YRKESHÖGSKOLAN NOVIA

Renewable Energy and Grid Code Testing

Grid Code Testing of Battery Energy Storage System

Mikael Hudd

Degree Thesis

Thesis for a Novia (UAS) - degree

Master of Engineering, Automation Technology

Vaasa 2022

DEGREE THESIS

Author: Hudd Mikael

Degree Programme and place of study: Master of Engineering, Novia University of Applied Science

Specialisation: Automation Technology

Supervisor(s): Joachim Böling

Title: Renewable Energy and Grid Code Testing

Date: 11.12.2022 Number of pages: 43 Appendices: 0

Abstract
Testing of grid-required standards is an essential part of power plants. Battery storage systems are relatively new, and their specific requirements are constantly in development. The technology is new as well. The combination of these factors creates areas of a practical need for companies to qualify their power plants for operation.

Requirements were collected and cross-referenced with internal experts and specialists. As a result, a template and case-specific commissioning procedure was developed. This procedure was validated through emulation and trials in the field before a final witnessed test with the grid operator.

The work identifies areas in need of development, and control operations to be implemented to fulfil the grid operator's requirements. A practical discussion was held with the commissioning manager to implement a hands-on guideline to perform the needed tests and which data to collect. There was a focus to highlight parameters and acceptance criteria.

Language: English
Key Words: Renewable energy, Electrical grids, Commissioning, Battery energy storage

Common abbreviations and definitions

- BESS - Battery Energy Storage System.
- BOP - Balance of Plant. BOP equipment often refers to Switchgear, Transformers Cabling, and Grounding and can include the civil works for a power plant. Can be used to refer to anything that is not directly part of the power generation equipment.
- Capacity, or energy reserve - combined energy reserves of the batteries. Measured in MWh or kWh.
- CCGT - Combined-cycle gas turbine
- C-rate - The ratio of Power/Capacity in a BESS. A 10MW, 20MWh plant is a 0.5C installation. Common C-rates are 1, 0.5 and 0.25. A 0.25C rate facility is a "4-hour installation".
- FCR - Frequency containment reserve. Frequency supporting features of BESS.
- FFR - Fast frequency response. Frequency supporting features of BESS.
- FRR - Frequency restoration service. A secondary backup to support the frequency.
- FSM - Frequency sensitive mode. Same as above.
- GEMS - Greensmith Energy Management System. A digital platform that includes several functions including the control system and controller in Wärtsilä BESS installations.
- ICE - Internal combustion engine
- LFSM - Limited frequency sensitive mode. Alarm situation that requires action from all operators
- LV/MV/HV - Low Voltage, Medium Voltage and High Voltage. Voltage ranges defined for power plants and electrical installations:
    - Low voltage is typically under 1000 volt
    - Medium voltage is 1000 - 30000 volts

    - High voltage starts where medium voltage ends, typically around 50000 volts. The term high voltage varies by discussion and type of installation.

- PCS - Power conversion system. Comes in various sizes and technical specifications. Also often called Inverters. Their task is to convert from one frequency to another, i.e., DC to AC but can also exist as DC to DC.

- POI/POC - Point of interconnection or common coupling. A definable point both contractually and technically where a power plant connects to the grid.

- Power - the output of the plant, measured in MW or kW.

- PPC - Power Plant Controller, The GEMS is a type of PPC.

- PV - Photovoltaic Cells, a type of cells used in Solar Power Plants to convert solar energy to electricity.

- RES - Renewable energy sources

- RoCoF - Rate of Change of Frequency. Anti-islanding indicator.

Table of Contents

1 Introduction

A need for evaluating the Belgian grid code requirements for an active project was identified. There was a need to do a detailed investigation into the interpretation of the Belgian grid code and how it applies to the equipment of Wärtsilä. A general look by experts concluded that it will be possible to pass the test, but the details were not defined. Further, there was a need for a step-by-step instruction for the commissioning team on how to execute the plan and what data to record. An emphasis on clear pass criteria and readymade tables to record data was desired. The plan for this work was laid out, and several discussions with equipment specialists and software engineers to enable the system to do the desired actions. Verification of the system was to be done through simulations and field tests. Finally, to be witnessed by representatives of the transmission system operator, or grid operator.

Grid code testing is a set of tests that varies by country, region, type of installation as well as which type of power generation and technology are used for the generation of power. The goal of these types of tests is to prove the functionality of the storage system as well as the reliability for the grid operator. For a power plant to be allowed to operate and take part in market operations, the grid code tests and applications must be approved. This specific type of battery power plant is referred to as a "*Type C*" installation as determined by the Belgian grid code. Each type has a slight variation in requirements for the tests to be performed. A combination of connection voltage at the point of interconnection, as well as energy capacity, defines the *Type*.

The battery system in this installation and the focus of this thesis includes:

- Batteries in modular containers
- A combiner panel for the modular containers
- Inverters, including transformers and ring main units
- Battery plant controller (control system)

The power plant contains switchgear of different levels of voltages and traditional equipment such as a grounding network, safety equipment as well as a control room. These systems will not be of focus in this thesis. The thesis will focus on the tests for the operation of the battery systems and the inverters.

To pass the requirements of the grid standard, certain tests need to be performed to show that the installation can perform and be relied upon. The goal, and the first research question is whether the equipment can fulfil the grid code requirements. An in-depth study of the applicable sections of the Belgium grid code will take place, cross-referenced with technical specifications of the equipment, and systems involved. Support from technical experts from different technical fields will be available. Once proven that the requirements can be fulfilled, the second part of the research is to develop a project-specific commissioning program that can further be adapted to a general template. This thesis work will include coordination of developing features, or modules, for the power plant controller in order to facilitate testing of the requirements.

1.1 Wärtsilä

Wärtsilä describes themselves as: *"Wärtsilä is a global leader in innovative technologies and lifecycle solutions for the marine and energy markets."* (Wärtsilä, 2022c)

Wärtsilä was founded in 1834. Revenue for 2020 was 4.604 billion euros. Employing around 18000 persons in approximately 80 countries with a global presence. Marine and Energy are the two main businesses within Wärtsilä. The battery-focused Energy Storage & Optimization department is located within the Energy business unit. In their own words, their vision:

"Wärtsilä Energy Storage & Optimisation is leading the introduction of disruptive, game-changing products and technologies to the global power industry. We are integrating energy solutions that build a resilient, intelligent, and flexible energy infrastructure – ***unlocking the way to an optimized sustainable future.***

By integrating renewables, energy management technology, and storage with traditional energy resources, we reinvent clean energy production from the largest and most complex grids to the most remote and essential islanded grids." (Wärtsilä ES&O, 2022)

2 Typical power plant layout

In power plants, the common electrical layout is designed around voltage levels and transportation of energy. (Jenkins & Ekanayake, 2017)

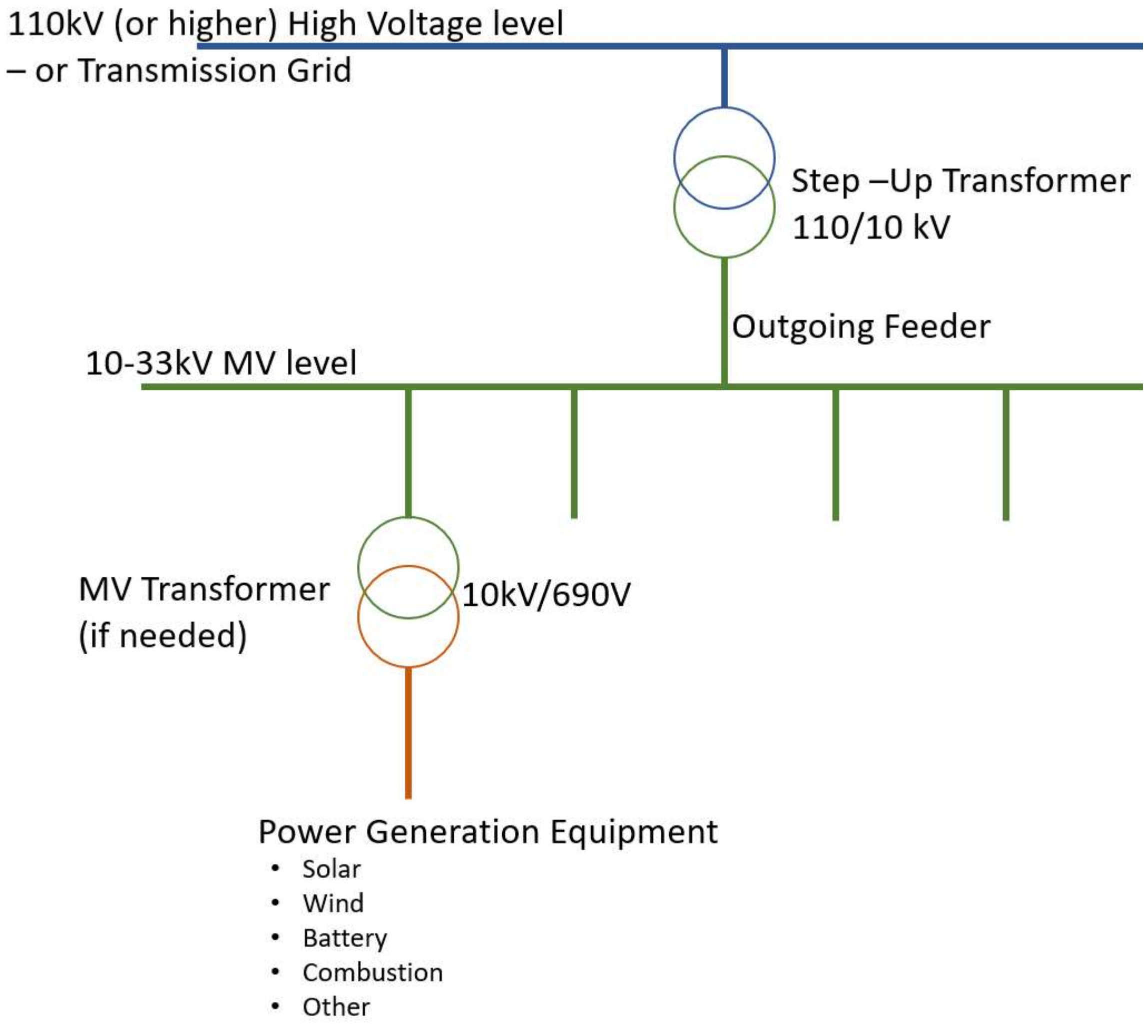

Figure 1: a typical layout of a powerplant with busbars.

Power plants are often built near high voltage substations or near a transmission line. When the power plant is connected at such a point, it is often referred to as the point of interconnection or common coupling. The voltage at the point of interconnection is referred to as transmission voltage and is typically in the range of 130-330kV, though it can also be higher. As per the laws of physics, a higher voltage enables the grid (and cables) to have a reduced current at the same energy level. In cabling and electrical installations, the losses stem from current, not from voltage. A reduction in the current results in fewer losses when energy is transferred. Connected between the substation and the power plant is a step-up transformer. The step-up transformer increases/decreases the voltage in the desired direction. The medium voltage level is often referred to as an MV switchgear. Voltage levels are typically 10-30kV. The medium voltage switchgear can be thought of as a “collection” equipment of electrical energy for all power generation equipment on one site. This layout is common and similar across multiple power plant types. e.g., wind, hydro, solar, battery, and many more.

The HV, MV, and transformer equipment can be referred to as the balance of plant equipment. BOP equipment includes cabling, and grounding, and, can include the civil works for a power plant. BOP can be used to refer to anything that is not directly part of the power generation equipment. The exact configuration, size, and location of the balance of plant equipment vary to match the specification and requirements. Commonly, low-voltage switch gear, grounding-, and DC systems are needed. Further, there are civil works as well as cabling and installation works that vary between power plants. The physical geographical properties of the location will have an impact on how a power plant is designed. The same equipment, but in two different locations can have different layouts even if they are electrically equal.

Globally, most of the energy demand is covered by synchronous generators. These generators are powered mainly by large fossil fuel-based power plants or hydropower installations. These types of power plants are easy to control on demand and the technology and control is familiar. Compared to renewable energy, which humans have far less experience with, other types of power generation have been used for a long time. The energy generation for most renewables is instantaneous and offers more challenges for operation and control. Another difference between conventional power generation and renewable sources is the generator. Renewable energy power plants often lack the rotating mass of a generator and instead rely on power conversion systems or inverters.

3 Renewable energy

"One of the greatest challenges facing our world today is climate change, brought about by the emission of greenhouse gases into the atmosphere in large part due to the massive use of fossil fuels to satisfy our society's ever-increasing energy demands." (Kang et al., 2022)

A transition to cleaner energy generation is required. Renewable energy sources offer multiple ways to solve this problem, while in turn, they offer challenges of their own. (Kang et al., 2022)

Andrea Herbst proposes a scenario in Möst et al., (2021): energy systems are not to be viewed as purely technical systems. Instead, they are to be viewed as socio-technical systems. Through the ever-changing dynamic between society and technology, the behaviour of people is changed. This can be seen in the transformation process as a measure of success, not only technology and economics; but also, societal preferences have an impact on policies and changes in society. In the future, the design of European energy systems, i.e., the optimal mix of decarbonization and flexibility, will be determined by:

- Economic constraints
- Technology
- Resource availability
- Preferences within society

Change is one of the common factors for all of the above.

In their text Möst et al. (2021) presents two scenarios to account for socioeconomic and socio-political changes. Their work is part of the REflex analysis. (REflex, 2022)

3.1 Background and drivers in Europe

Möst et al. (2021) describes different scenarios and drivers within Europe. There are several deals, goals, and agreements all with the target to reduce climate impact. For example, *The European Green Deal* was presented to the European Commissioning at the end of 2019. The target of the green deal is for Europe to be the first climate-neutral continent with no net greenhouse gas emissions by 2050. Separately, there are gas reduction emission targets for

2030. The goal is to reduce gas emissions to 50-55% when compared to gas emissions in 1990.

The REflex project charts a path of current goals achieved and a reference project established. The “high” scenario accounts for more ambitious policies and change. This scenario is further split into a centralized and decentralized model. Whereas the baseline reference project is considered a more adequate or average scenario. The “High-RES” model has a higher target for GHG emissions, a higher requirement for a share of renewable energy sources, as well as a higher requirement for energy efficiency. Drivers behind these higher targets are an increase in energy and CO_2 prices.

The moderate model, or Mod-RES as it is referred to as establishes the baselines based on the policies that have been implemented by end of 2015. I.e., no new policies are introduced into this model. “*The Mod-RES scenario emphasizes the continuation of existing policies on climate change mitigation, innovation, value systems, and economic growth. In particular, the Mod-RES scenario assumes that the current balance between the government and private sector is maintained in the future, and free trade remains a prime goal of international cooperation*.” (Möst et al., 2021)

The High-RES scenario is based on an increase in strong policies to reach goals in mitigating climate change as well as goals within society and for the economy. The economic growth is on the same level as in the Mod-RES model, while an increased partnership is considered to balance the impact on the environment and society. Health and education budgets are increased worldwide, institutions are of increased importance. E.g., EU and UN. While new ways of cooperation are discovered.

3.2 Decentralised Energy

Renewable energy enables a positive change in energy structure within the power grids. Burger et al. (2020) have expectations that decentralised renewable energy will lead to large improvements in the energy infrastructure across Europe. They compare the potential to the same changes that were noticeable with the development of the cell phone and the effect it had on communication infrastructure across Europe. There is a case, or possibility, that the future of the power generation portfolio is not the same as it used to be. Utilities might have a reduced presence and other technology-based companies might have an increased presence in the portfolio of Europe, and other developed countries. For example, the producers of electricity might reside in the manufacturing-, communication-, or information sectors.

Burger et al. (2020) expects micro-producers and start-ups to have an increased impact on the development of both the technological and economical aspects of the future in power generation. Core values such as business model, revenue stream, and risk allocation are expected to evolve.

The change is not only in the business model itself but also across the whole chain of stakeholders. Decentralisation is expected to occur and has already occurred for the technology, operation as well as ownership of energy. This decentralisation can be seen in smaller generation units but a larger number of units. The units are spread out over a larger geographical area instead of being focused on one small area. Compare wind power to a fossil fuel power plant. Several systems are becoming bi-directional instead of single-direction large utilities. Battery energy storage and home-produced energy are examples of new operators that can utilise the bi-directional properties. The owners of utilities have changed. Compared to older models, nowadays the utilities often have market niches and focus on certain features and services. For example, selling only “green energy”. (Burger et al., 2020)

3.3 Wind power

Generating electricity from the wind is one of the more cost-effective ways of harnessing renewable energy and increasing numbers of wind turbines are being installed in many countries. (Jenkins & Ekanayake, 2017)

This chapter is based on the works of Jenkins & Ekanayake, (2017).

Wind power has a history of multiple centuries, early adaptions were used to grind corn. In the USA wind turbines have had a vital role to power water pumps for agricultural demands. Historically, the low price of oils resulted in little interest in wind power. As a result of the 1973 oil crisis wind turbine interest increased. Several governments started the development of large turbines.

Table 1:Early wind power turbine projects, their size and year.

Country	Size, Diameter [m]	Power [MW]	Year
Germany	100	3	1982
USA	91	2,5	1982
UK	60	3	1988

Unfortunately, due to complications from predictions of the forces from the wind on these large wind turbines, the turbines never became available for commercial operation. Simultaneously, the development of small and uncomplicated turbines started elsewhere. Development and improvements on the small turbines lead to successful larger turbines that are now available. In modern wind turbines, composite materials are used to resist the forces that nature and the operation of the equipment exert on the turbine. Rotational speed can be varied in all modern wind turbines. The dynamic loads of larges turbines are managed with the assistance of control systems.

The advantages of wind power are cheap electricity, fast delivery times as well as a relatively large generation (up to 7MW). While disadvantages are often listed as ugly, noisy, and varied output due to the nature of wind. If the wind farms instead are built offshore, the advantages would be:

- Less (visual) impact on surrounding nature
- Mean wind speed is higher
- Less turbulence in the wind

Drawbacks for offshore are:

- Increased costs, both from the continuous operation and initial investment

Common practice and design are three-bladed wind turbines as they have proven to be most accepted by people. The aesthetics of the three-blade symmetry is favourable. Public perception remains one of the key challenges to overcome for successful wind turbine projects. The noise from wind turbines depends on the wing tip speed of the blades, rotational speed for equal energy generation is proportional to the number of blades. When built offshore, turbines can be constructed with fewer blades and a higher rotational speed, as the noise is not near settlements.

The power, P_{WT}, of a wind turbine can be calculated as,

$$P_{WT} = C_P P_{AIR} = C_P \frac{1}{2} \rho A U^3$$

Where:

- C_p is a factor called power coefficient. This coefficient is manufacturer specific and is the ratio of captured power from the wind to available power in the wind.
- ρ is the density of air. 1,25 kg/m^3
- A, is the swept area of the rotor
- U, is the free wind speed

A typical wind farm project has about 65-70% of the costs tied to the turbines and their erection. The rest consists of Balance-of-Plant equipment and project management costs. For the offshore project, the BoP costs are more than half of the total costs. A favourable approach to cost optimization is to build big wind turbine parks. Costs such as grid connection and project management costs have a reduced overall impact on the total project costs when compared to the cost per MW, for large projects. To reduce costs and increase reliability as well as the availability of components, a line-to-line voltage of 690V AC is often selected. 690V AC is suitable as it is considered a low-voltage installation. And spare parts and off-the-shelf parts are readily available. A medium-voltage transformer is often located within the tower or next to it. 10kV or 30kV are typical MV levels. Cables are connected to a step-up transformer to further increase the voltage and reduce losses when energy is transported. This voltage is referred to as transmission voltage.

3.4 Solar power

The goal of a solar power plant is to use the energy provided by the sun and transform it into either electric energy through photovoltaic cells or thermal energy.

This chapter about solar power is based on Jenkins & Ekanayake, (2017).

Two different classes of solar beams are defined:

- *Direct or beam radiation is the solar radiation received directly from the sun without it having been scattered or deflected by the atmosphere*
- *Diffuse radiation is the solar radiation received from the sun after its direction has been changed through scattering in the earth's atmosphere caused by clouds and particles.*

Solar power systems can be described as either flat panel systems or mirror systems. Systems to increase the irradiance 5- to 10-fold cannot make use of diffuse radiation. To solve and assist in the optimization of such systems, a system that tracks the sun is implemented to re-orientate the mirrors (or lenses). The counteroffer is a significantly simpler system of fixed equipment. Systems built around the collection of solar energy are less frequent, and only profitable in a narrower latitude band due to the geometry between the Sun and the Earth.

3.4.1 Terminology and units

Units used to describe solar power:

- *Irradiance (W/m^2) is the rate at which solar radiant energy is incident on a surface. The symbol G is normally used.*
- *Insolation (J/m^{2}or kWh/m^2) is the incident energy per unit area on a surface. This is found by integrating the irradiance over a specified time, typically a day although periods of a month or a year are also used. The symbol H is normally used for insolation over a day.*

Example data for five January days in California,

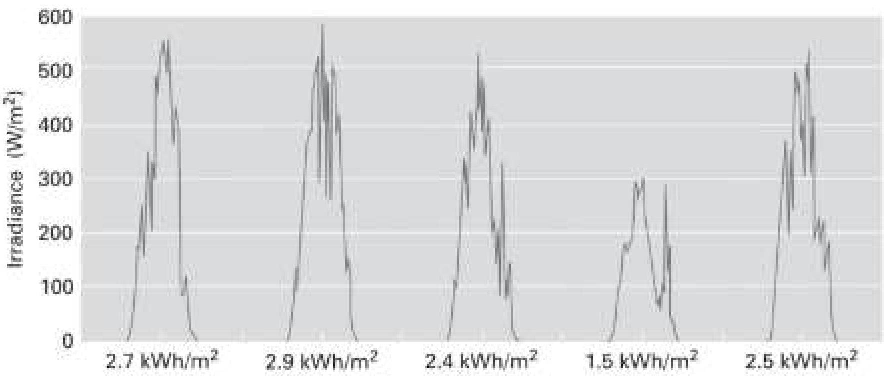

Figure 2: Solar irradiance in California over five days in January. ~~p.141~~ (Jenkins & Ekanayake, 2017, p. 141)

The graph illustrates hourly variation due to weather and day/night cycle. Notable that day four was cloudier than the other days.

Data from the EU Joint Research Centre (European Commission, 2022) shows the solar irradiance in Cardiff:

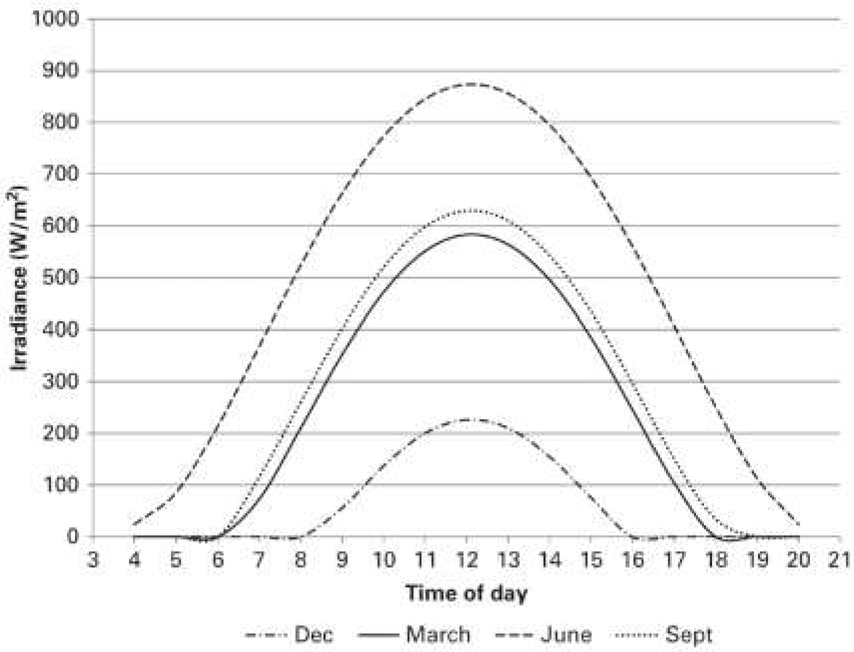

Figure 3: Irradiance variance over the seasons in Cardiff. (Jenkins & Ekanayake, 2017, p.141)

As the picture illustrates, there is a significant difference between summer and winter. Both the irradiance and duration available are reduced heavily in the winter. Clouds have been ignored in this data set, i.e., a perfect scenario is displayed. The difference between March and September is due to atmospheric absorption. Water vapour is one factor that contributes to this difference.

Further study on the topic of solar power availability and variations through the year and seasons can be found in Chapter 4.3 of Renewable Energy Engineering by Jenkins & Ekanayake, (2017)

3.4.2 Photovoltaic systems

"The direct generation of electricity from solar energy by photovoltaic panels is one of the most attractive and rapidly growing renewable energy technologies." (Jenkins & Ekanayake, 2017) Increased volumes in manufacturing combined with government incentives have stimulated rapid growth. Installation options are typically roof-mounted or on frames in large farms. Solar power is beneficial both in grid-connected applications as well as off-grid applications. PV cells have an expected technical lifetime of more than 20 years with minimal maintenance costs.

BloombergNEF, (2022), predicts that solar + storage will become the common norm and play a larger impact in future projects and how the market reacts and plan its operation around bid windows. Data on the growth of Solar power plants:

Table 2: Solar power installations for years 2010 and estimated until 2030.

Year	Installation Estimate [GW]	Increase from the previous year	Cumulative install base since 2010 [GW][1]
2010	18	-	18
2011	29	61 %	47
2012	31	7 %	78
2013	41	32 %	119
2014	45	10 %	164
2015	56	24 %	220
2016	75	34 %	295
2017	99	32 %	394
2018	108	9 %	502
2019	118	9 %	620
2020	144	22 %	764
2021	183	27 %	947

[1] For the comparisons in this table, end of 2009 is treated as a 0GW install base.

2022	228	25 %	1175
2023	236	4 %	1411
2024	241	2 %	1652
2025	252	5 %	1904
2026	266	6 %	2170
2027	277	4 %	2447
2028	292	5 %	2739
2029	312	7 %	3051
2030	334	7 %	3385

The data surprised Bloomberg. Based on the analysis in 2020, the installed capacity for 2022 was projected at 206 GW. Actual numbers are 10% higher than the best-case prediction. Price estimates are positive, and increases in production, as well as raw material supply, project the price to fall from 28 US cents in 2021 to 23 US cents for the second half of 2022. Polysilicon production is estimated to be up by 39% in 2022 from 2021 levels. (BloombergNEF, 2022)

Crystalline silicon is often referred to as first-generation PV cells. The second generation is defined by its thin film construction. Significant cost reductions can be achieved with second-generation PV cells. Second-generation PV cells utilize a reduction in the volume of needed semiconductor materials applied to an inert substrate. Material for the second generation includes CIGS – Copper Indium Gallium diSelenide and CdTe – Cadmium Telluride. Third-generation cells introduce new materials called *Perovskite material*, which is a dye-sensitized and organic/polymer technology based.

Photovoltaic cells convert light to electricity through the P-N (positive-negative) junction of silicon. If connected to an external circuit, DC power can be exported. For most commercial applications, additional equipment is needed. The DC power can be stored in batteries or connected to the grid through power conversion systems (inverters).

The advantages of Photovoltaic energy conversion:

- *Photovoltaic cells generate electricity with no moving parts and can be packaged into robust modules that require very little maintenance and have a life of more than 20 years.*

- *Established solar cell technologies are stable and have efficiencies that are broadly constant over time.*
- *Photovoltaic systems can be distributed on the roofs of buildings or constructed as large solar farms.*
- *Photovoltaic systems have limited environmental impact, and, at present, schemes usually enjoy public acceptance.*

3.4.3 Thermal solar power

This chapter will cover beneficial applications and power plants based on the heat of the sun. The main uses cases are:

- Heat for buildings
- Heated water
- Collection of heat to reach the high temperature for applications in power generation and processes

Use cases are generally split into high and low heat. High heat is temperatures above 150 °C. Low heat is under 150 °C. For the UK alone, 75% of heat demand is in the low-temperature range. This is more than 40% of the UK's total energy demand. 80% of this demand is generated through natural gas. Any reduction in required heat for buildings, for example through solar power, would be a direct impact on gas needs. Several initiatives exist in the UK to improve the heat efficiency of buildings. Government and local council standards require tougher thermal performance from new buildings. Where possible, these improvements are applied to older buildings. To increase the rate of adaption the government offers financial support to encourage more improvements. Challenges have been historical buildings. The preservation of aesthetics and functionality requires large budgets. In some other countries, Japan and Greece for example, domestic hot water needs are often covered by solar heaters. For a deep dive into domestic applications of solar power, pages 204 to 229 of (Jenkins & Ekanayake, 2017)provides further material and insights.

Concentrated Solar Power (CPS) is the means of focused thermal energy through mirrors and lenses onto a solar tower or in parabolic troughs. Often aided by solar tracking, known as heliostat. Compared to photovoltaic systems, there are far fewer thermal solar power plants. For high-temperature applications, the collected heat energy is used either directly in industrial applications or to power a turbine-generator pair.

The technology used for thermal solar applications has been known for more than a hundred years. Applications for markets and business needs have existed for over 30 years. Despite this, the total install base around the year 2017 is less than 5GW for thermal solar application. PV applications were more than 394GW by the end of 2017. Jenkins & Ekanayake (2017) are positive on the outlook for high-temperature thermal power of the future. A major contributor to the possible success is the integration into conventional power plants. Both thermal solar power and conventional turbine power have shared equipment in the turbine and generator as their mechanism of transformation of heat into electrical energy. In practice, the design would allow for solar-based electricity generation with combustion as a backup. Thermal solar has the potential to become a valuable add-on to strengthen the cost-effectiveness of the investment.

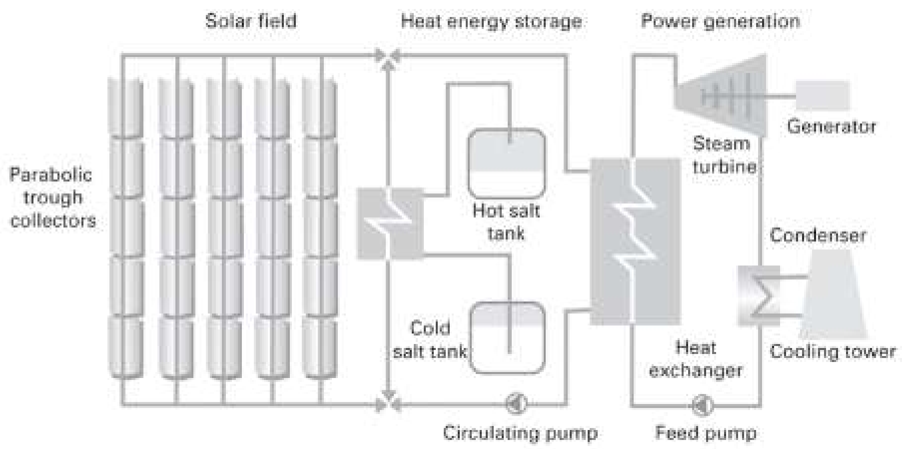

Figure 4: Solar power plant layout example. (Jenkins & Ekanayake, 2017, p. 232)

Figure 4 layout is designed with parabolic trough collectors.

The selection of location can prove a challenge. One major drawback of thermal solar is, the same as for photovoltaic cells; at temperate latitudes, the system is out of phase with the sun. Energy and heat demands are in the highest demand in winter and cold periods when there is the least amount of solar energy available.

Irradiance will continue to pose challenges to thermal power plants' cost-effectiveness. Target irradiance should be 1800-2000 kWh/m² or higher. Another limit is land availability. If connected to a steam turbine solution, the condenser needs large quantities of water for cooling. Construction of solar thermal power near or in deserts is an efficient way to reduce the impact of the first two limitations. Whereas the third limitation of cooling is a challenge due to the lack of water. Areas that have shown combined features to overcome these limits are the Mojave Desert as well as Spain.

3.5 Battery energy storage systems

For this thesis, battery technology is focused on Li-ion batteries.

Battery energy storage offers several features to balance out uncertainties introduced by renewable energy. Use cases include the construction of BESS adjacent to a wind farm to balance out uneven production. Or the time-shifted application of solar power. Batteries can be charged when electricity prices are low and discharged when prices are high. Batteries allow large generators to run optimised as surplus energy can be stored to cover peaks in consumption. Fast frequency response (FFR) ancillary services are the ability of BESS to compensate for the lost inertia due to renewable sources. FFR can supply energy to the grid faster than a governor-based generation. (Lehtinen et al., 2022). The injection of power into the grid acts in the stabilisation of the frequency and a reduction in the rate of change of frequency (RoCoF).

In practical terms, the addition of energy storage to supplement renewable energy sources enables the grid operator similar functionality and stability as with conventional power generation methods. The energy storage system can support the grid in both frequency and voltage operations. The addition of storage can either be done at the local level parallel to the renewable power plant or on a grid level to support critical points in the transmission network.

3.5.1 Revenue streams of battery energy storage systems

Braeuer et al., (2019) covers economic potential in the German market. Three main revenue streams are highlighted:

- Arbitrage trading
- Power control
- Peak shaving

Arbitrage trading, day-to-day trading of electricity. Buy low, sell high. There are two main considerations for the German market (Braeuer et al., 2019). The first one is the day-ahead auctions and the other is the intraday market. In some cases, a battery operator might even be paid to “buy” energy. The benefit of the powerplant operator is the ability to run at optimal load and values. The benefit, for the TSO, is the availability of inertia and support. If the operator would have to reduce production or even shut off some generation, the grid health overall would suffer.

Power control reserve is the act of support services or ancillary markets. Through these services, the BESS can offer services equivalent to the inertia of rotating mass power plants. The power control reserves in Central Europe are controlled by ENTSO-E. European Network of Transmission System Operators for Electricity. National, or local, TSOs handle allocations and deployment. The main types of reserves are:

- FCR, frequency containment reserve
- aFRR, automatic frequency restoration reserve
- mFRR, manual frequency restoration reserve

In a grid, when the governor or fast frequency response has failed and the frequency deviation is too large, FCR services are activated. If FCR is not sufficient, aFRR is activated. And finally, if these automatic processes are not sufficient in the recovery of the frequency manual input is required. The strength and properties of Li-Ion batteries coupled with inverters provide the necessary speed for the fast response required. (Braeuer et al., 2019)

Peak shaving is the act of discharging batteries to balance out a peak in consumption. In several markets, the distribution grid will invoice based on demand charges in 15-minute intervals, i.e., there is an extra fee to pay if an entity causes peaks in consumption. Based on multiple studies, the end benefit of peak shaving through BESS is commercial and household end users.

Lehtinen et al. (2022) identifies further use cases equivalent to both primary reserves as well as spinning reserve applications. A detailed example is covered in chapter 4.3.1.

3.5.2 Thermal and safety concerns of Li-ion batteries

The thermal runway is one of the main concerns for lithium-ion batteries. The topic has been researched for 30 years. (Rao et al., 2022). The nature of the phenomenon is a complex combination of chemical reactions, heat generation and heat transfer. Three main categories are highlighted:

- Mechanical stress

- Electrical stress
- Thermal stress

The trigger for the thermal runway, no matter the type of stress, is an internal short circuit inside the battery cell. To mitigate the risk a detailed plan is needed both from the manufacturer as well as from the integrator. A further risk to thermal runaway scenarios outside the stress factors mentioned above can be caused by operation conditions, chemical nature, and active materials as well as the specification of the battery itself.

When a thermal runaway occurs, a series of chain reactions occur inside the cell or battery pack. Alongside these chain reactions, a large amount of heat and by-products are generated, and as a result, an escalation of the faulty situation occurs. The reaction will generate gas, but the exact mix and nature have proven difficult to pinpoint. One of the gases released is oxygen, which further contributes to the thermal runaway. A key goal for safety design is to limit fire propagation, both between cells but also between modules and enclosures. The study by Rao et al. (2022) underscores the importance of "onion layering" of safety features at multiple levels: the system, the material, and the package.

3.6 Battery supplier and products

Batteries are mainly supplied from Asia, with CATL (Contemporary Amperex Technology Co., Limited) in the lead at almost a 30% market share for batteries for energy storage (Takomabattery, 2022). Samsung SDI is in the second position, followed by LG in the third position. The electric vehicle market is larger than the energy storage market. (Electrive, 2022)

3.6.1 Example system: CATL options

The battery cell technology used for prismatic cells is LFP Olivine Structure. CATL's racks are intended to be connected as a system of multiple racks that are monitored by a Master battery management unit (MBMU). The battery module and the battery rack are certified as required by safety standards. Applicable standards are defined by UL, IEC, and NFPA.

The CATL structure is based on battery cells. The cells are connected in series in a module, to increase the nominal voltage. (CATL, 2020) In CATL's indoor liquid-cooled rack, eight of these modules are connected as a rack. In the air-cooled version, two racks are installed next to each other. Both the liquid-cooled and air-cooled versions have the same specification for the battery cell. The difference stems from how they are connected and engineered into the rack.

Table 3: Battery module specification

	Dimensions [mm]	Capacity [kWh]	Rack capacity [kWh]	Energy density [kWh/m3]
Air-cooled battery module	950 x 516 x 234	17,9	286,4	156,1
Liquid-cooled battery module	1152 x 810 x 243.4	46,6	372,8	205,3

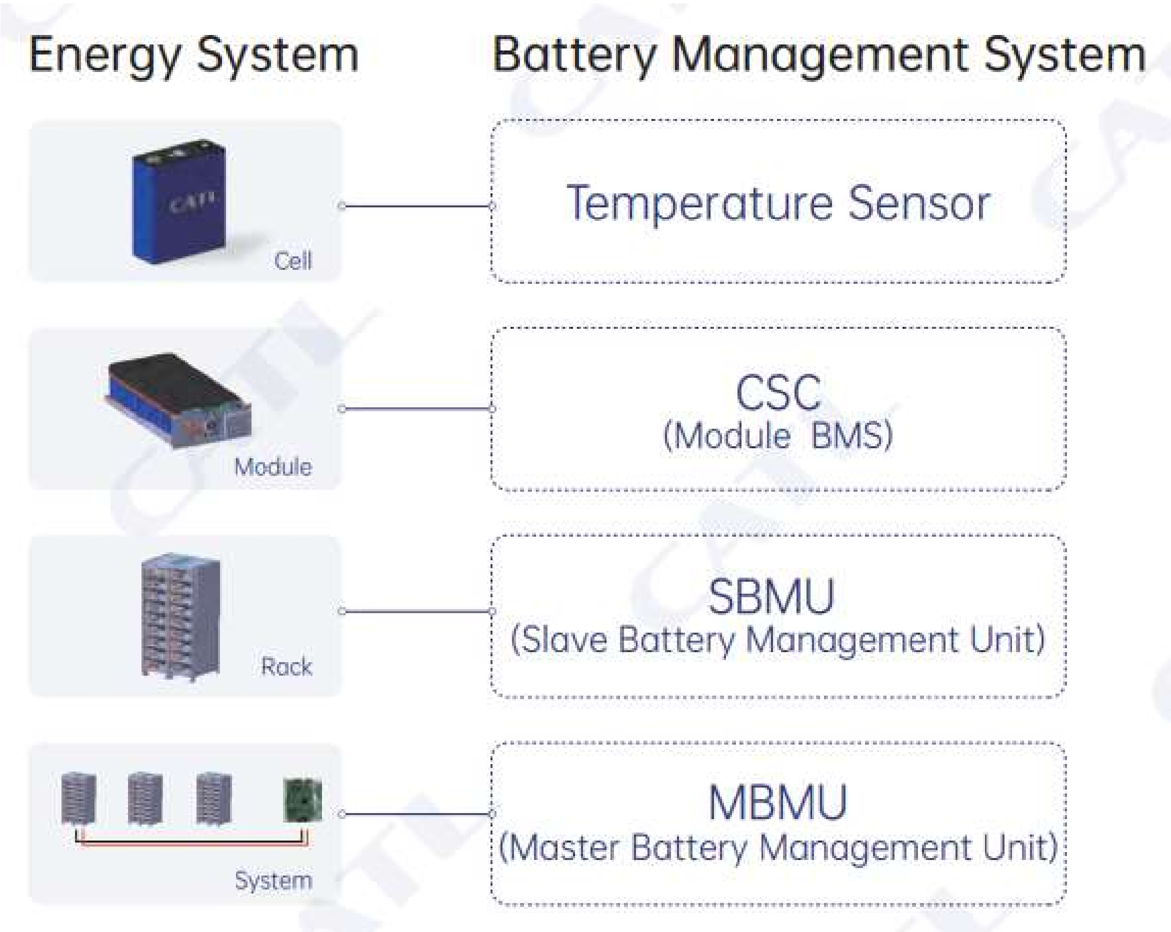

Figure 5: CATL battery system structure. Picture from a product brochure. (CATL, 2020)

Modules from CATL are available as either energy(E) or power(P) versions. The power version has a higher C-rate, i.e., it can charge and discharge more quickly. The power module is rated for 1C applications, while the energy module is rated for 0.5C applications. A C-rate of 1 means the module can move 100% of its capacity in one hour. A 0.5 C-rate moves 50% of its capacity in one hour, i.e., the module will require two hours to completely charge or discharge.

3.7 Battery energy storage system

A battery system is built from cells into modules, the modules into racks, and the racks are placed into climate-controlled containers to form a DC-bus. The containers are connected to a power conversion system to transform DC power into AC power. Transformers are needed after the power conversion system to increase the voltage of the AC output to the medium voltage level. (MKC Group, 2022) For one unit, the system is based on a shipping container with ten CATL air-cooled racks. This system can be multiplied to fit the need of the customer. In general, the size of the inverter and the need of the application will determine the configuration, setup, and layout of the project. Inverter manufacturers have their separate specifications and requirements on how to interface the DC system for optimal use.

A simplified version of the system:

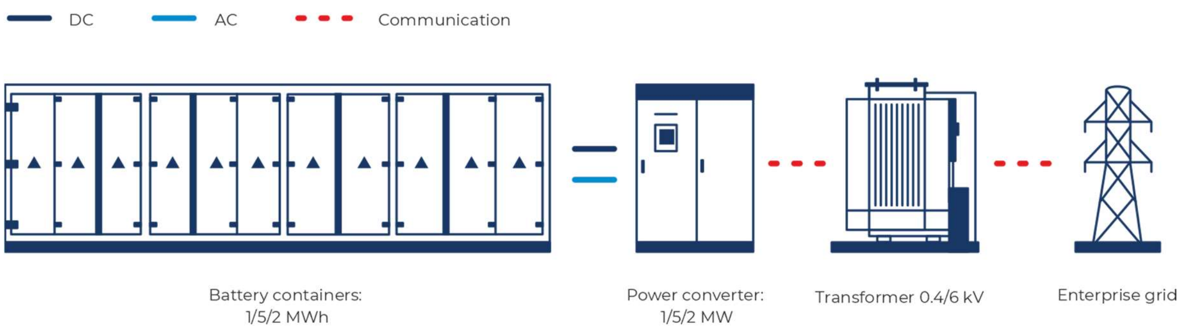

Figure 6: Battery energy storage system, simplified. (MKC Group, 2022)

A battery container typically includes:

- Fire safety
- Heating, ventilation, and air conditioning (HVAC)
- DC-combiner
- Control cabinet
- Batteries

The equipment is placed in a 40-foot shipping container,

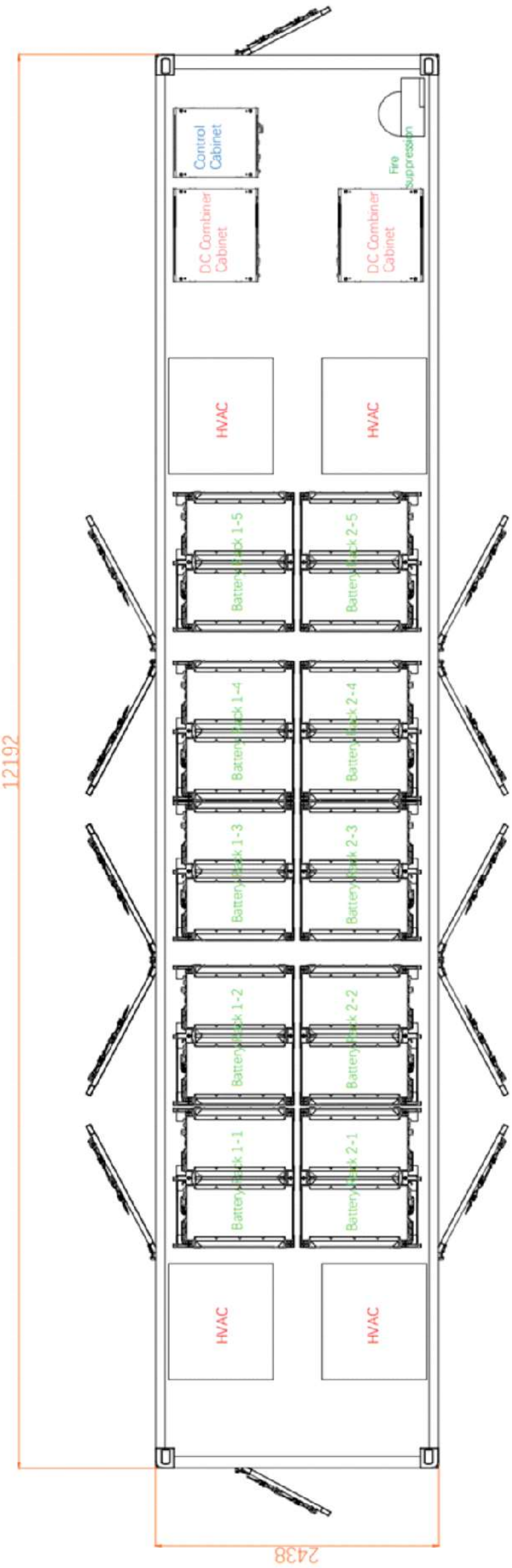

Figure 7: Equipment layout. (MKC Group, 2022)

3.8 Wärtsilä application

Wärtsilä's® GridSolv Quantum© application is a fully integrated solution based on liquid-cooled racks. (Wärtsilä, 2022b)

Figure 8: GridSolv Quantum (Wärtsilä, 2022b)

The solution allows for multiple systems to be installed in parallel to reach optimal configuration. As a system, the units arrive fully installed on-site. Batteries are pre-installed. The AC and DC cabinet, which is the interface between batteries and the inverter also supplies auxiliary power connections and communication.

4 Electrical grids and portfolio

Energy generation and consumption rarely occur in proximity to each other. A wind turbine can be located at sea, and the energy consumed is at a building in the city. Energy needs to be transferred to the location of the consumers. Consumers can also be referred to as load. Generation is also known as supply. This energy is not limited to electrical energy, liquids and gasses also contain energy and often need to be transported. For example, a local power plant can use the waste heat generated from the production of electricity to heat the district heating system. District heating greatly increases the overall efficiency of the power plant through heat recovery to heat buildings and houses throughout the city. The heat is transferred through insulated water pipes in the ground. This example and the transfer of energy can be referred to as "*energy vectors*".

The contents of this chapter are based on chapter 10 (Jenkins & Ekanayake, 2017). Additional sources are noted when applicable.

4.1 Active and reactive power

Power in a system can be either active[2] or reactive. The active power component governs the frequency. When the consumption and supply of active power are balanced, the frequency is stable at the designed nominal frequency. Fossil fuel and large hydropower plants employ a governor to measure the rotational speed of the shaft. If the speed drops, more power is requested, i.e., increased water to the turbines in a hydropower plant or an increase of steam- or fuel-pressure supplied to the engine. (Lehtinen et al., 2022)

In most of the world, 50Hz is the nominal frequency. Some countries, USA, have a system designed with 60Hz as the nominal frequency. Countries that have had a close relationship with the USA over history can have 60Hz systems as well. Some examples of countries that have a 60Hz system are Bolivia, Guyana, Aruba, Bahamas, Brazil, Canada, Cuba, Mexico, the Philippines, Japan, and Taiwan. Listed in no specific order. Note that occasionally, a country can have both 50Hz and 60Hz systems in use. e.g., Japan.

Reactive power controls voltage. Failure to have the supply and demand of reactive power balanced will cause deviations in nominal voltage. To support voltage regulation, transformers can be supplied with tap changers. A tap changer can be either on-load or off-load by the nature of the design. The tap changer changes the ratio of windings in the transformer to support the voltage demand. Traditionally power consumers are categorised as inductive or capacitive in their nature. An inductive load is said to consume reactive power while a capacitive load generates reactive power.

Scientific terms to describe power:

Table 3: Scientific terms and units used to describe power relationships.

Name	Symbol	Unit of measurement	Name of unit
Active Power	P	W	Watt
Reactive Power	Q	var	volt-ampere-reactive
Complex Power	S	VA	volt-ampere
Apparent Power	|S|	VA	*Magnitude of S
Phase of voltage	φ	°	degree

[2] Active power is also referred to as *real* power. Depending on author.

In a visual representation, the relationship for the units is:

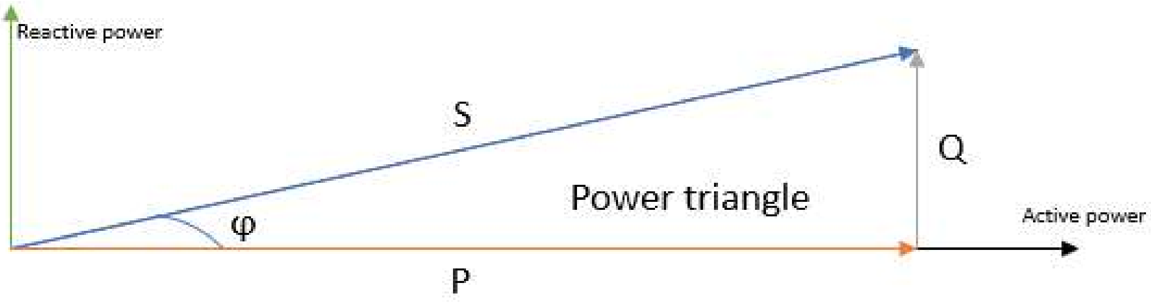

Figure 9: Relationship between Active, Reactive and Apparent power.

In most real-world applications, a factory for example, or in a city area, the loads are of mixed nature. The independent active and reactive consumers are equal to the power generated.

$$P_{supplied} - P_{Consumer_1} - P_{Consumer_n} - P_{losses} = 0$$

$$Q_{supplied} - Q_{Consumer_1} - Q_{Consumer_n} - Q_{losses} = 0$$

Renewable energy generation does not have the same possibility as fossil fuel and hydropower plants to support the grid frequency and balance. Hydropower plants and fossil power plants have vast amounts of energy available in terms of mass or inertia. The power plant can react to demands on the grid and support the stabilisation of nominal frequency. Primary through increased steam generation or by an increase in the amount of water in the turbine. Secondary through increased fuel consumption. For a large power system of suppliers and consumers, the complete system can be considered a rotating mass with inertia. The inertia stabilises the system and gives it a rigidness to withstand faults and events. If a great number of renewable sources are introduced to a system, the overall inertia is reduced. (Lehtinen et al., 2022)

4.2 Example: Addition of a solar power plant on grid stability

A scenario based on an example from page 369 (Jenkins & Ekanayake, 2017). This scenario highlights the initial change in frequency in the grid when a fault occurs and there is a loss of power generation. This initial change, or loss of frequency, depends on the inertia of the system.

The power system is based on a portfolio of power plants, solar power is introduced to reduce cost as well as be more environmentally friendly.

Table 4: Example portfolio of power generation.

	Original portfolio [MW]	New portfolio [MW]	Inertia constant, H
Coal	750	250	4.5
Oil	1000	250	6
Hydro	1250	1250	4.5
Solar	0	1250	0
Sum:	3000	3000	

The new portfolio will experience a reduction of inertia as:

$$H_{eq} = \sum_{i=coal,gas...} H_i \times \frac{S_i}{S_{sys}},$$

Where inertia constant $H_i$and MVA rating S_i are specific to each system.

$$H_{eq} = \frac{4.5 \times 750 + 6 \times 1000 + 4.5 \times 1250}{750 + 1000 + 1250} = 5.025s$$

After solar is introduced, the updated system inertia is recalculated:

$$H_{eq} = \frac{4.5 \times 250 + 6 \times 250 + 4.5 \times 1250 + 0 \times 1250}{250 + 250 + 1250 + 1250} = 2.758s$$

Expressed as a percentage, the reduction is 45%.

In case of a fault in the system, the new system is more vulnerable. For example, a 250MW generator trips and is taken offline. If the frequency drops linearly, the new frequency after one second can be calculated:

If no solar power,

$$\Delta f = \frac{1}{2 \times 5.025} \times \left(\frac{250}{3000}\right) \times 50 \times 1 = 0.41\ Hz$$

The new frequency is: $50 - 0.41 = 49.59\ Hz$

With solar power,

$$\Delta f = \frac{1}{2 \times 3.142} \times \left(\frac{250}{3000}\right) \times 50 \times 1 = 0.76\ Hz$$

The new frequency is: $50 - 0.76 = 49.24\ Hz$

The grid company, or transmission system operator, aims to keep the frequency within ±500 mHz of the nominal frequency. A large deviation can eventually lead to a series of events that result in loss of power. The grid is designed to have a synchronous frequency across all power generation. If the frequency deviates, there is a risk of damage to equipment.

4.3 Portfolio planning

Fluctuations throughout the day vary from country to country and between the seasons. The hour of the day has a large impact on the power needed. The nature and form of the peak depend on multiple factors, for example, winter or summer, the profile of the consumers, and which sectors are represented, i.e., a country or region with a large tourism sector will look very different compared to a region with heavy industry and factories. To achieve a balance in the system, all power generation is rarely active at the same time. Based on the availability of power generation, a certain base load of power demand is determined and often generated by large power plants. The rest of the generation is on reserve or backup duty. When needed, the local dispatch has a priority list of reserves to activate first. The selection is based on cost-effectiveness, factors include:

- Cost of operation
- Maintenance
- Fuel
- Emissions
- Required capacity

To handle these choices, a dispatch centre exists. The centre can be for a region or nationwide. Or for a specific market. It can be centralised or de-centralised.

Deviations in the generation and consumption of power regularly occur in all grids. The size of a deviation varies from minor to critical. The minor fluctuations are often handled by automatic governor adjustments for large power plants. Medium events such as sudden loss or gain of a large consumer can be planned for through spinning reserve. Spinning reserve is the operation of a power plant at less than 100% load. The difference between the current load and the maximum load can be considered a spinning reserve. More severe faults, such as loss of generation or a (large) power plant or partial loss of the transmission network can have critical consequences for the stability and availability of the grid. Plans to handle these events are a must. Even though the risk is low, the impact is massive. To mitigate the impact of events of this magnitude, the grid operator employs several different strategies. The response strategy is based on how critical a load is considered. Available operations include an increase of power from other power plants, backup power plants, and finally load shedding. Load shedding is the act of *dropping*, i.e., disconnecting, non-critical loads. A grid operator has a pre-determined priority for the priority of loads. As renewable energy is introduced into the portfolio of, an uncertainty or fluctuation in power generation is introduced.

The classical approach to reserve generation involved a combination of contingencies to match the size of the largest power generator plus fluctuations in the demand estimate. With variations in power generation from renewable sources, this needs to be accounted for in modern portfolio plans. The inertia requirement creates a maximum share of renewable sources within the system. This can result in limitations of wind- and solar power that can be added to a system. (Lehtinen et al., 2022)

4.3.1 BESS simulation report

A continuation of chapter 3.5, ,Lehtinen et al., (2022) can demonstrate the strong benefits of BESS applications in a simulation environment.

To prove the benefits of the addition of batteries to supplement a portfolio, multiple simulation cases were created in Plexos and Simulink. Plexos is an energy market simulation software, and Simulink is a simulation environment developed by Mathworks.(Energy Exemplar, 2023; MathWorks, 2023)

The main consideration for the simulation is to have a model of ten generators. The reference is the IEEE 39-bus standard test system or the New England 10-generator system. Considered to be a benchmark model and test environment for power system models. Within this system, the main approach was defined:

1. A model is created, without inertia consideration.
2. Test the stability of the system through dynamic simulation to identify the minimum inertia required.
3. Re-run the test with this inertia as a requirement.

The test steps are simulated for multiple models,

- Base unstable, S1A
- Base stable. S1B
- Flexible unstable, S2A
- Flexible stable, S2B
- Flexible stable without ICE, S3C

For the simulation, the 500 MW nuclear power plant and 2x200 MW hydropower were locked in as must-haves. The rest was left to the simulation and model to freely decide generation within the different sources. The simulation considers a typical one-year demand with a max peak of 6.1 GW.

The worst scenario was identified and verified from the system model in step 1 of the above list. Care was taken to review the complete year and the same condition occurred more than once over the year, i.e., it was not a one-time situation. Most of the time, in the model, power generation was provided by a mix of solar, wind, and locked nuclear and hydropower. Additionally, five CCGTs were required to be in operation at low load to support the grid. Based on this scenario of power generation, an instantaneous snapshot was taken. The simulation shows that the critical moment where the system is most vulnerable is when there is a combination of low demand and low inertia. E.g., a windy night.

The New England 10-generator layout:

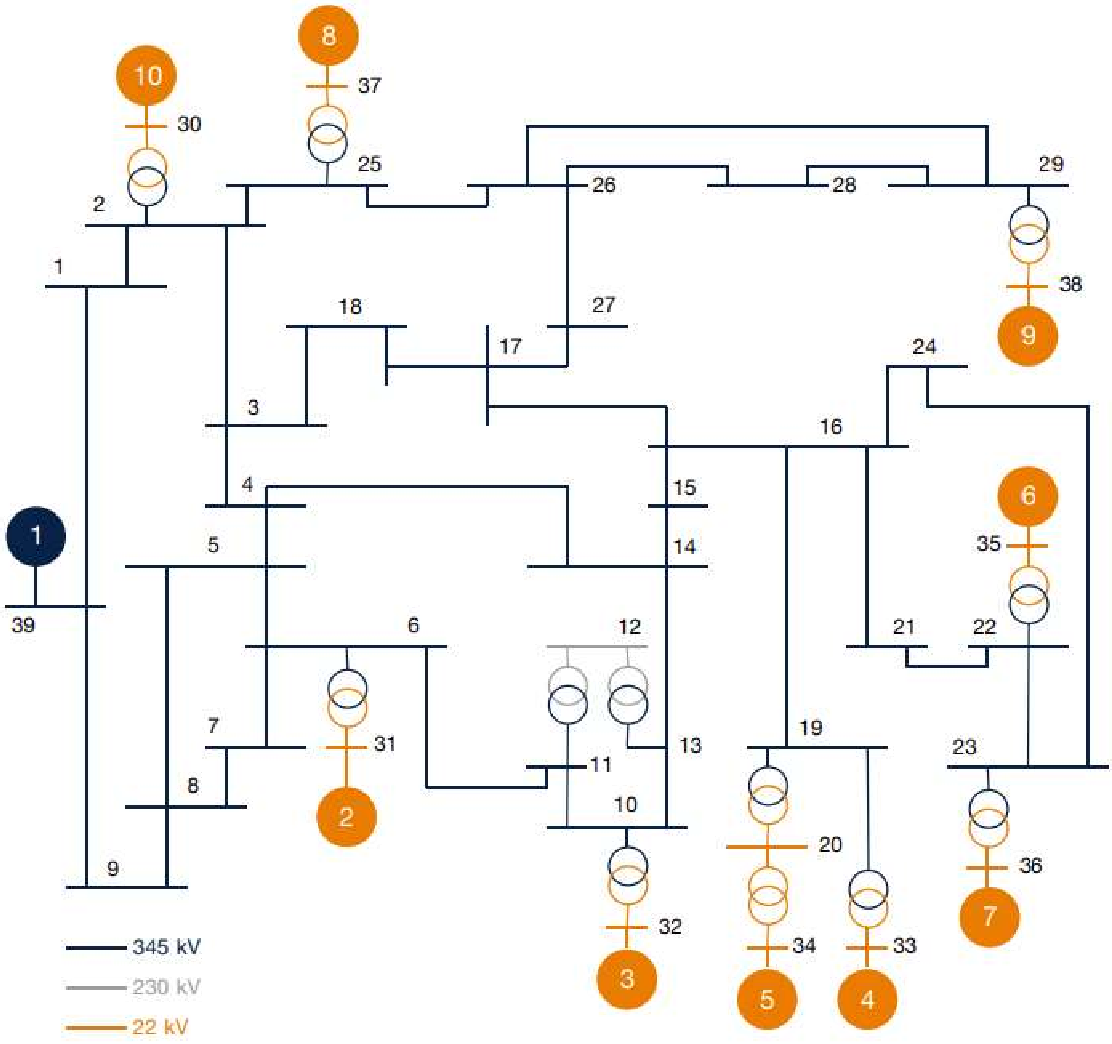

Figure 10: Single line layout of the New England 10-Generator. (Lehtinen et al., 2022, p.12)

For their model, Lehtinen et al., (2022) locked a 500 MW nuclear power plant to bus 32 and hydropower of 200 MW each to busses 31 and 35.

The BESS introduces two scenarios for evaluation,

- Scenario 1: If loss of the 500 MW nuclear power plant, which is the single largest unit on the grid, the BESS provides a static 350 MW step-response.
- Scenario 2: If the frequency deviates more than 0.1 Hz, the BESS provides energy to the grid based on a droop curve. Max provided power is 150 MW.

Scenario 1 is based on the loss of the nuclear power plant on bus 32. Scenario 2 is to cover for smaller faults and occurrences in the system.

In the base model, unstable vs. stable, the allowed renewable energy sources had to be reduced to fulfil the requirement of inertia and stability in the system. The unstable model allowed as much as 50% renewable share. When the requirement for inertia was applied, the renewable share had to be reduced to 38%. To make the initial model stable there was a need to increase the inertia with six 300 MW combustion power plants, inertia constant, H, = 6 s.

The addition of the BESS and the capability to perform FFR allows the model to update its behaviour. In the flexible simulation, there was only a need to add one single 300 MW power plant to change the unstable flexible into a stable flexible model. When the BESS is not needed for FFR, the batteries can act as a time-shifting service for the renewables. The required inertia for a stable flexible model was 5.5 GWs. Whereas for the stable model without BESS the required inertia was 25.3 GWs. The introduction of a battery energy storage system allows the model to rely on 58% renewable energy.

Plexos, the simulation tool, requires cost optimisation built into the selection process of power plants to consider. The different scenarios end up with the below mix of power generation:

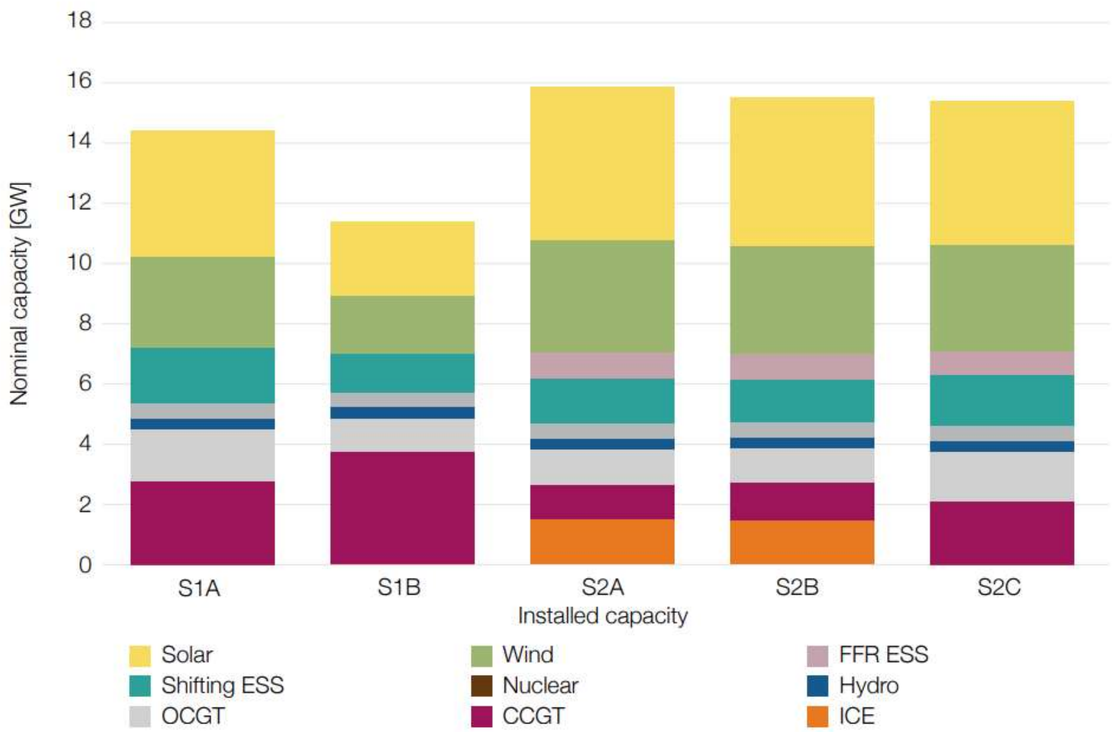

Figure 11: Simulated power plant portfolio to introduce more renewable energy into the power plant portfolio. (Lehtinen et al., 2022 p.22)

The highlight and comparison of scenarios S2B and S2C are the benefits of ICE power plants to further increase the share of renewable energy. With engines, the renewable share was increased by 1% units for a total of 58%. Based on the calculations, Lehtinen et al.,)2022) determine an 11% cost saving can be achieved.

5 Grid code and requirements

The share of renewable energy in grid and power plant portfolios has increased. Challenges encountered by inverter-based technologies include restrictive requirements in how the renewable resource supports the grid in case of fault events. (Saponara & Mihet-Popa, 2020)

The practical case for this thesis is based on the Belgian grid codes and requirements. (Elia, 2018, 2019) Belgium's grid is in cooperation with the EU, central Europe, and the nations around Belgium.

Elia is the Belgian transmission system operator. Elia states the following as their values and vision: "As system operators in Belgium (Elia) and Germany (50Hertz), our mission is to realise the climate ambitions of the European Green Deal. Elia Group is therefore accelerating its investment programme. We are preparing our on- and offshore grid infrastructure for the integration of large volumes of renewable generation to electrify our society sustainably. We are increasingly doing this in cooperation with other sectors and other countries." Elia is part of the *European Network of Transmission System Operators for Electricity*, ENTSO-E. ENTSO-E is an organisation that represents 39 different transmission system operators from 35 countries.

The grid codes and requirements of Belgium are country-specific versions of the ENTSO-E requirements. Elia refers to these requirements as federal requirements. The goal and purpose of Elia, (2019) are to establish minimum technical requirements for the connection of a battery energy storage system to the electrical grid. Harmonisation between power plants that generate power and storage parks has been one of the goals. Through the document, the terminology storage park module (SPM) is used. The power park module is referred to as PPM. When there is no distinction needed between a storage park module and a power park module, the general requirements of the power park module apply to the battery energy storage system. The document harmonises terminology and terms to facilitate discussions and creates a common understanding of the technical capabilities expected by a storage system operator.

Within Elia's grid there are four classes, or groups, for energy storage systems:

- Type A: $0.8 \text{ kW} \leq \text{P}_{\text{max}} < 1 \text{ MW}$
- Type B: $1 \text{ MW} \leq \text{P}_{\text{max}} < 25 \text{ MW}$
- Type C: $25 \text{ MW} \leq \text{P}_{\text{max}} < 75 \text{ MW}$
- Type D: $75 \text{ kW} \leq P_{max}$

The practical works and focus are on the Type C storage system. As some of the features and operations in the power plant will fall under the network code for requirements for generators (NC RFG), some tests and input from (Elia, 2018) will be considered. The specific tests to perform are split into two halves, the first section considers frequency services and active power control. The second part focuses on voltage support and reactive power tests. For both aspects, some common terminologies will be covered first.

For tests with specific set points or steps,

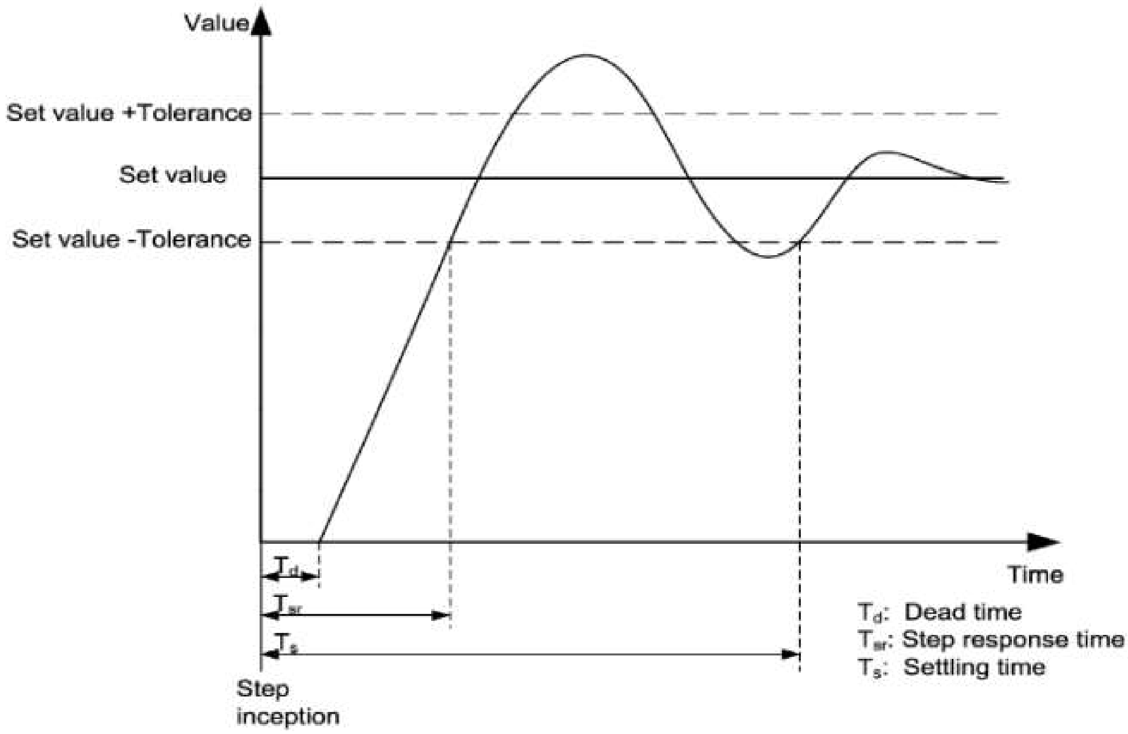

Figure 12: Definition of PGM (Power generation module) response,.(Elia, 2018, p.11)

- T_d: Dead time before the equipment starts to respond to a set point change

- T_{sr}: Step response time. The time from a set point change until the system reaches the specific tolerance for the first time.

- T_s: Settling time. The time from a set point change until the oscillations stay within the allowed tolerance.

Common requirements are that the default droop is 5% but is selectable between 2% and 12%. Frequency activation is to occur at 50.2 Hz. Dead time must be as fast as the equipment allows, with no artificial or intentional delays.

Droop is defined as,

$$s[\%] = 100 \times \frac{|\Delta f| - |\Delta f_1|}{f_n} \times \frac{P_{ref}}{|\Delta P|}$$

Example of frequency response during limited frequency response:

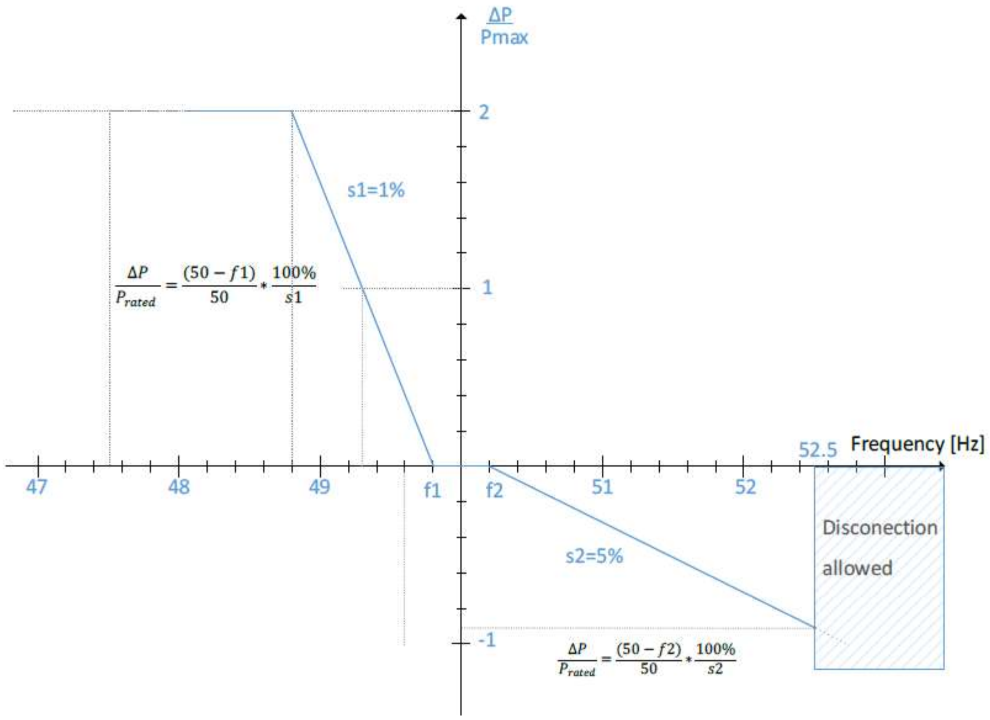

Figure 13: Example frequency response and droop[3] curves for limited frequency response, (Elia, 2018, p.5)

[3] Note: Formula should not be 50-f_n for the LFS. As there is a dead-band of ±200 mHz before LFS is activated.

5.1 Frequency control and active power tests

Frequency control and active power tests are to verify the operations of functions and services that will support grid stability. The activities are coordinated across continental Europe as a complete region to ensure stability and services across the full area. Belgium and Elia are part of ENTSO-E, and the current guidance is based on the *Implementation Guideline Documents.*

The applicable tests for a plant C installation are defined as:

- Frequency control tests
    - Active power control
    - Limited frequency sensitive mode_over
    - Limited frequency sensitive mode_under
    - Frequency-sensitive mode
    - Frequency restoration reserve

The purpose of active power control is to measure the accuracy and behaviour of the power plant to define a baseline from step tests. When the default step behaviour is confirmed and accepted, a test to verify different aspects of the frequency services can start.

In the hierarchy of the above functions, frequency sensitive mode (FSM) is the first level of services when the grid requires support to balance and stabilise the grid. The FSM as a service exists within a predefined, relatively, short range from the nominal frequency. In the specific case of Belgium, it is defined as up to ±200 mHz. The purpose of the FSM service is to act as a primary reserve. In practice, an operator bids in different sizes of |MW|[4] for time slots where the operator commits to the availability of their services. The amount of power to supply is defined through an activation curve with a slope of 2% to 10%.

Frequency restoration control, often called aFRR for automatic frequency restoration reserve, is the secondary reserve of the grid. As FRR becomes activated, FSM is made available to support as the primary reserve once again. The frequency is restored and balanced with a set point from the grid operator to the power plant operator. Until tertiary

[4] Note that the magnitude denotes both directions of services. To balance frequency events in both directions.

reserves can be brought online, or alternative means of generation can be secured, the power plant will receive a set point to follow from the grid dispatch.

LFSM, limited frequency sensitive mode, is an alarm state where all power plants are required to act. Essentially an “all hands on deck” situation as a last resort to restore the grid before forcing load shedding. Even power plants with no scheduled or active output are required to act in an LFSM event. This feature can have other names in other regions or grids.

5.2 Voltage control and reactive power tests

Reactive power control exists to support the voltage of the grid. The voltage can vary between two different buses in the same system. The type of tests to be performed involves the operation of the equipment in the P/Q diagram corners, with certain times required at certain levels of voltage and durations. The order of tests starts as a simple manual test to verify basic operation first. In turn, the tests become more challenging to match the requirement and expectations of the power plant. For example, a Type A installation is only required to test for voltage withstand capabilities whereas type B includes reactive capabilities. In turn. C has additional requirements.

For a type C installation in Belgium the following tests are applicable:

- Voltage and Reactive Power Control Tests
    - General provisions test
    - Reactive power capability
    - Reactive power control mode tests
    - Voltage control mode tests

The general provisions tests exist as points to begin from. Careful step tests from 90% up to 110% voltage are carried out and measured the value and compared to the expected output. These tests are to be done by manual control. The voltage slope is measured and calculated, to establish the correct droop curve behaviour.

Reactive power capability is a manual test to navigate the max and min set points of the complete P/Q diagram. After verification of the equipment, the power plant is tested at different step tests of reactive power, Q, to measure the speed and precision as well as verify stability at these set points.

6 GEMS

GEMS, Greensmith energy management system, is the control system and controller of the Wärtsilä supplied battery storage system. (Wärtsilä, 2022a) Through the GEMS interface personnel can operate the equipment of the power plant.

As a platform, GEMS is a digital platform with multiple modules and functions. At the highest level, GEMS allows owners to view their power plants through the Fleet Director. The Power plant controller monitors and can control the specific power plant or storage it is connected to. IntelliBidder and Grid Controller offer additional services to support the commercial performance of the owners.

Through the graphical web-based user interface, operators can issue commands and operations. Each GEMS HMI can be tailored to fit the needs of the user. Standard options include energy meters, system monitoring and control of various *power devices*. A power device is a terminology used to describe for example "Voltage control mode". Other devices can for example be the signal follower and various frequency response curves and modes.

GEMS hardware consists of a server rack with redundant functionality. The rack houses additional equipment such as firewalls and network equipment. There is also an uninterruptable power source within the rack. A fibre-optic ring acts as the backbone of the equipment in the field. Through bus interfaces and communication protocols, various equipment can be connected to enable both monitoring and control through the GEMS interface.

The GEMS is not limited to only the battery storage system, various add-ons and possibilities exist to connect power generation equipment to the GEMS. Example from the Wärtsilä specification sheet:

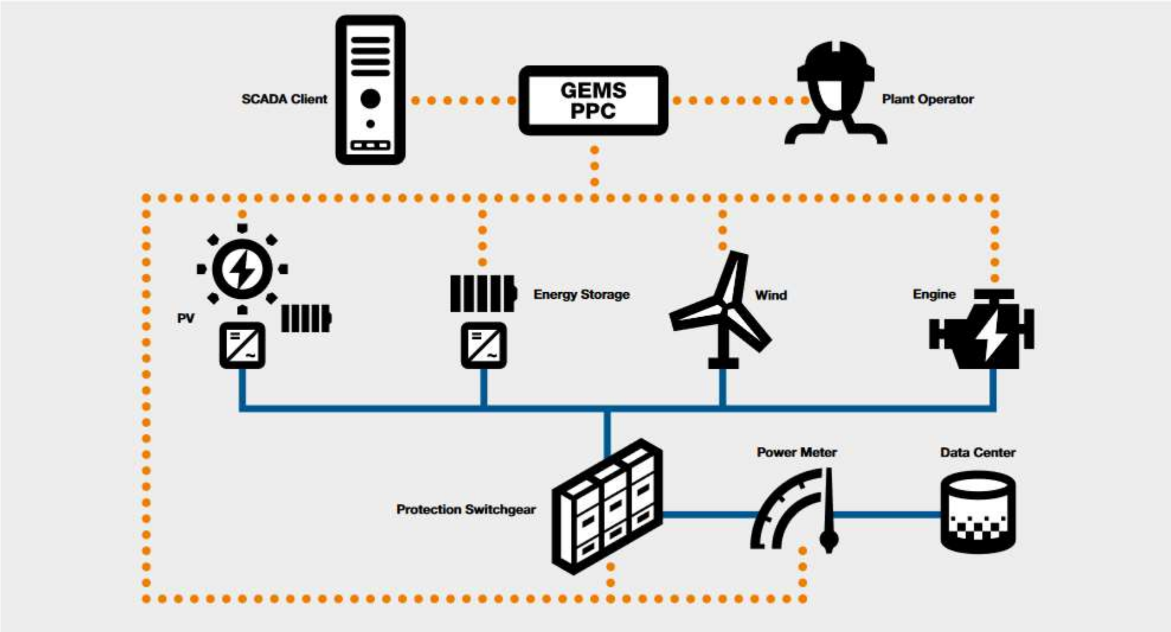

Figure 14: Example layout for a GEMS-powered portfolio. (Wärtsilä, 2022a)

7 Grid code tests for a battery energy storage system of Type C in Belgium

This chapter covers the practical works for the thesis.

7.1 Roles

For a power plant project, there are often multiple stakeholders. Both internal and external. From the point of view of equipment delivery, which was Wärtsilä's role, there is often a core project team led by a project manager. The project manager can have a technical background or a commercial. The technical lead is referred to as a system engineer. The goal of the system engineer is to understand the different systems and their interactions.

7.2 Requirements

For the specific project, the Belgian grid requirements are communicated through both official documents and contractual requirements. (Elia, 2018, 2019) The requirements include both features within the hardware as well as functionality and specific modes the equipment must support. The main technical features, or operation modes, include frequency and voltage-related functions and scenarios. The requirements are a combination of energy storage-specific requirements and general requirements based on the services the storage system will sell.

7.3 Practical thesis work and requirements identification

To map the requirements, the system engineer was in the lead of documenting contractual and grid requirements in a structured way. Meetings were held to determine capabilities of the both the equipment involved as well as how the control is defined. Throughout these discussions, the initial part was to identify if the equipment on a hardware level can operate as desired. The next step was to identify how to operate the equipment in the desired way. Items or requirements that would need special consideration were carefully noted and highlighted with the development team. Review sessions were held to validate functions and to follow the progress of the development of the system. Constant schedule meetings were held to align the different stakeholders involved. Cases and tests were categorised into tests that "These tests are ready to execute." I.e., no special action is needed. Tests that could be executed through re-adapting existing modules were mapped out and categorised as a second group. The final category was tests and functions that involved the development of new features. Background or motivators for being placed in the third category varied, but all features on this list needed development time.

7.4 Goal

The goal of this thesis was to develop a detailed step-by-step procedure for how to operate and control the power plant to prove that Wärtsilä's system fulfils the requirements. Also known as a *commissioning procedure*. Before this work, the exact requirements were not identified on a detailed level. The technical- and system experts were confident in the equipment and the system, while the practical side of how to complete the required qualification had not yet been explored. The commissioning procedure is not only a document on how to perform the specific tests; but also, a contractual requirement to be verified by safety coordinators before work can be carried out.

The target of the works was a procedure and structure with definable steps and actions. For each test, the pass requirement and/or criteria with tolerances were noted down. The structure of the commissioning procedure has the form:

1. Name of test to be performed
    a. Intro
    b. Acceptance criteria
    c. GEMS devices and expressions
    d. Execution of test
    e. Data to be recorded

The intro describes the test and what the overall goal is and how it is achieved. Total test run times and requirements are noted. Applicable droop curves, variables, or constants for the test run. GEMS devices and expressions are to inform the operator of which modules and parts of the systems are needed. As the testing is done during ongoing commissioning, some functions or resources might be offline or locked in review. The final header, Data, provides ready-made tables to fill in data while doing the test. Graphs or key metrics to record are mentioned.

Example for power set-point test:

1. Active power control

    a. During this test the plant will be operated at different power levels for three minutes each. The settling time is to be recorded for each step.

    b. The test is passed if the settling time for each step is within the allowed time of 60 seconds. Tolerance: 5%

    c. GEMS devices and expressions to be involved and activated.

    d. Disable all modules not involved in the testing. Command the system, starting from 90% power level, to do steps as defined by the table in the results section. Hold for three minutes at each level.

    e. Fill in the table, record step level and settling time. Add the graphs and data to the results document.

More advanced tests, such as the limited frequency mode have introductions for the function and relevant graphs and curves to follow during the test.

7.5 Testing

The next step was to perform the complete series of tests in a virtual emulator. The emulator is designed to match real-world equipment and functionality. The virtual tests were carried out over the autumn of 2022 and passed successfully. Note that not all aspects of all tests are possible to emulate. Some require a certain balance of plant equipment to be set up in specific ways. Other tests depend on factors or conditions from the grid.

7.6 Verification

With approved simulation tests, site verification follows. These tests are planned for later this winter and will not be part of this thesis.

7.7 Official testing

The witnessed tests and records are to be performed in early 2023 and will not be covered here.

8 Discussion, conclusion, and further reading

As has been discussed and shown throughout the earlier chapters, the move to renewable energy sources poses several challenges for both consumers and suppliers. If mishandled, the health and stability of the grid can be jeopardised.

When new projects and opportunities present themselves, interfacing with existing infrastructure is critical for the success of these technologies. Grid companies can be at times old fashioned, resulting in the suppliers having to do their due diligence in proving their capabilities in a world that predominantly has been ruled by conventional means of power generation. The experience of battery energy storage is only a few years old, renewable energy sources a decade, or up to a few decades depending on technology; Coal-fired and other conventional generation methods have been around for more than a century.

With the goal for this research and works in mind, the outcome was successful. Pending final field testing. Significant amount of time was invested in analysing the requirements and adapting them to the system delivered. In-depth discussions with technical experts assisted greatly in understanding the aim of tests and developing a testing method. The experts have a broad background and have not been limited to one field of expertise only. To ensure a successful outcome of this work, hardware, grid company, software, and GEMS-specific experts have been consulted. The strong background within the team and across the teams has been utilised, as the team has experts from multiple regions and countries. There is also expertise with grid company experience and experts with supplier experience.

A detailed procedure was investigated and developed to support the commissioning manager and team in proving that the storage facility fulfils the grid codes. The follow-up goal will be a more generalised template that can be adapted to most of the European requirements. If not directly translatable between different countries, then at least provide support in understanding expectations and preparing the design of the control of the facility to enable quick adaptation. One possible challenge is that on a local and/or federal level, the language used is not unified between the regions. Some features might have one name in one region or grid of certain operators, and the neighbour might have different terminology to describe the same feature. Even though the intent and technical specifications are unified.

Sadly, the requirements age very poorly. Many of the requirements are dated 2017-2018. During the early years of battery storage when these were written, capacity was much smaller than what is available with modern battery technologies. Some tests require run times or windows of 15 to 30-minute durations, which for most grid-sized applications, is no challenge at all. The test partially loses significance. The speed provided by the inverters and the insulated-gate bipolar transistor technology is significantly faster than conventional methods, such as governors, having no challenges in providing output on demand. There were challenges in identifying all applicable requirements, they are rarely available from one source or website. Often spread across multiple documents and occasionally from different sources, the groundwork to map these documents was demanding.

Throughout the project, the emulation environment has been of immense value. With access to the test system quick checks and turn around have been possible. Verifying if the system can handle certain tasks or how to execute them has been possible to achieve immediately. On the other hand, as many of the experts and support needed have been spread across multiple time zones, the coordination of availability and overlapping work hours has posed a challenge. The work hours and availability have not been a unique challenge to this thesis. Throughout discussion and sharing of ideas and experience the change brought by the pandemic has at the same time brought teams across the globe closer but the way we work together has changed. In previous projects in my career, similar discussions as to this requirement mapping have often been held during intensive full-day workshops with different stakeholders scheduled in a variety of constellations to have the needed expertise available.

One book I cannot recommend enough is Jenkins & Ekanayake, (2017). The book is slightly outdated in the storage chapters, as it was published in 2017, for everything else it is of great value. Some chapters cover general concepts and ideas, detailed technical details as well as general important items such as project execution and important aspects to keep in mind. Further, there are detailed sections with mathematical formulas to aid in engineering and understanding different renewable energy sources. Battery storage and what to expect next, Bloomberg has had multiple articles and analyses on what they expect to see next. Other research papers exist on multiple levels. These papers cover both detailed chemistry and new inventions, how to integrate discoveries into commercial products and how to interface the commercial products into existing infrastructure to gain the most benefits. Many corporate articles and analyses exist. As has been referenced in these works, Wärtsilä has published articles and studies on this topic.

9 References

BloombergNEF. (2022, January 26). *BloombergNEF - 10 Predictions for Solar*. Https://About.Bnef.Com/Blog/Solar-10-Predictions-for-2022/.

Braeuer, F., Rominger, J., McKenna, R., & Fichtner, W. (2019). Battery storage systems: An economic model-based analysis of parallel revenue streams and general implications for industry. *Applied Energy*, *239*, 1424–1440. https://doi.org/10.1016/j.apenergy.2019.01.050

Burger, C., Froggatt, A., Mitchell, C., & Weinmann, J. (2020). Decentralised Energy: A Global Game Changer. In *Decentralised Energy: A Global Game Changer*. Ubiquity Press. https://doi.org/10.5334/bcf

CATL. (2020). *CATL_BESS_Product_Brochure*. CATL: Corporate Brochure. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjilcL7lfH7AhX2cfEDHetmDr8QFnoECAwQAQ&url=https%3A%2F%2Fwww.catl.com%2Fen%2Fuploads%2F1%2Ffile%2Fpublic%2F202010%2F20201026135925_y06ysmij9p.pdf&usg=AOvVaw1Z9osPi-Hw64XXLCLjboAm

Electrive. (2022, August 8). *EV Battery market shares*. Https://Www.Electrive.Com/2022/08/08/34-per-Cent-of-the-Worlds-Ev-Batteries-Come-from-Catl/.

Elia. (2018). *RFG REQUIREMENTS OF GENERAL APPLICATION Following Art. 7(4) of the NC RFG*.

Elia. (2019). *PROPOSAL FOR STORAGE CONNECTION REQUIREMENTS TSO proposal complementary to the EU Network Codes*.

Energy Exemplar. (2023). *Plexos*. Https://Www.Energyexemplar.Com/Plexos. https://www.energyexemplar.com/plexos

European Commission. (2022, November 20). *EU Joint Research Data*. Https://Ec.Europa.Eu/Info/Departments/Joint-Research-Centre_en.

Jenkins, N., & Ekanayake, J. (2017). *Renewable Energy Engineering* (1st ed., Vol. 1). Cambridge University Press.

Kang, Y., Cao, A., Clément, R., Chou, S., Lee, S., & Miao, Z. (2022). Battery technology and sustainable energy storage and conversion as a new energy resource replacing fossil fuels. *Battery Energy*, *1*(1), 20220200. https://doi.org/10.1002/bte2.20220200

Lehtinen, O., Alahäivälä, A., & Wärtsilä. (2022). *Towards stable and reliable 100% renewable energy grids*. https://www.wartsila.com/insights/whitepapers/energy/towards-stable-and-reliable-100-renewable-energy-grids

MathWorks. (2023). *Simulink*. Https://Www.Mathworks.Com/Products/Simulink.Html. https://www.mathworks.com/products/simulink.html

MKC Group. (2022). *ESS Solution*. Mkc.Ae.

Möst, D., Schreiber, S., Herbst, A., Jakob, M., Martino, A., & Poganietz, W.-R. (2021). *The Future European Energy System Renewable Energy, Flexibility Options and Technological Progress*.

Rao, Z., Lyu, P., Du, P., He, D., Huo, Y., & Liu, C. (2022). Thermal safety and thermal management of batteries. *Battery Energy*, *1*(3), 20210019. https://doi.org/10.1002/bte2.20210019

REflex. (2022, November 20). *REflex - Analysis of the European Energy System*. Https://Reflex-Project.Eu/.

Saponara, S., & Mihet-Popa, L. (2020). *Energy Storage Systems and Power Conversion Electronics for E-Transportation and Smart Grid*. www.mdpi.com/journal/energies

Takomabattery. (2022, December 11). *Storage battery suppliers market position*. Https://Www.Takomabattery.Com/Top-10-Energy-Storage-Battery-Cell-Manufacturers-in-the-World/.

Wärtsilä. (2022a). *GEMS digital energy platform*. Https://Storage.Wartsila.Com/Technology/Gems/.

Wärtsilä. (2022b). *GridSolv Quantum*.

Wärtsilä. (2022c, February 20). *This is Wärtsilä*. Https://Www.Wartsila.Com/About.

Wärtsilä ES&O. (2022, November 11). *Wärtsilä Energy Storage.* Https://Storage.Wartsila.Com/About/.