Run time management of HVAC systems	Manual setting	Runtime setting of heating and cooling plants following a predefined time schedule	Heating and cooling plant on/off control based on building loads	Heating and cooling plant on/off control based on predictive control or grid signals	
Monitoring and control	Detecting faults of technical building systems and providing support to the diagnosis of these faults	No central indication of detected faults and alarms	With central indication of detected faults and alarms for at least 2 relevant TBS	With central indication of detected faults and alarms for all relevant TBS	With central indication of detected faults and alarms for all relevant TBS, including diagn osing functions	
Monitoring and control	Occupancy detection: connected services	None	Occupancy detection for individual functions, e.g. lighting	Centralised occupant detect ion which feeds in to several TBS such as lighting and heating		
Monitoring and control	Central reporting of TBS performance and energy use	None	Central or remote reporting of realtime energy use per energy carrier	Central or remote reporting of realtime energy use per energy carrier, combining TBS of at least 2 domains in one interface	Central or remote reporting of realtime energy use per energy carrier, combining TBS of all main domains in one interface	
Monitoring and control	Smart Grid Integration	None - No harmonization between grid and TBS; building is operated independently from the grid load	Demand side management possible for (some) individual TBS, but not coordinated over various domains	Coordinated demand side management of multiple TBS		

Appendix 2. Reserve obligations and their respective sizes as stipulated by Fingrid

The table was retrieved from Fingrid. (n.d.).

Reserve product	Obligation	Procurement channel	Maximum contracted capacity
Frequency Containment Reserve for Normal operation (FCR-N)	121 MW	Yearly market Hourly market Other Nordic countries Russia Estonia	68 MW 253 MW - 90 MW[15] 35 MW[16]
Frequency Containment Reserve for Disturbances Upwards (FCR-D up)	≈ 290 MW	Yearly market Hourly market Other Nordic countries	345 MW 733 MW -
Frequency Containment Reserve for Disturbances	170 MW	Yearly market Hourly market	186 MW 248 MW

[15] The procurement from Russia has been suspended at the moment.
[16] A temporary increase to 50MW is viable.

Downwards (FCR-D down)[17]		Other Nordic countries	-
Fast Frequency Reserve (FFR)	0 to 60 MW	Hourly market Estonia	123 MW 50 MW
Automatic Frequency Restoration Reserve (aFRR)	46 to 62 MW (certain hours of the day only)	Hourly market Estonia Russia	- - -
Manual Frequency Restoration Reserve (mFRR)	880 – 1300 MW	Balancing energy and balancing capacity markets Fingrid's reserve power plants Leasing reserve power plants	- 927 MW 278 MW

[17] The procurement initiated in 2022 and volumes will be gradually augmented. The peak demand is around 280 MW.