OULUN AMMATTIKORKEAKOULU

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ENERGY STORAGE OPTIMIZATION FOR HYBRID RENEWABLE ENERGY

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Opinnäytetyö
Kevät 2024
Energia- ja ympäristötekniikka
Oulun ammattikorkeakoulu

ABSTRACT

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Energy and environmental engineering

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Title of thesis: Energy storage optimization for hybrid renewable energy
Supervisors: Sami Orajärvi and Jukka Ylikunnari
Term and year when the thesis was submitted: Spring 2024
Number of pages: 42 + 2 appendices

This thesis aimed to identify the limitations and regulations for constructing a battery energy storage system (BESS) in the Puutionsaari project area and to develop a preliminary plan for the system. The plan includes basic technical parameters, site outlines, and an example layout. The Puutionsaari project is a hybrid renewable energy park with a planned capacity of 350 MW of wind power and a 100 MW solar park. It was determined that the BESS should be approximately 10% of the hybrid park's capacity with a charge time of two hours.

The data was collected through literary research as well as inquiries, meetings and e-mail conversations with battery storage suppliers. It was found that lithium iron phosphate (LiFePO4 or LFP) is the dominant technology, preferred due to its decreasing price, high efficiency, safety, and energy density, despite some risks like thermal runaway. Redox flow batteries were also noted but were less common.

A BESS includes batteries, a battery management system, a power conversion system, a cooling system, automatic fire suppression, and an energy management system. Standards for electrical installations form the basis for system requirements, but additional restrictions from local legislators, fire departments, and insurance companies need further investigation. Currently, permitting is relatively simple but expected to become stricter as regulations evolve. The Land Use and Building Decree and local building regulations in Haapavesi set general construction restrictions.

Technical specifications vary among suppliers. The design of the storage system is based on production data and connection point size, with a typical delivery time of around one year. This delivery includes the design, delivery, and installation of batteries and PCS with transformers, cabling, an Energy Management System (EMS), commissioning, and yearly maintenance. Excavation work may be performed by the supplier or subcontracted.

Potential BESS sites are around the southern substation due to restrictions around the northern substation, including property ownership and safety zones. The example layout shows a 40 MW BESS connected to the substation's transformer. A comparison between solar + storage and wind + storage could be useful for getting the best feasibility. Utilization of available services regarding, for instance, safety and optimization would enhance reliability of the system.

Keywords: Battery storages, energy technology, lithium-ion batteries, fire safety, project development

TIIVISTELMÄ

Oulun ammattikorkeakoulu
Energia- ja ympäristötekniikka

Tekijä: Maria Väliahde
Opinnäytetyön nimi: Energy storage optimization for hybrid renewable energy
Työn ohjaajat: Sami Orajärvi ja Jukka Ylikunnari
Työn valmistumislukukausi ja -vuosi: Kevät 2024
Sivumäärä: 42 + 2 liitettä

Tämän opinnäytetyön tavoitteena oli kartoittaa akkuenergian varastointijärjestelmän (BESS) rakentamisen rajoituksia ja säädöksiä Puutionsaaren projektialueella sekä laatia alustava suunnitelma kyseiselle järjestelmälle. Suunnitelmaan sisältyy järjestelmän tekniset ominaisuudet, alueiden rajaukset ja esimerkkiasettelu. Puutionsaari-hanke on uusiutuvan energian hybridipuisto, johon on suunnitteilla 350 MW tuulivoimaa ja 100 MW aurinkovoimaa. Akkuvaraston koon tulisi olla noin 10 % puiston kapasiteetista ja sen latausajan kaksi tuntia.

Tiedonkeruu toteutettiin kirjallisuustutkimuksen sekä kyselyiden, kokousten ja sähköpostikeskustelujen avulla akkuvarastojen toimittajien kanssa. Tutkimus aloitettiin tarkastelemalla BESS-ratkaisujen teknisiä näkökulmia ja asiaankuuluvia rakennussäädöksiä. Kävi ilmi, että litiumrautafosfaatti (LiFePO4 tai LFP) on yleisin teknologia sen useiden hyvien ominaisuuksien vuoksi.

Akkuvarasto sisältää mm. akut, akkujen hallintajärjestelmän, tehonmuunnosjärjestelmän, jäähdytysjärjestelmän, automaattisen palonsammutusjärjestelmän ja energianhallintajärjestelmän. Sähköasennusstandardit muodostavat järjestelmän vaatimusten perustan, mutta paikallisten lainsäätäjien, palokunnan ja vakuutusyhtiöiden asettamat lisärajoitukset vaativat lisätutkimuksia. Tällä hetkellä lupamenettely on suhteellisen yksinkertainen, mutta sen odotetaan tiukentuvan sääntelyn kehittyessä. Maankäyttö- ja rakennusasetus sekä Haapaveden paikalliset rakennusmääräykset asettavat yleiset rajoitukset rakentamiselle.

Mahdolliset BESS-sijainnit ovat Puutionsaari-hankkeen eteläisen sähköaseman ympäristössä, koska pohjoisen sähköaseman alueella on rajoituksia, kuten omistuskysymyksiä ja turva-alueita. Esimerkkiasettelussa on esitetty 40 MW akkuvarasto, joka on kytketty sähköaseman muuntajaan. Vertailu aurinko+varastointi ja tuuli+varastointi -ratkaisujen välillä olisi suositeltavaa parhaan hyödyn saamiseksi ja laajempi katsaus akkumarkkinoiden erilaisiin palveluihin, kuten optimointi- ja turvallisuuspalveluihin, voisi antaa objektiivisemman kuvan systeemin heikkouksista ja lisätä varmuutta lopulliseen suunnitelmaan.

Asiasanat: Akkuvarastot, energiatekniikka, litiumioniakut, paloturvallisuus, hankekehitys.

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Abbreviations

BESS – Battery energy storage system

A system for storing electricity that includes the batteries, power conversion devices, controllers, battery management and cooling systems, and automatic fire suppression.

BMS – Battery management system

Ensures that the battery modules of a BESS operate in pre-determined values.

DoD – Depth of charge

The amount of charge (%) taken out of the battery's total charge level.

EoL – End of Life

The point at which the battery must be decommissioned/changed due to its degradation.

EMS – Energy management system

A third-party subsystem of the BESS's controller that determines charging and discharging patterns, optimizes BESS performance as well as collects and analyzes data.

LFP – Lithium Iron Phosphate

A lithium-ion battery chemistry ($LiFePO_4$) *commonly utilized in the grid-scale battery systems.*

PCS – Power conversion system

The devices that convert the electricity bi-directionally between alternating and direct current and between low and medium voltages.

SoC – State of charge

The level of charge (%) in a battery cell relative to the battery's total capacity.

SoH – State of Health

Describes the operational condition of the battery (%) by how much of the nameplate capacity the battery can provide.

1 PREFACE

The aim of this thesis is to make a preliminary plan of a battery energy storage system (BESS) for the Puutionsaari hybrid renewable energy park. The scope includes limitations and requirements caused by laws, standards and other possible parties, a technical overview of the available battery systems and a comparison of different suppliers. This thesis has been made in the guidance and supervision of Sami Orajärvi from VSB Uusiutuva Energia Suomi Oy and Jukka Ylikunnari from Oulu University of Applied Sciences.

The Puutionsaari project, located in Haapavesi consists of wind power totaling to 350 MW in power and a 100 MW solar park. The construction phase is planned to start in 2025 and partial production in 2028. (1.) In the company's strategy for 2024, VSB Uusiutuva Energia Suomi Oy has specified an objective to incorporate battery energy storage technology into their projects. The focus is on battery storage systems that are available in a span of few years and fit the requirements for the Puutionsaari hybrid park.

In Finland, the growth in wind power production from 2021 to 2022 was 41 % and it contributed to 14 % of the total electricity demand (2). Finland has committed to reducing its greenhouse gas emissions to mitigate climate change effects and thereby has set a goal of increasing renewable energy production to cover over 50 % of the total energy demand by 2030. (3.) Because of the increasing volume and volatile nature of renewable energy production, energy storage solutions are needed to create stability, flexibility, and reliability for the energy sector. Battery energy storage systems, in short BESS, are currently the most promising available technology for large scale energy storing. (4.)

2 INTRODUCTION OF VSB

VSB Group is an engineering company founded in Germany in 1996 and focuses on renewable energy project development. It consists of operational companies of VSB in Germany, France, Poland, Romania, Finland, Italy and Croatia. VSB Uusiutuva Energia Suomi Oy (later in the text referred to as VSB) is the Finnish branch of the VSB Group located in Oulu, Finland. VSB Group has over 500 employees worldwide of which about 20 are in Finland. (5.)

Globally, there are over 700 turbines and 87 photovoltaic plants built by VSB Group totaling to 1300 MW installed capacity. In Finland, VSB realized and sold their first wind farm portfolio, “Juurakko & Karahka”, in 2022 with a capacity of 190 MW. (5.) There are also five projects in the development phase in Finland of which three are hybrid parks and the remaining two are wind farms (6).

The first step towards battery storage implementation by VSB Group was taken in Germany in 2019 with the pilot project “Battery Storage Wölkisch” that has a total capacity of 4.8 MW. The system, Siestorage, was supplied by Siemens but the batteries were from Samsung. The system was made of 660 lithium-ion battery modules and VSB carried out the development, operation management and construction of the project. (7.)

VSB is now looking to incorporate battery storage in Finland, specifically in their Puutionsaari hybrid park. The Puutionsaari project area consists of 4 000 hectares of land located 11 km to the west from the centre of Haapavesi, Finland. The plan includes around 350 MW of wind power generated with approximately 49 wind turbines and an additional 100 MW solar park. (1.) The general plan of the project layout was approved by the city government and council in 2021 and it is presented in figure 1. The plan is not yet legally validated. (8.)

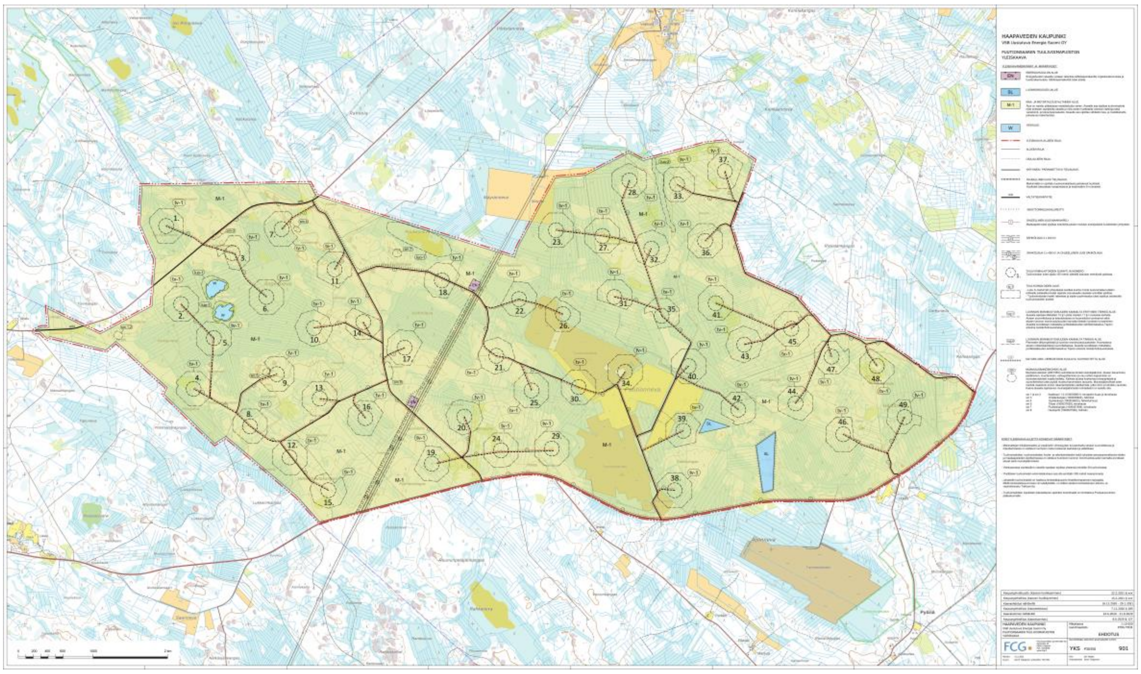

FIGURE 1. The general plan and site layout of the Puutionsaari project (8)

The construction plan of the site includes two 400 kV substations that connect the energy production to the national grid. These plans are done in cooperation with OX2. Their locations are on or near the areas assigned for energy management, marked in the plan with purple colour and code EN. Research for the BESS's placement should be focused near these areas to minimize costs for cable constructions. A new 400 kV overhead power line will be built next to the two existing 400 kV power lines. It starts from the northern substation and continues to the southwest. (9.) The preparatory plan of the substations is as follows:

Northern substation

- Two 33/400 kV transformers
- 33 connected wind power plants (~7 MW each)

Southern substation

- Two 33/400 kV transformers
- 16 connected wind power plants (~7 MW each)
- 100 MW connected solar park

It is to be determined if the battery energy storage system should be placed near the southern or northern station or split between the two. Ultimately, the power capacity of the substation's transformers determines the maximum power of connected energy production and storage. In the preliminary plan, there would be about 230 MW of connected power production on the northern substation and about 210 on the southern substation. The dimensioning is also affected by the source of power, the purpose of the battery and cost-effectiveness. The placement of the system depends on laws, standards and the project area's features. The purpose of the BESS in this project is to stabilize the electrical grid, increase profitability and balance changes between production and demand. (10.)

A closeup of the energy management areas is presented in figure 2. The northern EN area is at a close proximity to the wind turbine number 18 and to the border of the project area. The southern EN area also has two wind turbines, numbers 16 & 17, close-by and a snowmobile road right beside it.

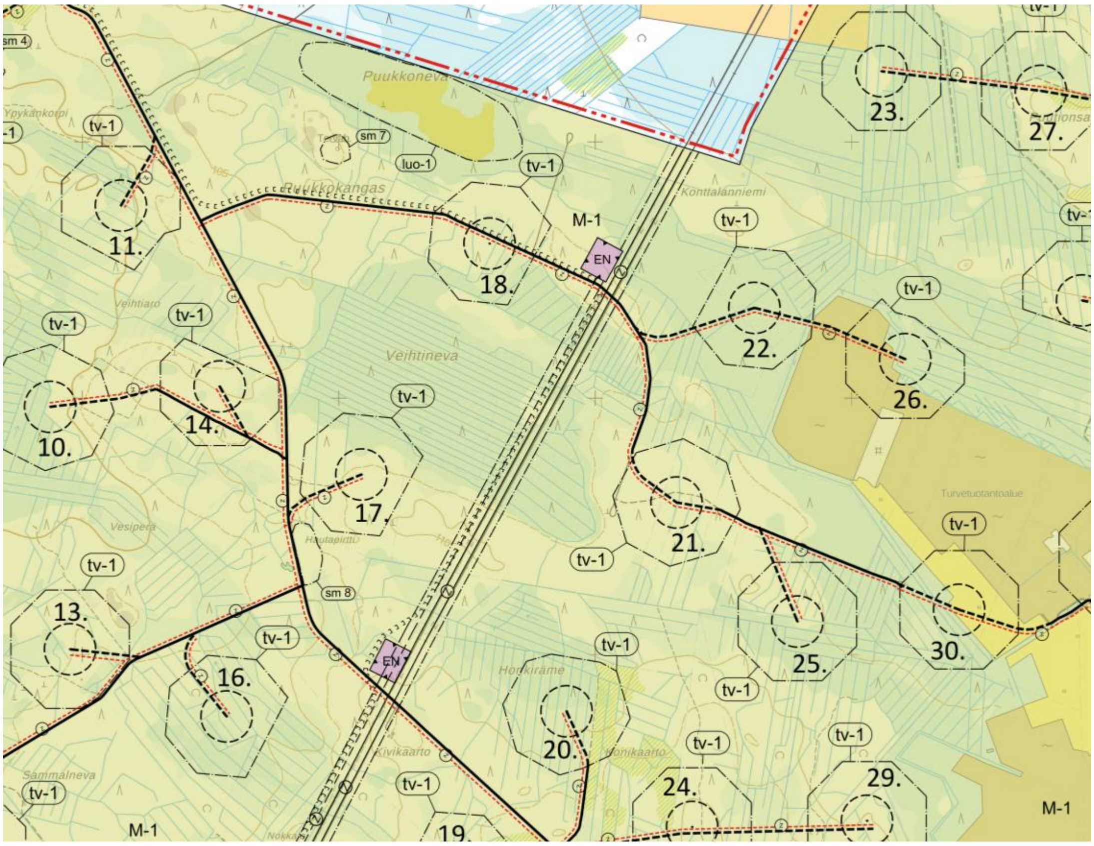

FIGURE 2. A closeup of the EN areas (8)

3 BATTERY ENERGY STORAGE SYSTEMS

Simply put, battery energy storage systems (BESS) are battery systems for storing energy in various commercial and technical applications. They consist of batteries, power conversion hardware and control logic and monitoring systems (11.) and they are the most scalable type of grid-scale energy storage. The battery storage market has seen fast growth in recent years and in the European Union, a series of policy action recommendations was published in 2023 to support greater deployment of electricity storage. (4; 12.)

Even though pumped-storage hydropower is globally the most used energy storage technology, grid-scale battery technologies are projected to be the largest contributor to storage growth. At the end of 2022, the total installed capacity of grid-scale battery storages came close to 28 GW, most of which was deployed during the previous six years. The United States and China, as the leaders of the market in 2022, each registered gigawatt-scale additions of battery storage. (4.)

3.1 Battery technologies

The most widely used battery types are lithium-ion, lead-acid, various flow batteries and variants of sodium, nickel, and zinc. (13, 151) The differences between common technologies used in grid-scale battery energy storage systems can be seen in table 1.

TABLE 1. Key properties of common battery technologies used in grid-scale ESSs (14)

	Li-ion	Flow	Na-S	Lead-acid
Specific energy (Wh/kg)	100 - 240	10 - 85	150 - 240	30 - 50
Specific power (W/kg)	500 - 2 000	45 - 166	150 - 240	180 - 200
Nominal cell voltage (V)	3.6 – 3.8	1.2 – 1.9	2	2
Energy efficiency (%)	> 98	> 75	75 - 90	75-85
Cycle life	1 000 - 10 000	6 000 - 14 000	> 2 500	500 – 1 000

Flow batteries consist of electrolyte solutions that contain two redox couples pumped through the battery cell stack. There are several variations of redox couples, the most common ones being vanadium (V/V), iron (Fe/Fe) and zinc-bromine (Zn/Br_2). The chosen redox couple affects the performance of the battery. (14.) Flow batteries typically have longer charge and discharge times scaling up to 12 hours (13, 209, 216).

The total capacity of operational vanadium redox flow batteries (VRFB) in 2020 was 130 MWh and more have been contracted and planned in the past few years (13, 205). The all-iron flow battery shows promise of future growth in the energy storage market as it is a nontoxic, nonflammable, and low-cost technology with a good life cycle expectancy. Zinc-bromine (ZBFB) is still in its early stages, and installations so far have been trial systems of under 1 MW, but the appeal is growing due to the low cost of the technology. (13, 209-210.)

The advantage of redox flow batteries is that their electrolytes do not degrade with cycles. The moving parts of the battery are the only ones that wear out. In the case of iron flow batteries, the electrolyte also does not corrode any internal parts which ensures that it can last its expected lifetime. (13, 217.)

Na-S batteries have been considered as a promising candidate for large scale battery storage because of the properties seen in table 1. Their downsides of Na-S batteries are the operating temperature requirement of 300-350 ˚C and their enhanced risk of fire due to the highly exothermic reaction between molten Na and S. (14.)

Lithium-ion (Li-ion) has the best overall properties with the highest specific power, nominal voltage, and energy efficiency (14). It’s cycle life, on the other hand, depends largely on how the battery is operated. An achievable cycle life for a grid scale energy storage is 5 000 - 10 000 cycles. (13, 184.) Lithium-ion batteries are the most widely used type of battery technology for grid-scale purposes (4) and due to decreasing prices and increased availability, their popularity is only growing (14). Therefore, the focus of this paper is on lithium-ion battery systems.

3.2 Lithium-ion sub-chemistries

When choosing a battery energy storage system, there is no specific formula for project developers and investors to determine the best solution. Even batteries based on similar technologies can have significant differences in performance. This is partly due to differing manufacturing processes, but the biggest impact comes from unique formulations of chemistry additives. (15.)

Lithium-ion batteries include a variety of chemistries. These variations have differing characteristics especially regarding their energy density and safety. In the early stages of lithium-ion utilization cobalt-oxide (LCO) was used exclusively, followed by manganese-oxide (LMO). The highest potential to store energy is in nickel-oxide (LNO) but with its thermodynamic sensitivity to abusive conditions, it is not safe to use unless it is mixed with the other two chemistries. Batteries with different ratios of nickel, manganese and cobalt are called NMC batteries and they have been extensively used as well as nickel, cobalt and aluminum (NCA) batteries. (13, 177.)

In contrary to the metal oxide cathodes, phosphate-based cathodes are known for their smaller risk of thermal runaway but, at the same time, the phosphate causes the battery’s energy density to be up to 20 % lower as well as decreased cell voltages. Phosphate requires carbon coatings or a metal dopant to become electrically conductive and improve its rate capability. The most common type of phosphate-based lithium-ion battery is the iron-phosphate known as LFP ($LiFePO_4$). (13, 177.)

3.3 Technical parameters

The most important technical aspects to consider when designing a suitable energy storage system are load characteristics, battery voltage, needed battery capacity, charge and discharge duration as well as transformer connection (16). In addition, aspects like depth of discharge (DoD) and cycle life significantly affect the battery’s usability and overall feasibility of the investment (13, 184).

Terminal voltages of battery cells are too low for grid level energy storages which is why they are connected in series to achieve nominal terminal voltages of 500-1500 V (13, 147). To find out how much energy a battery can hold, it’s rated capacity needs to be looked at. Rated capacity is expressed in ampere hours (Ah) and it indicates the amount of amperage a battery can provide for one hour. (17.) The capacity of a battery (C-rate) is commonly rated at 1C which means that a fully charged battery with 1 Ah rated capacity can provide 1 A of continuous current for an hour (18).

If the C-rate is higher than one, the battery can discharge quicker with a higher current, but there will likely be internal energy losses as some of the energy can be turned into heat. As a result, the capacity of the battery can be lowered by 5 % or more. The chemistry and design of the chosen battery determines how high the C-rate can be. Lithium batteries have an advantage in this aspect as they have the best tolerance of all battery chemistries for high C-ratings. (19.)

When the C-rate and the rated capacity of the battery are known, it is possible to calculate the available current in amperes with formula 1 and the amount of time it takes to discharge or charge the battery with formula 2 (19).

$$Cr * C = I, \qquad \text{(FORMULA 1)}$$

where
Cr = C-rate
C = Rated capacity (Ah)
I = Current (A)

$$t = 1/Cr, \qquad \text{(FORMULA 2)}$$

where
t = time (h)
Cr = C-rate

A battery with a C-rate of 0.5C and rated capacity of 2.3 Ah will be able to provide a current of

$$0.5C * 2.3\ Ah = 1.15\ A.$$

The amount of time the battery will take to discharge or charge fully is

$$t = \frac{1}{0.5C} = 2\ h.$$

Table 2 shows examples of calculated battery currents and charge times when the battery cell's rated capacity is the same (2.3 Ah) but the C-rate changes. When the C-rate is at 0.2C the battery can only provide a current of 0.46 amperes and it will take five hours for it to charge or discharge fully. A battery with a C-rate of 10C can provide a current of 23 A and can be charged or discharged in six minutes.

TABLE 2. C-rate's impact on a 2.3 Ah battery cell's current and charge/discharge time

Cr	C (Ah)	I (A)	t (h)
0.2C	2.3	0.46	5
0.5	2.3	1.15	2
1C	2.3	2.3	1
2C	2.3	4.6	0.5
10C	2.3	23	0.1

Rated energy is expressed in watt hours (Wh) and it describes the amount of continuous power flow in watts the battery can provide over an hour. Rated capacity (Ah) is the ratio of energy (Wh) and voltage (V) which means that all these factors impact the overall performance of a battery. (20) According to the SFS Standard 6000-5-57:2022, the capacity of the battery should be determined by the following formula:

$$C = \frac{P * t}{U}, \qquad \text{(FORMULA 3)}$$

where

C = battery capacity (Ah)
P = charging power (W)
t = operating time (h)
U = battery voltage (V)

The charging power of the battery can now be calculated with formula 3 which in the case of a 2.3 Ah battery cell with a voltage of 3.3 V and a C-rate of 0.5C is

$$P = \frac{C * U}{t} = \frac{2.3\ Ah * 3.3\ V}{2\ h} = 3.795\ W. \qquad (16, 8)$$

3.4 Cycle life and degradation

The longevity of the battery depends highly on the way it is used. In addition to keeping the battery in a suitable temperature range, charging and discharging processes must be optimized. Each cycle wears the battery down but charging or discharging the battery only partially will keep the degradation process slow. (21.) The term State of Charge (SoC) is used for describing the charge level in the battery cell relative to its capacity. At times, the term Depth of Discharge (DoD) is used to describe the amount of charge taken out of the battery's total charge amount. (22.) Lithium-ion batteries last longest when operated between 30 to 80 % SoC which means that the DoD should be only 50 % when aiming for optimal cycle life. The battery must be charged at temperatures above freezing and below 50 ˚C, the optimal temperature is at 25 ˚C. (21.)

State of Health (SoH) describes the condition of a battery cell, and it usually is presented in %. Ideally, the battery could provide 100 % of its nameplate capacity through its whole life cycle but, in reality, the battery will degrade over time. (22.) Cycle life is the number of times the battery can be discharged and charged before the battery has reached its end of life (EoL) capacity which is commonly rated at 60 % SoH for stationary storage systems. The battery's SoH percentage must be monitored as operating the battery below the 60 % point will accelerate the degradation process and possibly cause significant damage to the BESS. The battery must be replaced when the EoL capacity has been reached. (23.) When comparing a battery with a 100 % DoD (the battery is discharged fully) to a battery with an 80 % DoD the difference in cycle life can amount to 2000 cycles as is seen in figures 3 and 4 (24).

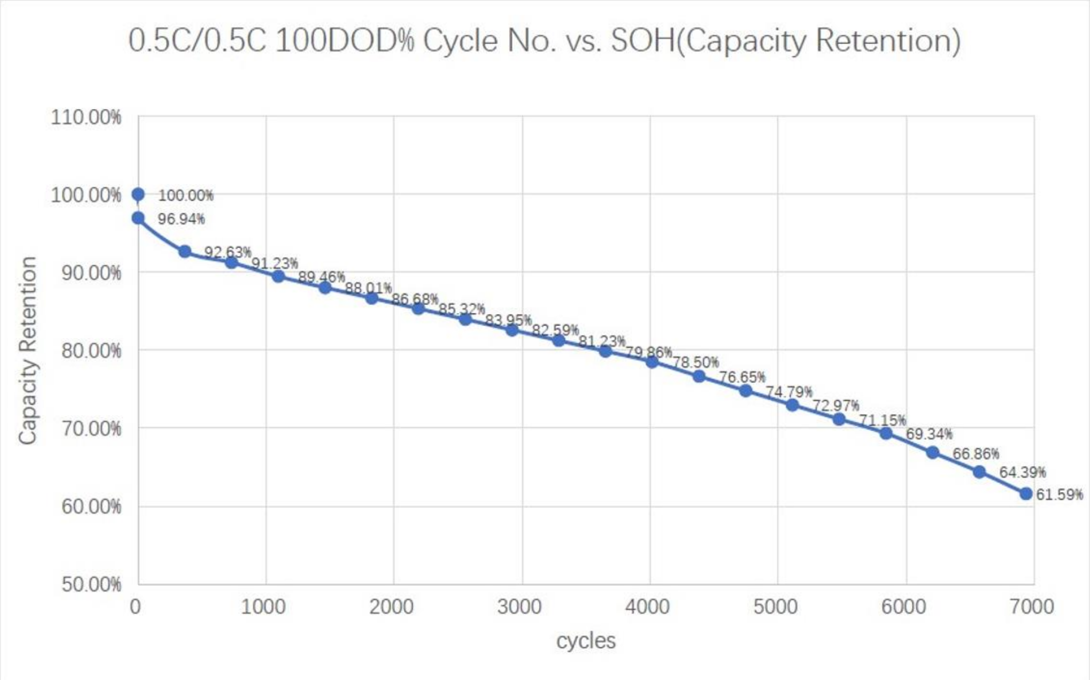

FIGURE 3. The degradation process of a two-hour battery with 100 % depth of charge (24)

The SoH starts to drop even before commissioning but during operation the battery's degradation can be significantly slowed down by decreasing the depth of discharge. With a 100 % DoD, a 280 Ah battery module rated at 0.5C reaches its end-of-life capacity after about 7000 cycles. Lowering the DoD to 80 % will slow down the degradation process, resulting in a cycle life of about 9000 cycles.

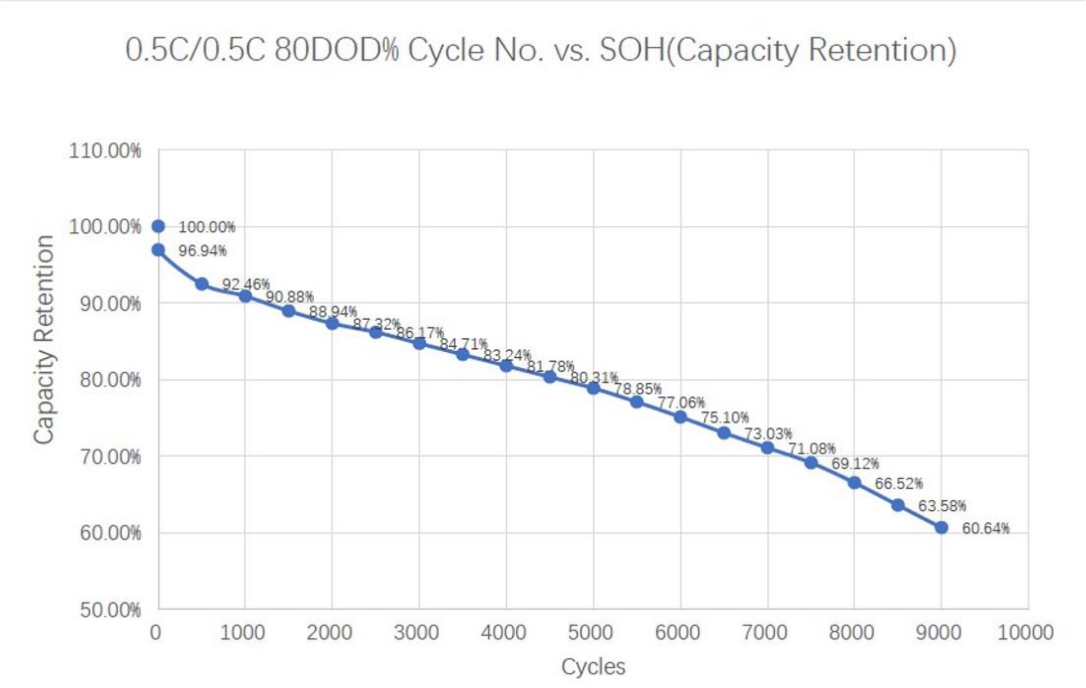

FIGURE 4. The degradation process of a two-hour battery with 80 % depth of charge (24)

By tweaking the mentioned operating parameters, the cycle life of the battery can be optimized for different needs. It should be noted that by setting the number of cycles per day at one, the battery lasts almost twice as long compared to operating with two cycles per day. For example, a 125 MW/125 MWh BESS degrades to about 60 % SoH in 11 years when operated at two cycles per day and 80 % DoD. The same system, when operated at one cycle per day can last for 20 years before it must be replaced. These are only approximations since it is not possible to predict the actual degradation speed of the battery. (24.) Instructional and required operating parameters for lithium-ion batteries can be seen in table 3.

TABLE 3. Operating parameters for lithium-ion BESS (21; 23)

Instructional	
State of charge (SoC)	Between 30 – 80 %
C-rate	Below 1C
Number of cycles per day	1
Storing	At 50 % SoC
Required	
Temperature range	0 – 50 ˚C
State of health (SoH)	Above 60 %

3.5 System components

Battery energy storage systems include various components which are depicted in figure 5. The most essential parts of the system are electrochemical cells which are connected in parallel and/or series to provide the wanted capacity and voltage. Several cells in a parallel-series configuration form a module and several modules arranged in racks constitute a battery string. (14.)

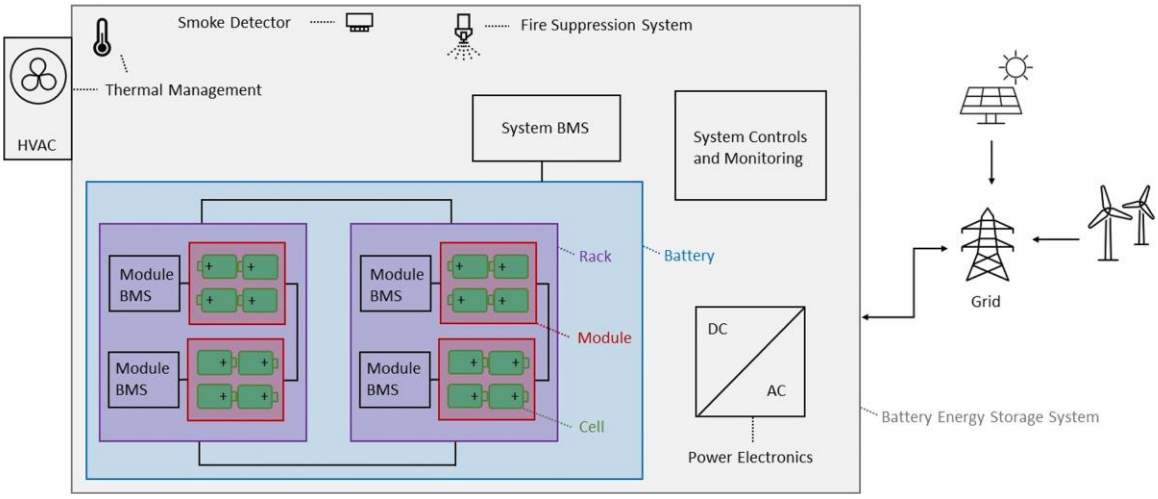

FIGURE 5. Battery energy storage system's integral components (14)

Any lithium-based system must have a Battery Management System (BMS). Its primary function is to protect the battery from damage in changing operational scenarios. In practice, the BMS ensures that the battery operates within pre-determined values for e.g. state of charge (SoC), state of health (SoH), voltage, temperature, and current. (24.)

As batteries store and deliver electricity as direct current (DC) while electrical systems and loads operate with alternating current (AC), a Power Conversion System or Hybrid Inverter is needed. These devices must be able to convert power bi-directionally, which means that AC power can be converted to DC power to charge the battery and the DC power from the battery can be converted to AC power to use in the grid or electrical loads. The PCS can be set to different operating modes and for it to be effective, it must have access to data from the battery. It can then, for example, automatically stop the battery from discharging at a set SoC point. (25.)

An example of the power electronics of a BESS are depicted in figure 6. They include a low voltage (LV) inverter, that changes the battery's direct current (DC) to alternating current (AC), a LV/MV transformer that converts to medium voltage (MV) and MV switchgear. There can be multiple battery containers or strings connected to one PCS unit. (26.)

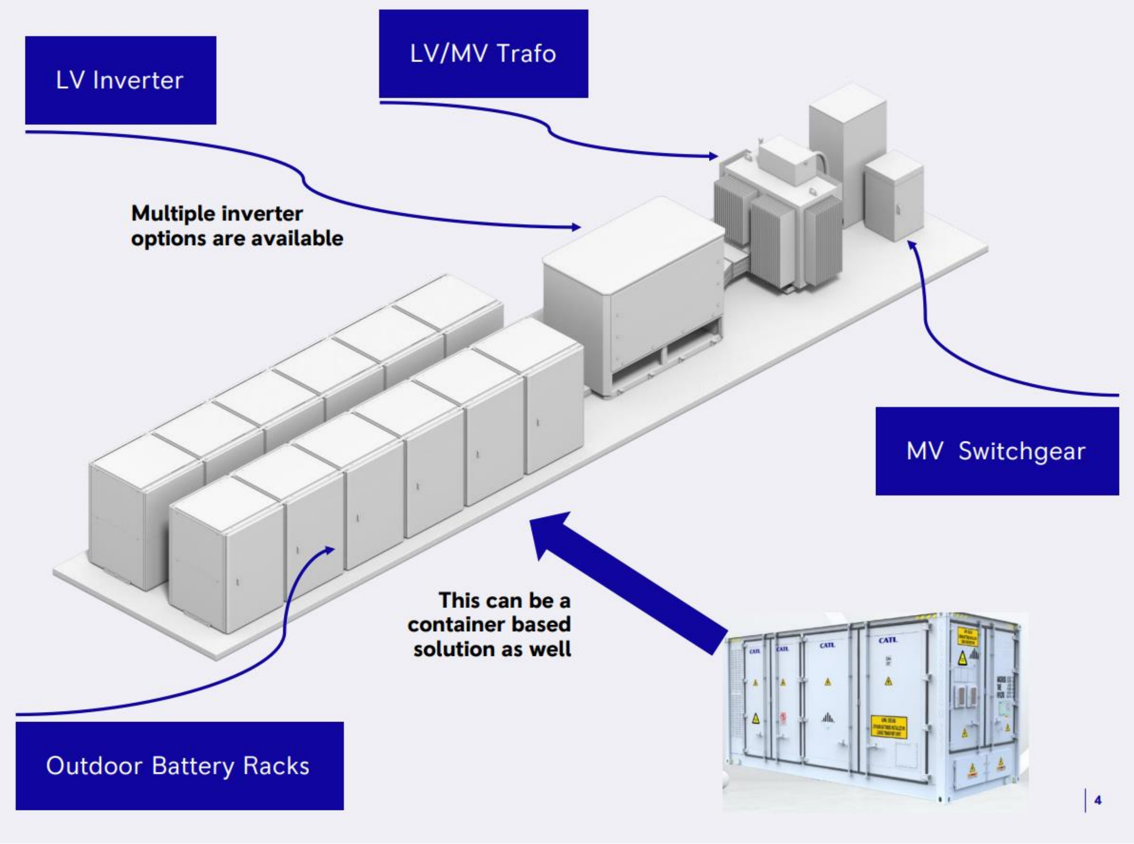

FIGURE 6. 3D-model example of the Rolls Royce BESS components (26)

In the case of solar + BESS applications two types of PCS configurations are possible, AC-coupled and DC-coupled. In the AC coupled system presented in figure 7, the battery is connected separate from the solar PV system to the AC side of the PV inverter. The battery has its own AC/DC inverter in this configuration. (25.)

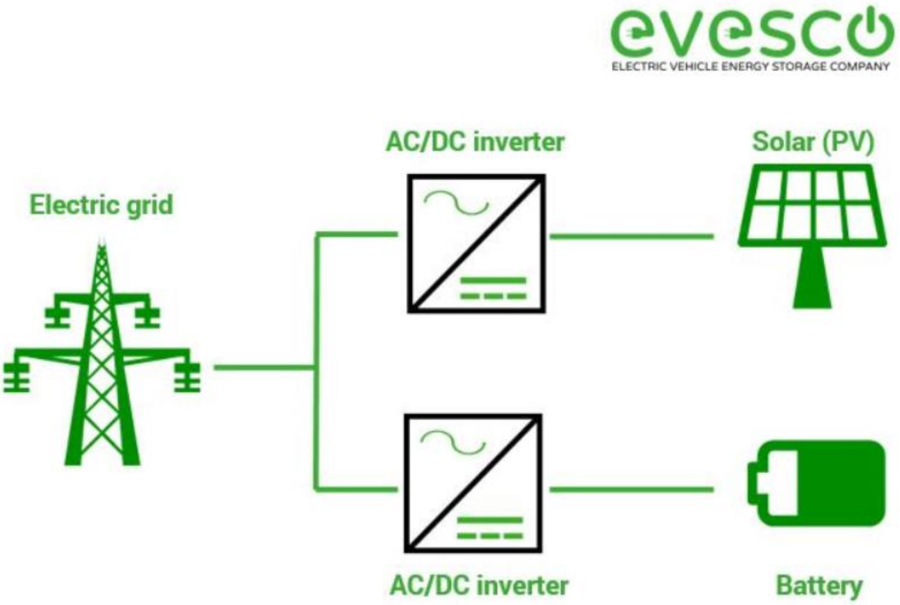

FIGURE 7. AC coupled solar + storage configuration (25)

Figure 8 shows a DC coupled option where the battery is connected to the DC side of the solar PV system and the two share a hybrid AC/DC inverter (25). Aspects, such as grid characteristics, legislation, and site availability will determine which of these options is the best choice. AC-coupled BESS have a higher cost and require a larger space but on the other hand they are more suitable for ancillary services as their response time is quicker. In the case of a DC-coupled configuration, removing the battery will result in having to reassess the size and the electrical design of the PV system. Even though it has a better efficiency, DC-coupled BESS is less flexible and resilient than AC-coupled, due to being reliant on a single inverter. (27.)

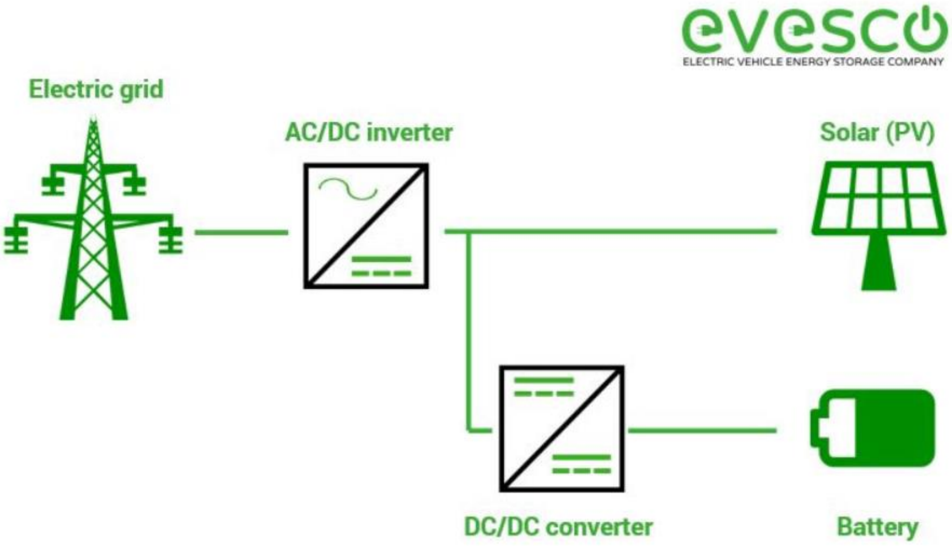

FIGURE 8. DC coupled solar + storage configuration (25)

The controller is the brain of the BESS, monitoring, controlling, protecting, communicating, and scheduling all its subsystems. The Energy Management System (EMS) is a third-party subsystem. It communicates with PCS/Hybrid inverter and BMS while also keeping up with external data from the electric grid, transformers, PV arrays, and loads. The EMS determines when and how the battery is charged or discharged, optimizes BESS performance as well as collects and analyzes data. (25.)

Heating, ventilation, and air conditioning (HVAC) is a compulsory part of a BESS because it ensures a safe temperature and good air distribution inside the battery system. Without a well-designed HVAC the battery system's longevity, safety and functionality will be negatively affected. Even with a thought-out thermal management system, the battery cells can overheat and cause thermal runaway which can result in a fire hazard. For that reason, a fire suppression system must be integrated in a BESS. It will activate through gas, smoke or heat detection and suppress the fire with an agent that cools down the battery and absorbs the heat. (25.)

In figure 9, two examples of battery configurations are shown. The figure from Merus power depicts a single battery container without power electronics, and the figure from Hitachi Energy shows what the battery modules look like in a string without a container. The PCS is also included in the figure.

FIGURE 9. Example of a battery container from Merus Power and a battery system with battery strings and PCS from Hitachi Energy (28; 29)

4 REGULATIONS AND STANDARDS

The requirements for battery systems used and installed in Finland are set by the European Union, Finnish legislation, and appropriate international and national standards. The European Union's new battery regulation (EU) 2023/1542 came into effect on August 17th, 2023, and it will replace the current battery directive 2006/66/EC in 2025. The new regulation encompasses a broad scope of batteries and distinguishes different battery categories according to their design and use. For the purposes of the regulation, energy storage batteries in private or domestic environments should be considered as industrial batteries. (30.)

The regulation places new requirements for battery manufacturers to ensure a low carbon footprint, minimal use of harmful chemicals and less rare materials needed from outside the EU. It also strives to achieve a high degree of circularity by setting rules on the collection, reuse and recycling of batteries inside the EU. (31.) The law implements some special requirements for industrial batteries that have a capacity of over 2 kWh. For example, the batteries must have a digital battery passport that can be retrieved through a QR code on the battery. Battery manufacturers must have proven and documented electrotechnical performance and sustainability parameters for their batteries. (32.)

To ensure the safety and sustainability of industrial batteries, the regulation demands battery energy storages to be safety tested as well as documentation on the minimum concentration of recycled cobalt, lead, nickel and lithium raw materials. Collecting and recycling of used industrial batteries must be executed similarly to consumer batteries, which means that a free national collection network is needed. (32.)

The Electrical Safety Act 1135/2016 obliges operators to design, construct, manufacture, repair, maintain and use electrical devices and systems so that they cause no threat to anyone's life, health or property. The electrical devices also should not cause excessive electrical or electromagnetic disturbance or be disturbed easily electrically or electromagnetically. (33, 6 §.) Electrical devices conform to safety requirements if they are in accordance with appropriate and official standards. If a device doesn't comply with the intended standards, conformance must be otherwise indicated. (33, 28 §.)

There are several standards that need to be looked at when designing, installing, maintaining, and using a battery energy storage system. The standards to be referred to for BESS installations using lithium-ion batteries are listed in table 4.

TABLE 4. Finnish standards in relation to lithium-ion battery systems

Standard	Relation to lithium-ion BESS
SFS 6000 – Low voltage electrical installations	Part 5-57: Selection and erection of electrical equipment. Erection of stationary secondary batteries.
SFS-EN IEC 62485 – Safety requirements for secondary batteries and battery installations	Part 5: Safe operation of stationary lithium-ion batteries.
SFS 6001 – High voltage electrical installations	Distance requirements for live parts of over 1 kV. Transformer installation requirements.
SFS 6002 – Safety at electrical work	Safety requirements for all electrical work.
SFS-EN 60079 – Explosive atmospheres.	Part 14: Electrical installations design, selection, and erection.

4.1 Placement restrictions

There are 18 km of 400 kV overhead power line to be built in the Puutionsaari project. (9) The Finnish transmission system operator Fingrid Oyj expropriates a limited right of use for the transmission line area. This restricts the landowners free use of the area and creates new requirements to ensure safe operation. (34, 7.)

The width of the building restriction area depends on the power line type and voltage level. The main limits to land use planning are described in the expropriation permit of the power line and the purpose for these restrictions is to prevent an electric safety hazard caused by the lateral swing of the overheard power line. No buildings or integral parts of a building should be constructed on the building restriction area. A permission from Fingrid is needed before placing or building structures that exceed two meters in height but, for electric safety reasons, an intersect statement is needed for all structures placed on the transmission area. These structures include, for example, poles, roads, fencing, lighting fittings and power lines. The restriction also concerns underground construction. (34, 22.)

Fingrid has published a collection of system requirements for energy storages, SJV2019, which will be updated in 2024. Its current version includes specific study requirements for grid energy storage systems of 30 MW or more. When planning a system of this scale, Fingrid must be requested to assess the need for these studies. If Fingrid finds it necessary, the research should be done at the latest when designing the battery storage system's connection point, in collaboration with Fingrid and the network operator. (35, 11.)

According to Haapavesi's building regulations the distance between a building and the construction site's border outside the town plan zone should be equal to the height of the building but no less than five meters (36, 10). A fire hazardous building (e.g. a transformer) must not be placed closer than 15 meters to an area owned or managed by another or closer than 20 meters to a building situated on such area. Other buildings should be placed at a minimum distance of 10 meters to a building located on another's land unless there is a specific reason to decrease the distance. (37, 57 §.)

Buildings must be placed at a minimum distance of 30 meters to the center line of a main road and 20 meters to other public roads. The distance requirement to a private road is 12 meters without a permit. (36, 10.)

A minimum distance of three meters between two battery containers is recommended by insurance companies (24). According to Tukes, the distance should be at least one meter and all flammable materials should be placed at least one meter away from the battery. The batteries can be placed in open racks if the battery room is closed, and only authorized personnel are able to get inside. To ensure that an unauthorized person is not able to get inside the battery space, there must be a locked, sufficiently high fence around the area, a locked room for the batteries or a locked fireproof cabinet inside other spaces. (38, 67.)

4.2 Transformer installation requirements

When designing transformer installations, the risk of fire hazards must be considered. The safety requirements for installations placed outside depend on the amount of fluid stored inside the transformer. Parts that are not essential to the transformer itself should have a great enough distance in respect to the transformer to avoid damages from potential fires caused by it. Oil volumes of over 200 liters are required to have sufficient distances G_1 and G_2, which are presented in table 5. (39, 69-70.)

TABLE 5. Distance requirements for oil-insulated outdoor installed transformers (39, 70)

Liquid volume (l)	Distance G1 (m)	Distance G2 (m)	
200 <…< 2 000	3*	8	
2 000 ≤…< 20 000	5*	10	
20 000 ≤…< 45 000	10	20	
≥ 45 000	15	30	
* Distances must still conform to building regulations			

The distances between outdoor electrical units and other structures can be determined through a risk analysis conducted by the holder of the units in question. If an automated fire extinguishing system is used, the distances G1 and/or G2 can be reduced. G1 is the distance between transformers or a transformer and fireproof construction surfaces, and G2 is the distance to a flammable construction surface (39, 70). Figure 10 shows the distances G1 and G2 in practise.

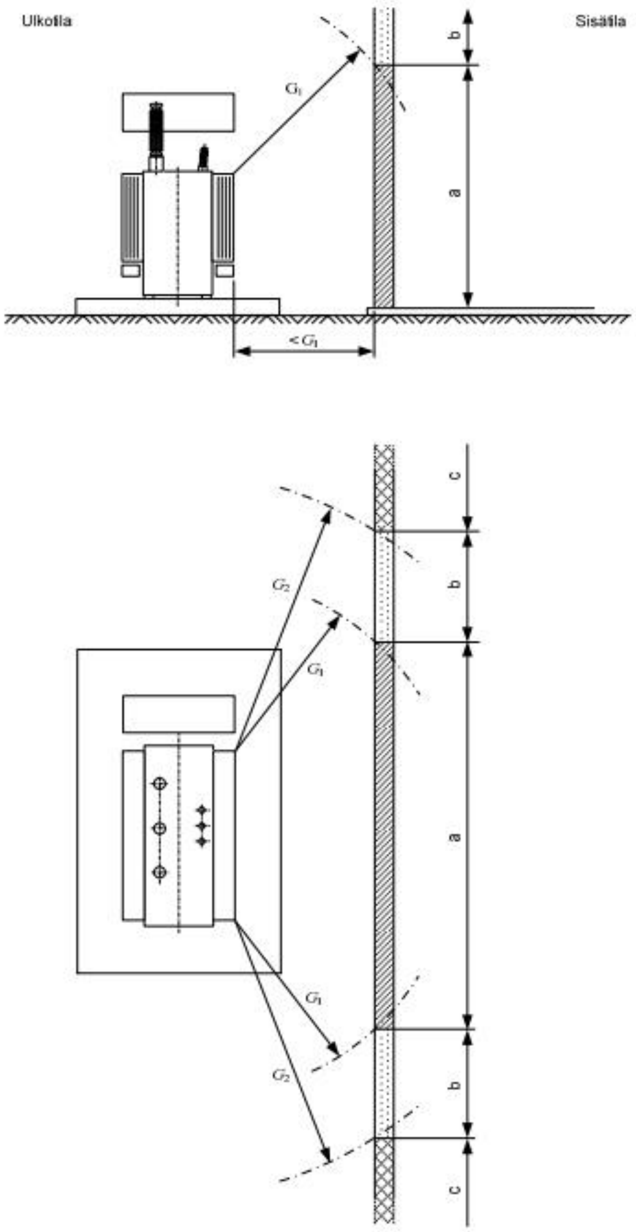

FIGURE 10. Distances G1 and G2 between an outdoor transformer installation and other structures (39, 77)

If there are any unprotected live parts on the site, that exceed 1 kV in voltage, they must be placed according to SFS 6001 High voltage electrical installations standard. For outdoor installations, the size of the transformer's collector tray is recommended to be calculated with formulas 4 and 5. (39, 74.)

$$L = L_t + 0.2H_t, \qquad \text{(FORMULA 4)}$$

where

L = length of the collector tray

L_t = length of the transformer

H_t = height of the transformer with the expansion tank

$$W = W_t + 0.2W_t, \qquad \text{(FORMULA 5)}$$

where

W = width of the collector tray

W_t = width of the transformer

H_t = height of the transformer with the expansion tank

Standard IEEE 980 recommends that the collector tray expands to at least 1.5 m outside any part containing fluids (39, 74).

4.3 Operation

The assembly and installation of the batteries should be done by following the manufacturer's guidelines precisely. It is recommended that the installations are done by the manufacturer that has carried out testing of the product and ensured that it suits the application. (38, 79.) Batteries can only be charged in a space that does not have a risk of explosion unless it has been approved in the certificate and the battery manufacturers guide includes a permission to do so. If the requirements set by a fit international or national standard (for example IEC 62485-2) are met, battery rooms are not normally considered as explosive spaces. (40, 45.)

However, each lithium-ion battery technology imposes risks of fire, electric shock and chemical hazards. The risk of fire is based on the thermal runaway phenomenon in which the battery chemicals degrade, catch fire and burn when the temperature rises. The rise in temperature can be caused, for example, by an outside heat load or a short circuit. (38, 8–9.)

The battery space must have air conditioning to keep the temperatures in the guidelines provided by the manufacturer and to direct the produced warmth outside the batteries. There should not be any sources of heat, like direct sun light or a heating system, near the battery. (38, 66.)

The SFS-EN IEC 62485-5:2021 standard specifies that batteries with maximum voltages above U_{DC} 120 V with respect to earth or between terminals, should be located in an enclosure with restricted access achieved by locks or other equivalent means. (41, 15.) If the battery is placed inside a separate container, there must be a three-meter vicinity around the container that is free from flammable vegetation and fire loads. All snow barriers must be eliminated to ensure direct access to the batteries for the fire department. (38, 66.)

The battery system should include an appropriate Battery Management System. In larger batteries, a remote monitoring system is needed to gain timely data on the state of the battery. A decent monitoring system will alert when the set thresholds are not met. Examples of such deviations are overvoltage or undervoltage, short circuit, temperature deviation or gas formation. (38, 67.)

The automated fire suppression system can be a sprinkler system that cools down the battery, a noble gas-based system or both. In closed spaces, Argon is a commonly used gas for fire suppression. Gas does not damage the control and electrical systems like water does but it also doesn’t effectively cool down the battery. Additionally, it can cause formation of non-combustible fire gases which can lead to explosion. It is recommended that the battery space includes a separate system for removing the gas. (38, 67.)

4.4 Maintenance

Maintenance of the batteries also sets requirements for the space. For emergency situations there must always be an exit of at least 750 mm free of obstacles. When the highest battery voltage exceeds 120 V DC, the requirements of standard IEC 60364-4-41 on Electrical installations and prevention of electric shock should be applied. Increasing the size of the exit is recommended so that temporary equipment can be placed on the exit space. The increased size can be based on the size of the temporary equipment, or it can be 1.5 times its size or 1200 mm if no other data is available. (41, 26.)

5 CONCLUSIONS FROM SUPPLIER RESEARCH

The focus of the market research was on companies that can provide MW scale battery solutions that are realizable in a few years. Capacity range in the beginning was 60-180 MWh but was later set at 80 MWh. Focus was on batteries with a charging time of two hours or more so the battery's charging power should be 40 MW. Most of the available battery energy storage systems are either 20 ft standard battery containers or open battery racks in a hall building. Some suppliers recommend placing the batteries and PCS skids inside a building due to the cold temperatures in Finland. (42; 43.) Considering that lithium-ion technologies shouldn't be operated in below freezing temperatures, a hall solution seems to be the best option (21).

The specifications and system features differ between companies. LFP seems to be the main chemistry used in the battery cells. (24; 42; 43.) The PCS system can be delivered as a turnkey "skid" solution. It has been installed and tested before delivery and it fits inside an open roof 40 ft container. At the site it can simply be lifted out and placed into the system. The PCS usually includes the inverters, a transformer, medium voltage equipment, an auxiliary transformer, and an UPS. (43; 24.) Placing a system of this scale inside a hall building does create challenges for PCS installations as they must be constructed and tested at the site (43).

The design of the storage system is done based on the production data and connection point's size. Most suppliers estimate the delivery time to be about one year. (24; 26; 42; 43.) For the Puutionsaari project, the delivery time does not create an issue. The delivery usually includes at least the following:

- The design, delivery and installation of batteries and PCS with transformers
- Cabling between the containers and PCS skids
- Energy Management System (EMS)
- Commissioning
- Yearly maintenance.

There are differences in whether the excavation work will be carried out by the supplier company or left up to the customer. It can be subcontracted to a company that the customer wants to use, but in some cases the supplier company carries it out by themselves. (24; 42.)

Technical data provided by the suppliers also vary. A comparison of different battery suppliers is shown in table 6. The voltage range is about 750-1500 VDC per battery rack and the cell capacity up to 306 Ah (24; 26; 42; 43). The maximum capacity of a unit is reported per PCS unit or per battery container unit. For example, Hitachi Energy (company C) promises a maximum nominal capacity of 6 MWh per PCS unit (43) and Merus Power's PCS unit can have up to 5 MW of connected battery power. With a 2-hour charge time, the connected nominal capacity per PCS can be 10 MWh. (42.)

TABLE 6. Comparison of battery energy storage systems from different suppliers (24; 26; 42; 43)

Company	A	B	C	D
Product type	Containerized BESS	Containerized BESS	Varies	Battery racks in a hall
Battery voltage DC (V)	1 331.2		1100–1500	
Cell capacity (Ah)	280–306	280		
Charge time (h)	1–2	1–2	0.5–4	1–2
Max connected capacity to PCS unit (MWh)		~4.4	6	10
LV/MV transformer power (MVA)	4.39 MVA	~2.2 MVA	1–12	1–5
Battery size	20 ft container	20 ft container	Varies	20 ft container
PCS size	Varies	40 ft container	Varies	Max 10.9 x 2.4 x 1.2 m

An important aspect to note is that the guaranteed capacity of the battery is lower than the nameplate capacity as shown in figure 11. Rolls Royce expects that the AC usable capacity at 33 kV is at best 85.8 % of the nameplate capacity. They guarantee an 83.8 % usable capacity that considers possible challenges caused by inaccuracies in SoH and SoC evaluations. (26.)

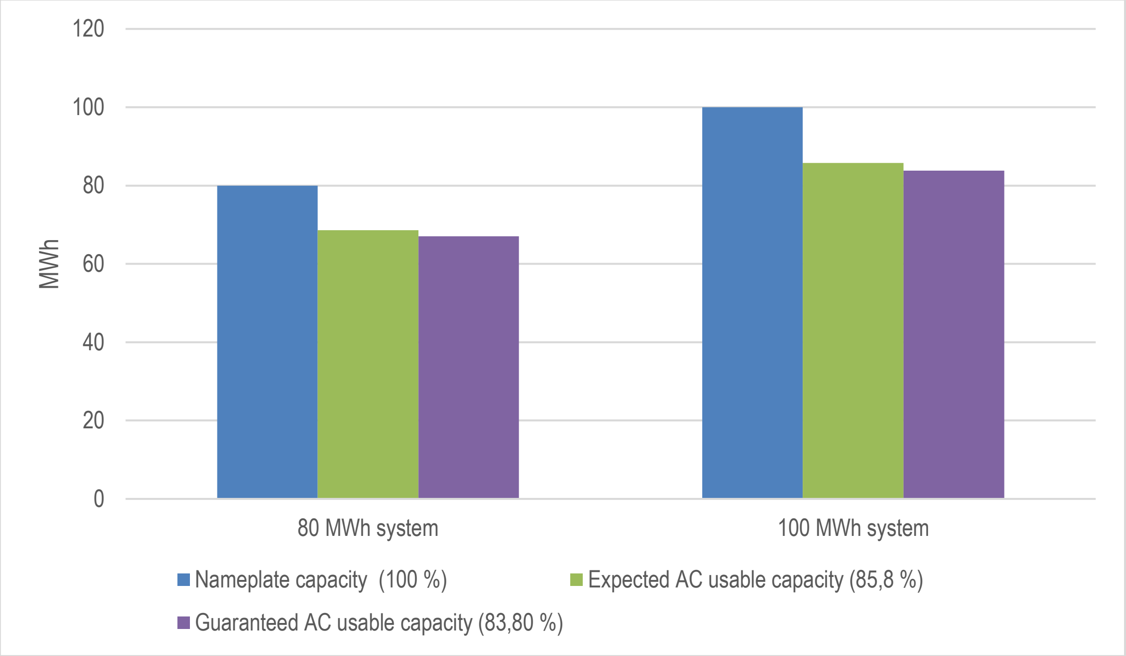

FIGURE 11. The capacity loss of a BESS before commissioning (26)

5.1 BESS sites and layout

The possible BESS locations are depicted in appendix 1. The locations were chosen based on the Puutionsaari project plan in figure 1, property data, laws and regulations and the substation plans provided by VSB. The possibility of connecting a battery storage to the northern substation was ruled out due to several restrictive aspects. The area around the northern substation is owned almost completely by one party. If they don't approve of the battery storage on their property, there are no other reasonable site options left as the Puutionsaari project area's border prevents going further north. Other limiting aspects are the wind turbine safety zone next to the substation and the new power line that is being planned in cooperation with OX2. The substations' preliminary plan also implicates that there is more 'room' for additional capacity at the southern station as it has 20 MW less connected power supply.

All the prospective locations are situated around the southern substation. The restricting factors include wind turbine safety zones, the high voltage powerline, properties without contracts and built environment.

An example layout of a 40 MW battery energy storage system can be seen in appendix 2. It considers the standardized safety distances and the minimum requirements from insurance companies.

6 DISCUSSION

The main goal of this thesis was to find out the limitations and regulations for battery energy storage construction in the Puutionsaari project area and create a preliminary plan of the system. The plan includes basic technical parameters of the system, outlining the sites and creating a layout for the system. Based on these findings, project development continues at VSB.

The Puutionsaari project is a hybrid renewable energy park that includes 350 MW of wind power and a 100 MW solar park. In the beginning of the research, it was determined that the size of the BESS should be about 10 % of the hybrid park's capacity. The needed charge time was set at two hours. Other technical specifications were not specified. The two possible locations to be looked at were the surroundings of the two substations at the project area. Based on these attributes, the research started with an overview on the technical aspects of BESS solutions and the regulations that can restrict the construction. Lastly, an exploration on suppliers was conducted to determine what the available technologies are.

After only a quick overview on different suppliers, it was imminent that the dominant technology is currently lithium iron phosphate ($LiFePO_4$), more commonly known as LFP. Another technology that had a decent number of suppliers was redox flow. Some companies had different options for battery chemistry, but most were shifting their focus on LFP. The cause for this is probably the decreasing price which gives the technology more utilization opportunities and makes the investment profitability higher. This technology is also safer than most other battery technologies though it does include a risk of thermal runaway that can lead to a fire. Lithium-ion batteries in general have high efficiencies and energy densities. Their downside is the difficulty of predicting their life cycle. The degradation of the battery starts even before it is commissioned, and its flexibility is not great. Operating the battery should be done according to the supplier's guidelines and recommendations to ensure the longevity, safety, and cost-effectiveness of the system.

An integral part of a battery energy storage system are the batteries which can be open racks in an enclosure with restricted access or placed in 20 ft containers that are placed outside. The system also includes a battery management system, a power conversion system, a cooling system, automatic fire suppression and an energy management system.

It was found that electrical installation standards create the basis for the system requirements but other parties, such as local legislators, the fire department or insurance companies, might have more restrictive guidelines which must be further examined. Currently, the permit procedure is still light, but it will likely be changed in the future as legislation catches up with the quickly developing market. The Land Use and Building Decree as well as the building regulations set by the town of Haapavesi determine the general restrictions for construction. After outlining the BESS locations, the process continues with a more thorough investigation of the sites. A permission for further land use and construction activities is needed from the property owners. Conversations with battery suppliers should be continued at the same time.

Large scale battery energy storage systems are a fairly new part of the energy system, especially in Finland. Making a thorough analysis of different market players is difficult because there are no standardized solutions or system configurations and companies are not always willing to share their information publicly. Technical terms have enough variations to make research confusing and naturally, each company will try to make a good impression on a potential customer, so the provided data should not be taken at face value. Many companies were ready to give out better data only after VSB's representatives had discussed with them and they saw a real sales opportunity. It is to be expected that companies do not want to waste time on a discussion that they might not get value from. What was interesting to see, was that often a company I had contacted on my own seemed to be interested in having a meeting until I told them about my thesis and asked if it is okay to use them as a reference. Luckily, this was not always the case and some companies turned out to be immensely helpful. Ultimately, more specific data was always behind an NDA, which made technical comparisons quite difficult.

The problem with many battery technologies is the need of rare materials and as a result the high prices. Due to the low cost and safe materials in LFP technology, the deployment of large-scale battery storages will grow at a rapid pace in the future. This will help the energy system with its current problems regarding the growth of volatile renewable energy sources.

A comparison of solar + storage and wind + storage could be included in project development but from discussions with some suppliers, the presumed choice seems to be solar + storage because of its better predictability. The battery could also be charged with electricity from the grid when solar energy is not available, and electricity prices are low. It is important to keep contact with different BESS suppliers and determine the best solution through careful consideration of supplier reliability, suitability to the project and availability. There should also be further investigation into the different companies that are providing services for BESS optimization and safety.

Overall, this study was very interesting and rewarding. At the beginning, I wasn’t sure if this type of system would be a reasonable investment at current time as I didn’t know much about the battery markets. I was intrigued by the topic and the opportunity to get a glimpse of what project development looks like. The results of the market overview were difficult to comprise into a coherent form which hindered the progression of the thesis. Ultimately, the focus was shifted to outlining the locations for the systems and making an example layout that considers the restrictions found in the research.

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