Zuzana Korankova

Balancing the Power Grid Using Adjustable, Mobile Power Plants and Thermal Batteries

Bachelor's thesis in Renewable Energy Engineering
Supervisor: Ann Rigmor Nerheim
Co-supervisor: Alemayehu Gebremedhin
May 2023

Bachelor's thesis

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Preface and Acknowledgements

This project is motivated by attempts to find a solution to the current power crisis happening in both EU and Norway. The essential impulse for the topic of the bachelor's thesis happened during a course on topic "Nuclear power as a propulsion system on ships", organised by Blue Maritime Cluster at the Norwegian Maritime Competence Centre in Ålesund on the 5th of October 2022. During this course both Jan Emblemsvåg, professor at NTNU, and Claire Blackett, senior research scientist at IFE, held their presentations on small modular reactors. Both agreed on the relevance of the chosen topic for a bachelor's thesis. Later, during another NTNU event "Nuclear power for sustainability" was gained the approval of relevance of the topic also by Ann Rigmor Nerheim, supervisor for Renewable Energy projects. Next step was research of the possible tools for simulation of a simple grid model. During this phase scientists from CINELDI and SINTEF got involved in the ongoing consultations, which resulted in a decision to include offshore wind power in the grid model. Further search revealed an already existing topic of a hypothetical offshore transmission line parallel with the coast. This topic sparked an idea of an offshore platform converted into a power grid unit supporting the onshore power grid through a HVDC cable connection. On a higher level, such grid units could create a whole supportive network for the onshore power grid [48]. But problem solving at such a scale won't be achievable within this bachelor's thesis. This project is a great opportunity to achieve my personal goal to gain a practical experience with simulation of a power system.

I am grateful to all of those with whom shared their knowledge and insights with me. In particular I would like to thank my supervisor, Assosiate Professor Ann Rigmor Nerheim and my co-supervisors, Professor Alemayehu Gebremedhin and Professor Jan Emblemsvåg for their guidance during the thesis.

In addition I would like to express my gratitude to SINTEF scientist Iver Bakken Sperstad for his insights and knowledge he shared with me in his spare time.

Nobody has been more important to me in the pursuit of this project than my partner, Espen Ekornes Rekdal, to whom I wish to thank for his undying support.

Zuzana Koránková

Zuzana Korankova
Ålesund, 16th May 2023

Sammendrag

Hovedmålet for denne oppgaven er å undersøke hvordan justeringer av komposisjon av et hybrid energisystem (HES), bestående av to typer av kraftproduksjon og to typer av energilagring, kan påvirke kraftbalansen i systemet. Justeringene fokuserer på analyse av systemets evne til å kompensere for etterspørsel på land og for ubalanse i kraftproduksjon forårsaket av økt andel av intermitterende vindkraftproduksjon.

Denne oppgaven er en case-studie. Det ble utviklet tre scenarier med gradvis økt kompleksitet i HES-systemet. Hvert scenario har tre modifikasjoner i form av caser, noe som gir totalt ni caser for HES-effektbalanse-simuleringen.

Scenario I ser på offshore del av det hybride energisystemet. Scenario II ser på hvordan offshore delen av det hybride energisystemet klarer å balansere kraftbehovet til onshore delen, Sørlandet. Scenario III ser på en utvidelse av Scenario II basert på fremtidsplaner om vindpark i Sørlige Nordsjø.

Alle casene er skapt ved hjelp av justering av parametere til de tilsvarende scenarioene. Tilfeller av Scenario I ser på kraftsituasjonen under dominans av enten justerbar eller ikke-justerbar, intermitterende kraft. Cases of Scenario II ser på kraftsituasjonen under dominans av den ene eller den andre av de to typene energilagring. Cases of Scenario III ser på kraftsituasjonen ved økt bruk av en spesifikk type energilagring.

Alle casene er simulert i Simulink og videre evaluert ved hjelp av et egendefinert system av effekttilstander. Resultatene presenteres grafisk i form av kakediagrammer, som viser distribusjon av krafttilstander, og i form av diagrammer, som viser timeverdier for kraftbalanse.

Det påpekes noe usikkerhet i det definerte systemet av effekttilstander. Årsaken til usikkerheten er identifisert i logisk kontroll til termisk lagring.

Resultatene indikerer minimal effekt av batterilagringsteknologi som et middel for å balansere en vindpark.

Siste kapittelet gir flere forslag til videre arbeid i form av konkrete utbedringer av oppbygging av HES-systemet og eventuelt systemets utvidelse.

Summary

The main objective for this thesis is to investigate how adjustments of composition of a hybrid energy system, consisting of two types of power production and two types of energy storage, affect power balance in the system. The composition adjustments focus on analysis of the systems ability to compensate for onshore demand and for imbalance in power production caused by increased share of intermittent wind power production.

This thesis is a case study. There were developed three scenarios of the HES system with gradually increased complexity. Each Scenario has three modifications in form of cases, giving a total of nine cases for the HES power balance simulation.

Scenario I represents offshore part of hybrid energy system, Scenario II represents hybrid energy system balancing onshore power and Scenario III represents an expansion based on plans for future.

Scenario I looks at the offshore part of the hybrid energy system. Scenario II looks at how the offshore part hybrid energy system manages to balance the power demand of the onshore part, Southern Norway. Scenario III looks at an expansion of Scenario II based on future plans for a wind farm in the Southern North Sea.

All cases are created by adjusting parameters to the corresponding scenarios and give results in form of power difference and distribution of states. Cases of Scenario I looks at power situation under domination of either adjustable or non-adjustable, intermittent, power. Cases of Scenario II looks at power situation under dominance of one or the other of the two types of energy storage. Cases of Scenario III looks at power situation in case of increased use of a specific type of energy storage.

All cases are simulated in Simulink and further evaluated using a custom made system of power states. Results are graphically presented in form of pie charts, showing distribution of power states, and in form of charts, showing hourly values of power balance.

Some uncertainty in the defined system of effect states is pointed out. Cause of the uncertainty is identified in logic control of thermal storage.

The results indicate minimal effect of battery storage technology as a means of balancing a wind farm.

The last chapter gives several suggestions for further work in the form of concrete improvements of the HES structure and possibly an expansion of the system.

Contents

Abbreviations

AC	Alternating Current
CMSR	Compact Molten Salt Reactor
DC	Direct Current
ESS	Energy Storage System
GW	Gigawatt
GWh	Gigawatt-hour
HES	Hybrid Energy Systems
HVAC	Hybrid Voltage Alternating Current
HVDC	High Voltage Direct Current
MATLAB	Matrix Laboratory
MSR	Molten Salt Reactor
MSTS	Molten Salt Thermal Storage
MW	Megawatt
MWh	Megawatt-hour
PID	Proportional Integral Derivative
PEM	Proton Exchange Membrane
RES	Renewable Energy Systems
S I	State I
S II	State II
S III	State III
S IV	State IV
Simulink	Simulation link
SMR	Small Modular Reactor
SOE	State of Energy
SPADE	Stakeholders, Problem, Alternative, Decision, Evaluation
TEES	Thermoelectric Energy Storage

TX	Transformer
VRFB	Vanadium Redox Flow Battery
ESS	Energy Storage System

Software Tools

MATLAB	The Language of Technical Computing, version R2022b ”MATLAB® is a programming and numeric computing environment used by millions of engineers and scientists to analyze data, develop algorithms, and create models. MATLAB provides professionally developed toolboxes for signal and image processing, control systems, wireless communications, computational finance, robotics, deep learning and AI and more. MATLAB combines a desktop environment tuned for iterative analysis and design processes with a high-level programming language that expresses matrix and array mathematics directly. It includes the Live Editor for creating scripts that combine code, output, and formatted text in an executable notebook. Prebuilt applications allow users to interactively perform iterative tasks.” [31]
Simulink	Simulation and Model-Based Design, version R2022b ”Simulink® is a block diagram environment for multi domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB®, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.” [73]
Microsoft Office Excel	version 2303 Excel provides spreadsheet based data analysis and computation.

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1 Introduction

The Norwegian Centre for Intelligent Electricity Distribution (CINELDI) asks in the recent annual report 2022 [15] the following question:

“How can we make our electricity grid more efficient, flexible, and resilient?”

This question reflects well the current stability challenges caused by both increasing electrification of the Norwegian society and growing share of renewable energy sources (RES) in the Norwegian energy mix.

When it comes to the aforementioned increased electrification, the main concerns apply to charging of electric vehicles (EVs) and electrification of oil and gas industry. Norwegians have become champions in use of electric vehicles (EVs) [47]. The unpredictable pattern of power demand caused by EV charging presents a challenge for grid stability and might be solved by a higher demand on consumer flexibility [74], [16]. That won’t be an option for the Norwegian oil and gas industry, which needs a constant access to a secure and stable energy source. That is supposed to be provided by quite reliable hydro power via High Voltage Direct Current (HVDC) cable [40]. Unfortunately, these do not always provide a secure service [67].

When it comes to the aforementioned effect of RES on the power grid stability, the main concern applies to wind power intermittency [75]. Wind farms change shape of power production curve from smooth to quite spiky [52]. Such unstable power power production conditions can present a great threat for power grid stability [28], which is a main topic of this thesis.

Recent energy policies in Norway raise the share of renewable resources to even higher level [30]. Such development demands increased focus on the power grid stability that might bring forward effective solutions to the challenge that increased share of RES in power mix presents [65]. In recent report about the energy crisis in Europe and the Norwegian power marked, CINELDI warns about consequences of high share of intermittent power production in the European grid and calls for adaptation of the power system to variations in weather and wind [48].

Furthermore, the Norwegian Water Resources and Energy Directorate and the International Energy Agency warn in their reports [32] and [5] about power deficit in the future. In addition to the power deficit, there are several bottlenecks in the Norwegian power grid. These prevent other renewable power resources from relieving hydro power in the areas most exposed to power shortages.

The Sustainability Development Goal number 7, is a main driver behind the expansion of renewable power in general. The Norwegian energy policy is based on the notion that increased production of renewable power leads to a more sustainable future [51]. At the same time, it is necessary to find a flexible solution providing balance to the variable renewable power production in the power grid. This happens by strengthening the power grid and by active measures, which can deal with bottlenecks [78]. Construction of this type of resilient infrastructure, accompanied by innovation, covers aspirations of the Sustainability Development Goal number 9 [54].

Maintaining balance between power production and power demand in the grid is a requirement for answering the opening question [56]. This thesis will simulate the introduction of active measures on the power production side. These active measures are in the form of a hybrid energy system (HES), a system that combines multiple types of energy generation and/or storage [21]. Specifically, it consists of adjustable, mobile power plant combined with wind turbines, and flow batteries combined with thermal storage.

1.1 Approach

The thesis will simulate the hybrid energy system and look at how it can affect power demand in terms of balance and peak shaving. The task is dealt with through development of three scenarios, further elaborated in three cases, giving a total of nine simulations. The scenarios represent various examples of HES build up, with gradually increasing complexity from Scenario I to Scenario III. The cases are meant to highlight some specific challenges, created by their setup. Cases er created through variation of HES parameters of a scenario, thus representing various setups of one particular scenario.

The simulation doesn't take into account power production flexibility of the onshore grid, represented by hydro power. In addition the simulation is run at a time resolution of 1 hour. This results in a limitation of dynamic response of the system, for instance load following ability of the mobile power plant.

The output of HES simulation gives total number of hours of power deficit and power surplus. Results of the simulation are evaluated based on share of power deficit relative to power surplus. The goal is to create a realistic approximation of the HES. Another main goal is to simulate how a surplus of power in the system can affect another power system, for example an offshore platform or a part of the Norwegian coast.

2 Theory

Electricity is a perishable good, it must be therefore consumed at the same time as it is produced. This means that electricity must be produced at the exact rate in which it is used. In order to achieve this state, both production and consumption must be in perfect balance [56]. This chapter introduces the various components of the studied power system. To make things clear, the system components are divided into two groups, "major components" and "minor components". The difference between these two groups lies in whether their dimensioning is affected by parameters used in the simulated cases. The major components get affected while parameters the minor components stay the same. Further on, in the last two sections of this chapter, comes explanation of how the major parts affect power balance of the simulated system.

2.1 Hybrid Energy System - Power Production

The major components, introduced in the following two subsections, create together a system combining various types of power generation and energy storage. Such system is called a hybrid energy system (HES).

Power generation using HES can help with integration of renewable power in the conventional electricity grid system [21], increasing their share in the power mix. HES could be a useful concept of alternative power supply of coastal regions with energy demanding industry [44].

The remote coastal areas using HES gain primary access to a stable source of power while saving the cost of building expensive transmission and distribution lines from the central grid. Power generated by HES could have considerable positive impact in remote areas depending on power generation from diesel generators. Otherwise fuel price fluctuations can mean no electricity for these communities for a period of time.[21]

2.1.1 Wind turbine

Wind power is produced by wind farms, made up by wind turbines. Wind turbines represent the first major component of the simulated power system. A wind turbine is a device that converts kinetic energy of wind into electricity. This process is described in detail in the following section.

Wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades. These work on the same physical principal as an airplane wing or helicopter rotor blade. Their design makes the airflow slide along the upper surface travels a longer distance across the blade that the airflow under it. This difference in distance introduces a difference in pressure between the two blade surfaces as shown in Figure 2.1.

Therefore when the wind flows across the blade, the air pressure on one side of the blade increases. This creates a difference in air pressure across the two sides of the blade, creating lift and drag forces. The lift force, being stronger than the drag force, makes the rotor part of wind turbine to spin.[36]

The rotor is connected to the generator, either directly or through a shaft and a series of gears that speed up the rotation and allow for a physically smaller generator [36]. This translation of aerodynamic force to the rotation of a generator generates electricity. Electricity is produced at varying power, defined by a power curve. Since power output of a wind turbine is based on its design, each model of wind turbine has its own power curve.

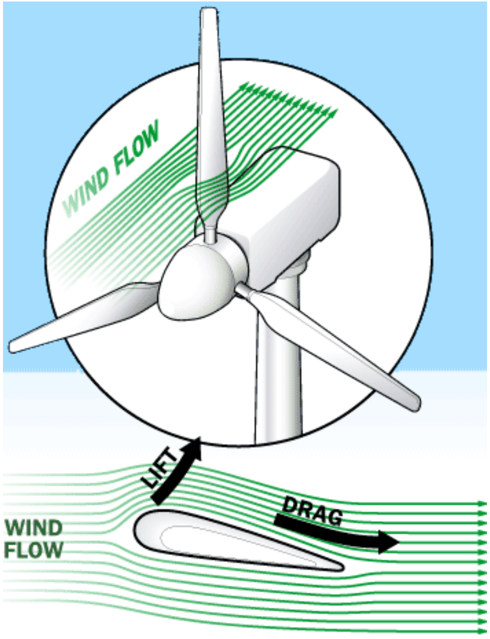

Figure 2.1: Wind Turbine Blade Aerodynamics [22].

A group of wind turbines makes a wind farm. Current Norwegian plan for increased energy security includes a wind farm in the area Southern North Sea [29]. This wind farm is expected to be built at a size of 1500 MW installed power. Approximation of its power production will be covered in simulations of Scenario III, described in Section 3.4.

2.1.2 Molten Salt Reactor

The most recent development within nuclear power has brought a comeback of Molten Salt Reactor (MSR), representing the second major component of the simulated power system.

MSR is a type of Small Modular Reactor (SMR). SMR is a physically small, advanced nuclear reactor, at a fraction of the size of a conventional nuclear power reactor, having a power capacity of up to 300 MW per unit. This corresponds to about one-third of the generating capacity of a traditional nuclear power reactor. SMR produces energy through harnessing of nuclear fission [43]. Generated heat is then transformed using steam turbine for power generation.

In case of MSR, the primary nuclear reactor coolant and possibly also the fuel is a molten salt mixture. MSR use molten fluoride salts as primary coolant, at low pressure [7]. Operation at low or atmospheric pressure is one of several key features giving MSR a unique inherent safety quality [68].

Currently there are divided opinions on the potential of these reactors in Norway [83]. Nevertheless, as a source of clean power and fulfilling the demand of adjustability and mobility, an MSR seems as a more relevant option than a mobile gas power plant. In addition there are projects on floating MSR power plants, convenient for the intended offshore location of the HES. Such a self-contained, floating power plant that operates independently of local resources or infrastructure is called power barge [46].

MSR also offers unique efficiency and flexibility. While being a dispatchable source of power, MSR can adjust output accordingly to power demand. Such operation mode is called load-following. Through this ability MSR qualifies for interaction with the power grid [14], [33].

2.2 Hybrid Energy System - Grid Scale Energy Storage

Third and fourth major components of the simulated power system are represented by two different types of energy storage.

Power grid deficit due to increased electrification and growing share of intermittent renewable wind power represents a serious challenge. This situation is on a general basis alleviated by means of grid-scale energy storage, providing temporary support to the overloaded power grid. [60]

This subsection introduces two types of grid-scale energy storage, molten salt thermal storage and vanadium redox flow battery. These technologies were chosen based on their high capacity, long lifetime, sturdiness, accessible resources and ultimately suitability for simulation with low-resolution power demand data.

From the range of utility scale applications potentially interesting for energy storage systems (ESS) are the following applications relevant for this project: Integration of RES and peak shaving. [60]

2.2.1 State of Energy

In order to keep track of the current state of energy storage capacity, it is necessary to introduce an adequate measure of it.

State of Energy (SOE) is used as an estimation of current amount of available energy, measured in MWh. SOE is thus a real-time indicator of the actual energy the battery can dispatch. SOE is defined as the ratio of remaining energy to the total energy of the battery [90]. However, it is important to notice that SOE term will be used in an alternative interpretation in the HES simulations, as described in subsection 3.3.3.

2.2.2 Molten Salt Thermal Storage

The fist type of energy storage used in the simulated power system is thermal energy storage.

Thermal storage is a form of energy storage that is compatible with both wind power and MSR power production. In addition, power conversion of wind power to thermal power gives minimal losses. The same applies for heat exchange between MSR and thermal storage. [53]

Molten salt thermal storage (MSTS) is a well-known technology. Thermal energy storage applied to power generation is not a new concept either [53]. On the other hand, merging of MSTS with wind power production is just about to be demonstrated at a cogeneration plant in Bornholm, Denmark [27].

Figure 2.2 shows operation of thermoelectric energy storage in power grid with connected wind power. Excess of wind power produced mainly during periods of off-peak power demand is converted into heat using resistors.

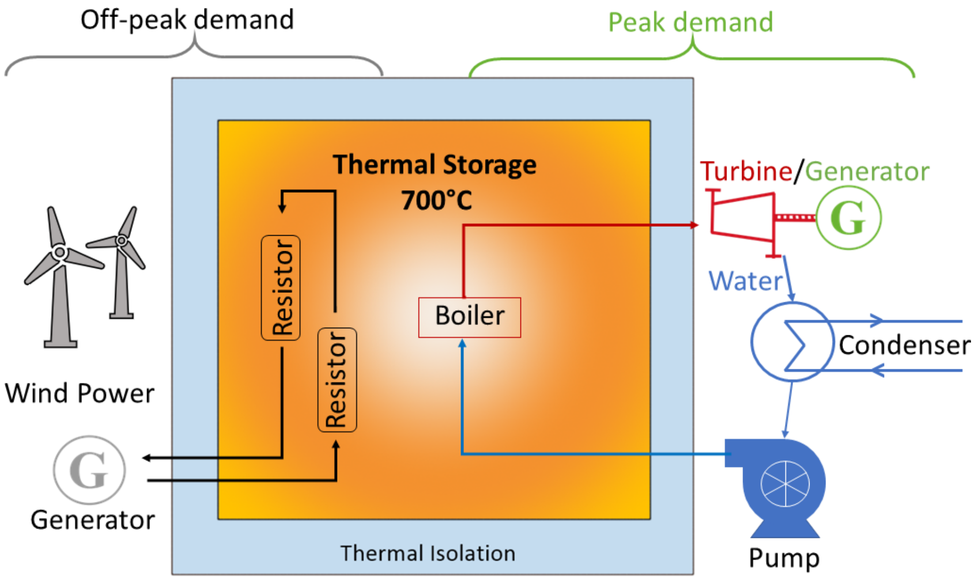

Figure 2.2: Thermoelectric energy storage (TEES) scheme showing processes active during periods of off-peak and peak demand. This scheme is based on illustrations from article [17] and [60]

.

This way the thermoelectric energy storage (TEES) gets charged and the energy is stored in the TEES. The stored energy is converted back to electricity during peak demand. This is done using boiler for heat exchange between TEES and external water loop. Produced steam drives steam turbine and generator, which generates power upon demand.

The aforementioned HES project in Bornholm utilizes MSTS produced by Hyme [41]. Parameters of MSTS in the HES simulations of this project are also based on approximation of Hyme's product.

2.2.3 Vanadium Redox Flow Battery

The second type of energy storage and the last major component of the simulated power system is represented by vanadium redox flow battery (VRFB).

VRFB is a rechargeable battery and a novel energy storage device, which is currently experiencing a revival in power grid applications [49]. VRFB is the most common flow battery, a hybrid between battery and fuel cell [88].

Figure 2.3 gives an overview of parts and electrochemical reactions in a standard VRFB. The battery consist of the following parts: reaction cell stack, reaction tanks, storage tanks, piping between tanks and mechanical pumps. Liquid electrolytes, anolyte and catholyte, are pumped through a core consisting of reaction stack. The region bordered by the grey electrodes is the reaction cell stack with reaction tanks separated by a membrane. [64]

The battery harnesses existency of vanadium's four different oxidation states in solution. The arrows between the reaction tanks indicate reactions during charging and discharging, which are mutually reverse. [18]

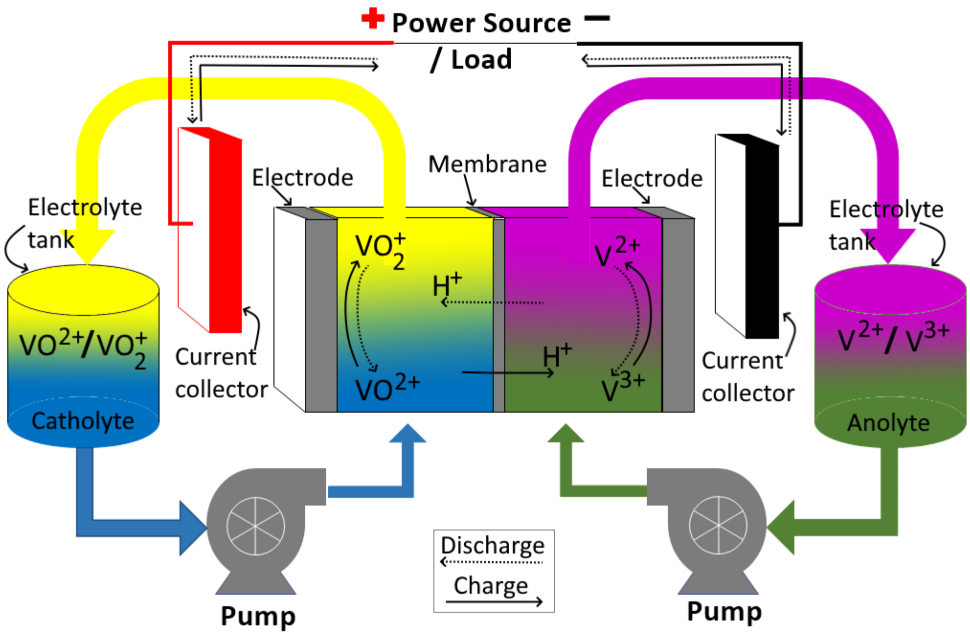

Figure 2.3: Scheme of VRFB processes and reactions based on illustration in an article [64].

Pumps and piping connecting storage tanks with reaction tanks provide flow of electrolytes, to the reaction cell stack, where the electrochemical reactions occurs. These reactions are in principle a proton (H+) exchange through the membrane between the reaction tanks, going one way or the other one.The ion exchange that occurs between the cathode and anode generates electricity.

This section shows reactions during discharge of VRFB. Charging reaction is reverse to discharging reaction.[64]

Anode side reaction:

$$V^{2+} \xrightarrow{\text{PEM}} V^{3+} + e^{-}$$

Cathode side reaction:

$$VO_2^{+} + 2\,H^{+} + e^{-} \xrightarrow{\text{PEM}} VO^{2+} + H_2O$$

Full cell reaction:

$$V^{2+} + 2\,H^{+} + VO_2^{+} \xrightarrow{\text{PEM}} V^{3+} + VO^{2+} + H_2O$$

Development of VRFB focuses on cost and size reduction, resulting in a modular system of containers that can be stacked [88]. VRFB cells are connected in series packed in a battery with a specific energy resembling to lead acid. Power density and response time resemble fuel cell [88]. VRFB has several inherent advantages compared to other energy storage technologies. It can be used to balance both grid loads and intermittent power sources, like wind power [49]. Other advantageous characteristics are the ability of deep discharge cycle, allowing utilization of the full installed capacity, high charge-discharge cycling capability, and ideally indefinite lifetime of the electrolyte. When it comes to the safety in use, VRFB electrolyte is a nonflammable aqueous solution with a high heat capacity. Therefore operation of VRBF poses no risk of ignition or explosion [10].

The durability of VRFB is utilised in hybrid Energy Storage Systems (ESS), combining fast responding lithium batteries with VRFB. The lithium battery is activated by the hybrid ESS only when the required response exceeds the response capability of VRFB, reducing number of charge-discharge cycles of the lithium battery. [89]

2.3 Power Distribution

This section gives overview of the other, "minor components". The minor components keep the same parameters throughout all the simulations. These parts of HES provide power conversion and power distribution.

2.3.1 High Voltage Direct Current Cable

High voltage direct current (HVDC) subsea cable systems connect the offshore part of HES with the onshore grid and carry electricity both ways [38]. In the simulation the HVDC is represented by approximate power losses on the cable.

Electron flow of direct current does not change direction and penetrates further into conductor than alternating current, resulting in minimal transmission losses and high transmission capacity [76].

HVDC cables send direct current in both directions depending on power demand and are therefore able to balance power demand between two separate power grids. Transmission using HVDC cable, compared to High Voltage Alternating Current (HVAC) cable, gives the benefit of lower transmission losses for wind farms placed at least 100 km from the coast. Alternating current changes direction periodically resulting in the same average amount of current flowing in both directions along a conductor. Alternating current can be converted into direct current using rectification process. [40]

Apart from providing an interconnection, HVDC cables can also help to create a supportive offshore grid by connecting offshore platforms and wind farms to onshore power grid. Offshore platforms can export electricity generated by offshore wind parks to shore, redistribute power for offshore activities, or put it in an offshore energy storage. [38]

2.4 Energy and Power Conversion

Energy and power conversion are essential parts of the HES system, making it possible to connect the different system parts together.

2.4.1 Transformer

A transformer is a device that transfers energy form one electrical circuit to another. It is used to either increase of decrease voltage between the two circuits. This process, together with power rectification and HVDC transmission, lead to loss of roughly 10% of power transported to the onshore grid [39] [82].

2.4.2 Steam Turbine

Steam turbine uses superheated steam to drive a shaft leading to generator. The steam flowing through the turbine structure creates a force against the rotor blades of the turbine, making it to rotate around its shaft. This process transforms thermal power into mechanical work. This project uses for simulation purposes some basic parameters of steam turbine model SST-600 made by Siemens [35].

2.4.3 Generator

Generator is a machine providing conversion of mechanical work to electricity. Generator consists of a rotating inner part and a stationary outer part. Electromagnetic interaction between these two parts leads to induction of electric current. Due to geometry of the generator's outer part the resulting output is in form of alternating current.

2.5 The Norwegian Power System

Norwegian power system is based on hydro power and thus represents a weather-based power system. Relevant data is displayed in International Energy agency report "Energy demand per sector and per fuel", Figure 2.7 "Electricity generation" [3].

In weather-based power systems, like the Norwegian, the power balance varies between the different regions. In addition there is not always sufficient capacity in the power grid to equalize the power demand between the regions. The network is therefore divided into five electricity price areas [79]. Figure 2.4 shows net power demand in the Norwegian power grid and its electricity price areas for the year 2022. Net power demand is calculated as a difference between power production and consumption from data manually collected from Nord Pool website [63].

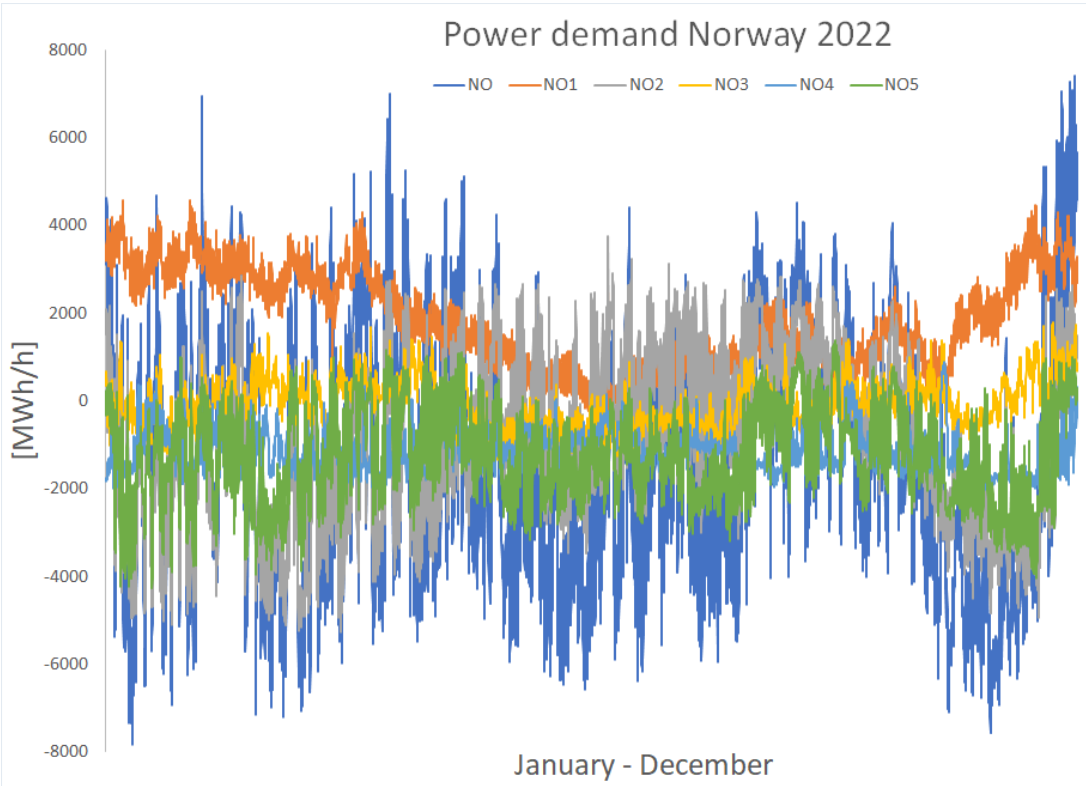

Figure 2.4: Net power demand for 2022 [63]: Norway in total - NO, compared to the electricity price areas, NO1 - Eastern Norway, NO2 - Southern Norway, NO3 - Central Norway, NO4 - Northern Norway, NO5 - Western Norway.

A closer inspection of Figure 2.4 reveals how much the imbalance in the net power demand varies between the different power areas. Positive values represent power deficits that needs to be imported. Negative values represent power production surplus that can be exported. Local imbalance in power demand is the identified problem that this project will focus on and attempt to find a solution for.

It is important to point out that there are locations where the capacity of the power grid is constrained. These so-called bottlenecks, shown in Figure 2.5, in the power grid make it difficult to equalize the power demand between the power areas. The segmented design of the Norwegian power grid makes even power distribution difficult to achieve. Therefore it is difficult to utilize any larger power sources in the power grid on land. This project will look instead at ways to balance the power grid using power sources located offshore.

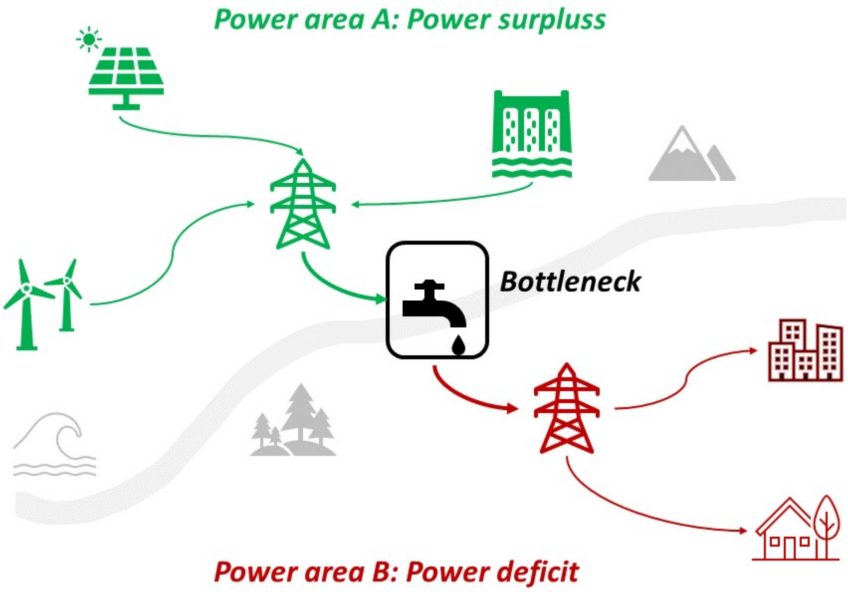

Figure 2.5: Scheme of a bottleneck in a power grid based on an animation published by The Norwegian Water Resources and Energy Directorate. [57]

Bottlenecks can lead to power grid congestion, causing an increase in current frequency and imbalance in the power system. Such situation can lead to a breakdown of the affected part of the power grid. [58]

Potential consequences of grid congestion due to bottlenecks in the power grid aren't included in the scope of this project.

2.6 Dispatchable versus Intermittent Power Production

Norwegian electricity is produced from both dispatchable and intermittent power sources. Dispatchable power plants are reliable sources of stable power production that can be switched on and off [12]. In addition, these need to be able to quickly adjust their power output in order to match fluctuations in power demand. This function is known as load following [91].

Energy produced from sources that are naturally replenished and do not run out is called renewable [37]. Wind power represents an intermittent renewable energy as it isn't constantly available and predictable [62]. Conversely hydro power represents a variable dispatchable renewable energy, currently widely used as an energy storage stabilizing intermittent wind power [85].

Both hydro and nuclear power plants are examples of zero emission, variable and dispatchable sources of electricity [4]. They are suitable to cover base load, the minimum amount of power delivered or required over a period of time at a steady rate [1]. In addition, based on their flexibility, they can to some extend balance sudden changes in power demand. These properties make both hydro and nuclear power suitable as balancing power sources for intermittent power production like wind power [81].

The importance of dispatchable power in the system is indirectly explained by the following definition of base load: "Base load is the minimum level of demand on an electrical supply system over 24 h. Base load power sources are those plants that can generate dependable power to consistently meet demand. They are the foundation of a sound electrical system (Energy Commission of Ghana, 2015)." [50]

Electricity generated by wind power is weather dependent. Its electrical output depends on many factors, such as wind speed, air density and turbine characteristics. Weather instability influences wind power production and prevents it from being continuously available. Wind power is therefore considered a highly intermittent and non-dispatchable power source [13].

This means that the green shift, characterized by increased introduction of renewable, intermittent power sources in the power grid, could lead to greater instability of the power system unless the system is balanced by appropriate proportion of dispatchable power [8] [85]. Such a coexistence of wind and nuclear power can be observed in Saint-Paul-Trois-Châteaux, France [3].

3 Methods

This chapter gives details on properties of the various parts of the studied energy system and explains how the decisions leading to its design were made.

For the purpose of this project a combination of nuclear and wind power generation together with thermal and electrochemical storage was chosen. The actual design of nuclear-wind hybrid energy system is a merged system consisting of nuclear reactor, wind power, energy storage and process control that can simultaneously address the need for grid flexibility. Figures 3.2 and 3.3 give an overview of the simulated HES system.

It may be speculated that such merging of nuclear and wind power might make these two technologies to bring out the best of each other [80].

3.1 Methodology

Approach in this project will strive to apply SPADE systems engineering methodology, used in projects with focus on sustainability [55]. This approach is valuable in dealing with complex problems in multi-actor environments [19]. SPADE consists of five problem-solving tools, shown in Figure 3.1.

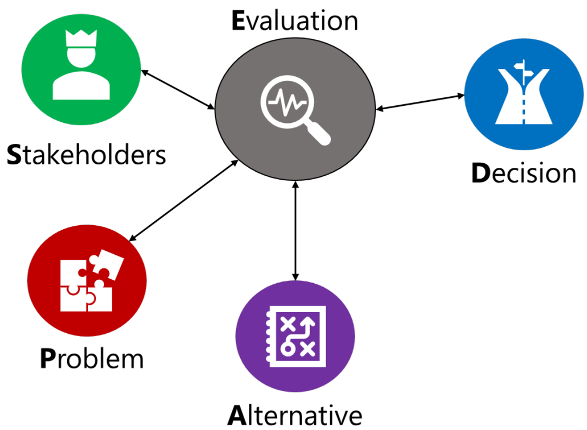

Figure 3.1: Essential elements forming SPADE thinking framework.

In the case of this project, the following applies:

- Stakeholders were identified as the oil and gas industry and the state.
- Problem was identified as a need for balancing the power grid.
- Options which were chosen are specified in the title of the assignment as "..adjustable, mobile power plants and thermal batteries".
- Decisions apply to geographical location of the system, delimitation of the system, definition of system states and simulation cases, including further expansion based on the latest offshore wind tender [61].
- Evaluation is a continuous process that creates a link between the rest of the elements, representing a main asset of this bachelor's thesis.

3.2 System Structure

The simulated power system includes both power production and power demand and is located both onshore and offshore as Figure 3.2 shows.

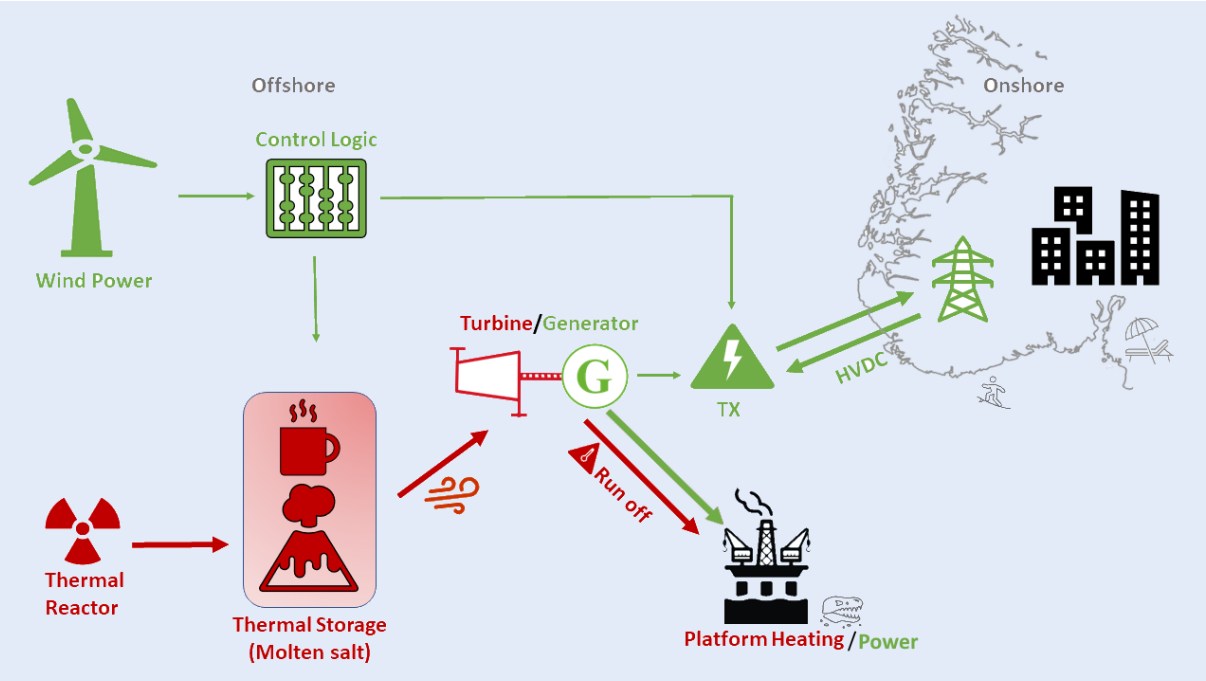

Figure 3.2: Scheme of the proposed Hybrid Energy System: Green colour marks electric power, red colour marks thermal power.

Figure 3.2 provides an overview of the processes involved in the proposed HES:

Black colour marks power consumers - offshore platform and onshore power grid. At times of power surplus, represented by negative power demand in the Figure 2.4, the onshore power grid can act as a power source for the offshore part of the HES.

Green color marks system parts participating in production or transmission of electric power. Renewable power produced by wind turbine is sent to a controller. Based on power demand the control logic sends electric power via transformer (TX) and High Voltage Direct Current cable (HVDC) to the onshore power grid. Eventual power surplus is sent from control logic to the thermal storage containing molten salt. Electric power is transported using power cables.

Red colour marks thermal power parts. Thermal power produced by nuclear reactor is sent to the thermal storage containing molten salt. Then the stored heat is used to generate steam, which drives the turbine/generator. These processes convert thermal energy into electricity.

Run off from the power conversion contains waste heat, which is sent to the offshore platform as a form of district heating. The offshore platform is the primary consumer of electricity generated through power conversion. This increases energy security needed for uninterrupted operation of the offshore platform. Thermal power is transported using heat exchangers.

3.3 Simulation

Both Python and Simulink were considered as a tool for simulation of the HES. Simulink is chosen because it gives option for less advanced level of simulation thus making the simulation task manageable with the resources given and within the given short period of time.

The model is run with fixed step size of 1 hour, representing the time scale unit in simulation. This results in each iteration giving output in MWh/h units.

Data input consists of datasets imported from Excel and data generated in the Simulink model. Input is processed by the simulation, giving data output. Output is then exported to MATLAB for further analysis. This way results in form of pie chart or graph of annual power balance are generated, presented in Chapter 4. MATLAB code for creation of pie chart output is shown in Figure 7.10, Appendix 7.6. Graphs showing annual power balance in HES are created using Data Inspector, a built-in MATLAB function.

Excel input data is represented by datasets for wind speed and onshore power demand. Wind speed creates input for the wind farm component generating wind power data, while onshore power demand is a direct input on the top level of the HES model.

Ekofisk power and heat demand data are generated in the Simulink model without prior input from external sources. This process is described in detail in section 3.3.7.

Figure 3.3 gives a top level overview of processes between the HES components. The Simulink model used in cases of Scenario I is shown in closer detail in Figure 7.6, Appendix 7.3. Simulink model used in cases of Scenario II and Scenario III is shown in closer detail in Figure 7.7, Appendix 7.3.

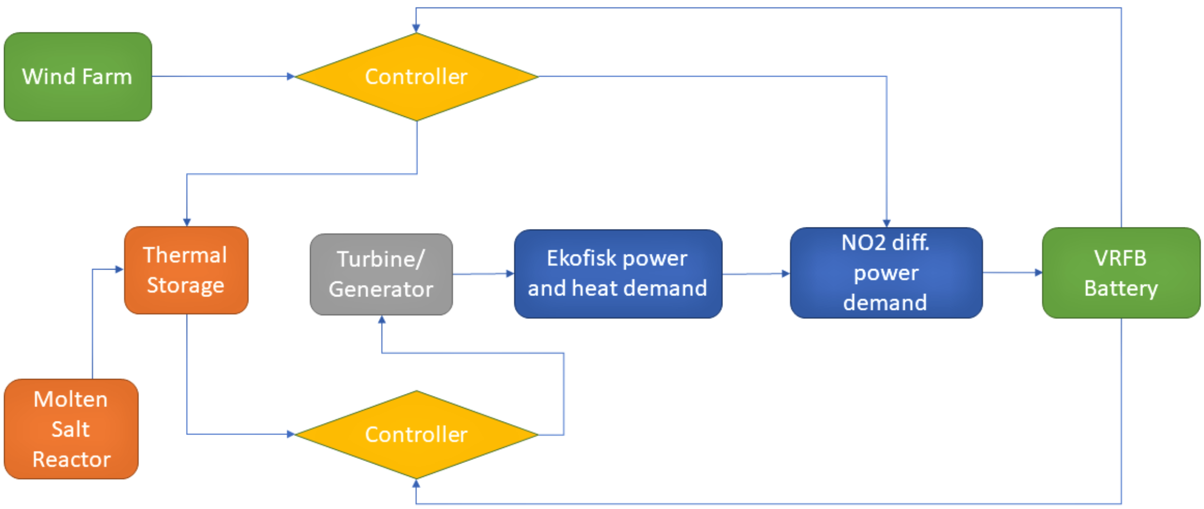

Figure 3.3: Flow chart of the simulated HES

Following subsection gives detailed description of the individual components of the HES system.

3.3.1 Wind Farm

Simulations performed in this project use power curve of DTU 10-MW Reference Wind Turbine [20]. This model of wind turbine was chosen as a relatively technologically neutral, academic product, that could possibly give minor chance of systematic error.

Figure 3.4 shows the power curve used in HES simulations. The DTU turbine has maximum power output given by it's power rating of 10 MW. Power rating of a wind turbine is given as an output limit with a safety margin put in to avoid physical overload of the turbine. A closer examination of the Figure 3.4 reveals that this detail is omitted in the simulation. The simulated wind turbine produces power at a maximum of 10.7 MW, which is therefore marked as the rated power of the turbine.

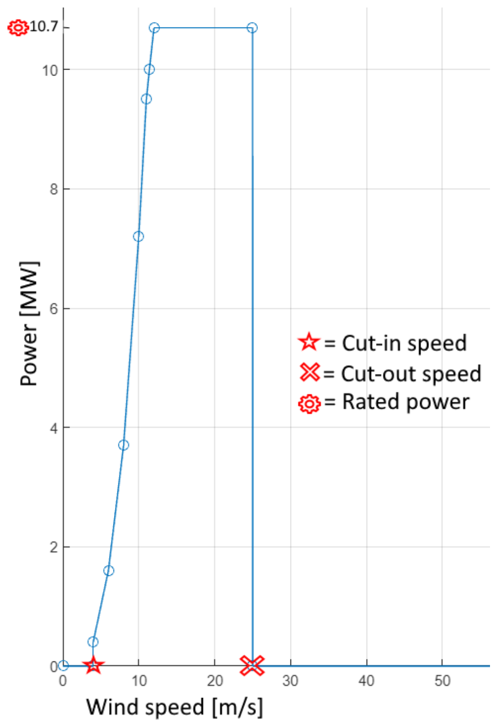

Figure 3.4: Power curve of the HES wind turbines.

On the other hand, the cut-in and cut-out speed, i.e. the maximum and minimum wind speed at which the turbine produces power, are the same as for the DTU wind turbine.

Wind power simulation is based on average wind speed data processed through the power curve of the DTU turbine [20]. The power curve indicates the power output based on hourly wind speed data from 2022 for the Ekofisk area. Thus the wind power output has MWh/h as unit of measure. Wind speed data are downloaded from website of the Norwegian Meteorological Institute [45] as set of annual wind speed data with 10 minutes intervals. Such resolution gives the best quality, i.e. minimum of gaps in form of missing values, for the given source, year and geographical area.

The downloaded dataset is processed in Excel in order to fill in the gaps and to make it with the other datasets used in the simulation. Missing values were filled in as gliding average, an Excel function. Then the 10 min intervals were used to calculate the hourly average wind speed. The resulting dataset of annual wind speed data is imported from Excel to the HES Simulink model as block "Ekofisk Wind Data for Year 2022" inside the HES component "Ekofisk Wind Farm [MWe]". The Ekofisk Wind Farm component is shown in detail in Figure 7.1, Appendix 7.1.

3.3.2 Molten Salt Reactor

Molten salt reactor (MSR), providing constant source of thermal power in the HES, is a simple approximation of Compact Molten Salt Reactor (CMSR) from Seaborg Technologies [59], shown in Figure 3.5. It's load following ability is moved further to the thermal storage component, thus giving it an additional function as a second circuit of the MSR. Nevertheless the simulation can't accurately model an MSR ramp rate of 10 % per minute [33], as each step in the simulation is 1 hour.

Power output of the simplified MSR model is based on a linear ramp. Parameter for conversion of thermal energy to electricity is derived from CMSR's power output, i.e. 100 MW electric power per 250 MW thermal power.

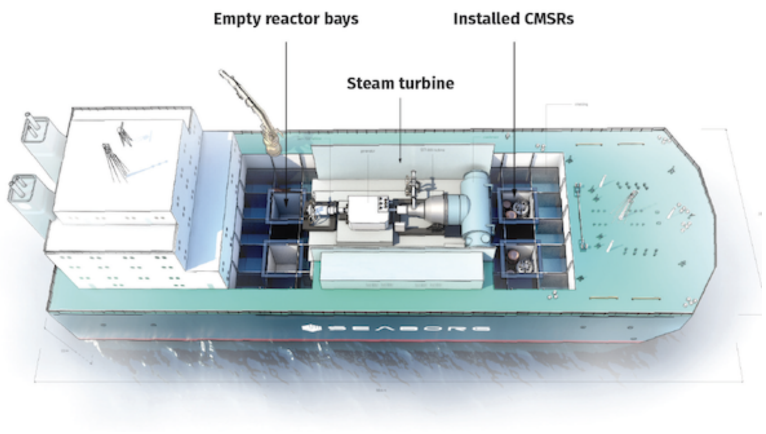

Figure 3.5: Power barge fitted with Compact Molten Salt Reactor (CMSR) from Seaborg Technologies [77]

Both MSR and thermal storage, made by two sister companies, are based on the same molten salt and are thus compatible for the intended concept. The MSR design is chosen based on this favorable quality, giving the thermal storage a double role. Simulink model of the MSR is shown in detail in Figure 7.2, Appendix 7.1.

3.3.3 State of Energy

As mentioned in Subsection 2.2.1 it is important to emphasize the alternative use of the term State of Energy (SOE) in MATLAB code in this project. For the purpose of energy storage simulations the SOE will be considered as the real time, absolute amount of dispatchable energy. This alternative SOE is represented by MATLAB Variable *soc*.

3.3.4 Thermal Storage

The HES component "Thermal Storage" represents thermoelectric energy storage (TEES) with 350 MWh capacity. It has a double function as both secondary circuit of the MSR and thermal storage for wind power. Principle of its function is explained in Subsection 2.2.2. The idea to combine nuclear power with TEES has already been studied in Oak Ridge National Laboratory in the USA [11]. However this project creates only an approximation of such complex systems in order to keep focus on the overall picture of HES.

As aforementioned, parameters the TEES based on the product made by Hyme [42]. For the purpose of this project the TEES is coded in MATLAB. Code of the "Thermal Storage" component of HES system is shown in Figure 7.9.

The TEES code works as a function with two input arguments *charge_req* (charge request) and *discharge_req* (discharge request) and four output values: *leftover_charge*, *charge*, *soc_out* and *discharge*. The core of the function is the persistent Variable *soc*. It keeps track of the state of energy of the TEES in MWh. In addition there are values that define the Maximum Capacity (*max_soc*), and the Maximum Input (*max_char_in*) and Output (*max_char_out*) per hour, all in MWh.

At the start of the simulation the state of energy (*soc*) is set to zero. The function is called once per simulated hour with either charge request, discharge request or both. The HES simulation is modeled so that the requests are either positive or zero, but never negative. The charge request is handled first. If there is available capacity, the state of energy is increased by the energy amount corresponding to the charge request, up to the available capacity. If the requests exceed maximum charge or maximum discharge capacity, then only the maximum is used. Charge (*charge*) is then adjusted by the efficiency, i.e. loss during charging and discharging, and added to the *soc*, i.e. state of energy. Leftover charge (*leftover_charge*), that doesn't get stored in the TEES, is sent further to the HES system.

The discharge request is analogous to the charge request just that it is calculated inversely. The resulting discharge is sent to the Output *discharge*. There is no leftover discharge output.

Finally the output of state of energy, *soc_out*, is produced.

3.3.5 Power Conversion using Turbine Generator

HES component "Turbine / Generator" transforms thermal power to electric power using block "Power Generation". This block provides a set of linear approximations of the following processes:

1. First happens the heat exchange between molten salt circuits of MSR and TEES, shown in details in Figure 7.13.
2. Then happens the second heat exchange between TEES molten salt and steam, shown in details in Figure 7.14.
3. Losses during the heat exchange are included [6]. These are represented by block "Losses 1", shown in Figure 7.4.
4. Finally happens the power conversion in a generator driven by a steam turbine, shown in details in Figure 7.15.

Block "Power Generation" is shown in detail in Figure 7.4. Parameters of the processes mentioned above are inspired by collaboration between Seaborg, Samsung and Heavy industries [72], [71]. Molten salt parameters are obtained from molten salt properties used both in CMSR made by Seaborg [77] and in TEES made by Hyme [70], [42]. Parameters of the steam turbine are based on steam turbine SST-600 made by Siemens Energy [35]. Generator is a simplified prototype of generator SGen-1000A [34], which is compatible with the steam turbine.

Structure of the HES component "Turbine / Generator" is shown in detail in 7.3. Run off value is calculated based on data for the combined heat and power plant in Jänschwalde, Germany. This information is included in the brochure about Turbine Siemens SST-600 under chapter "Reference examples" [35]. Value of "Losses 2" is given by efficiency of the generator SGen-1000A [34].

Block "Number of Generators" is used to distribute the incoming thermal power evenly across turbine generator sets. The number is decided based on the fact that maximum capacity of one turbine corresponds to constant MSR production. Thus the additional wind power creates demand for second turbine.

3.3.6 Vanadium Redox Flow Battery

Parameters of vanadium battery used for simulations in this project are obtained from the VRFB 80 MWh pack made by Sumimoto Electric. This battery has operating term of 21 years. [25]

Principle of VRFB operation is explained in subsection 2.2.3.

In order to see peak shaving of onshore power demand performed by VRFB, the onshore demand is first sent to VRFB. The resulting power processed by VRFB is then sent further to the system.

For the purpose of this project the VRFB is coded in MATLAB. The MATLAB code of the VRFB component of HES system is shown in figure 7.8. This code is a simpler version of the function created for the TEES.

The VRFB code works as a function with one input argument *charge_req* (charge request) and two output values: *leftover_charge* and *soc_out*. At the start of the simulation the state of energy (*soc*) is set to zero. The function is called once per simulated hour charge request. Contrary to the TEES function the charge request in VRBF can have both positive and negative value.

The core of the function is the persistent variable *soc*. It keeps track of the state of energy of the VRFB in MWh. In addition there are values that define the maximum capacity (*max_soc*), and the maximum input (*max_char_in*) and output (*max_char_out*) per hour, all in MWh. If there is available capacity, the state of energy is increased or decrease by the energy amount corresponding to the charge request, up to the available capacity. If the requests exceed maximum charge or maximum discharge capacity, then only the maximum is used. Charge (*charge*) is then adjusted by the efficiency, i.e. loss during charging and discharging, and added to the *soc*, i.e. state of energy.

Finally the output of state of energy, *soc_out*, is produced. Leftover charge (*leftover_charge*), that doesn't get stored in the VRFB, is sent further to the HES system.

3.3.7 Power Demand

- Component of the Simulink model of the HES system called "Ekofisk Platform [MW]", shown in detail in Figure 7.5 represents power and heat demand of the Ekofisk offshore platform, operated by ConocoPhillips [23]. This component is used in all scenarios and cases. It's data series are created by two sinus curves, representing annual and diurnal variation, varying power demand of 32 MW and heat demand of 13,3 MW. Power demand of Ekofisk platform is based on information given by a source from ConocoPhillips [24]. Heat demand is estimated based on amount of waste heat generated by the General Electric LM-2500PJ gas turbine currently providing power supply of the Ekofisk offshore platform [84].
- Onshore power demand is calculated as a difference between power production and consumption in Southern Norway, grid area NO2, from data for year 2022, manually collected from Nord Pool website [63]. The data set is processed in Excel and then imported into Simulink as component called "NO2 power demand data year 2022 [MWh/h]". The data have resolution MWh per hour and their output on graphs from simulations of Scenario II and Scenario III is called "Onshore Power".

3.3.8 Controllers

The controller decides how power in the HES is distributed. There are two logic controllers in the model, marked with a yellow diamond in the flow scheme in Figure 3.3. The top controller distributes produced wind power either to onshore grid or to thermal storage. This process is based on whether there is any demand for power at the given time. In the simulation this is solved in a very simple manner. If demand is greater than zero, the entirety of the electricity production is sent into the grid. The bottom controller detects unmet power demand and sends a discharge request to thermal storage.

3.4 Scenarios and Cases

The HES model is developed in three stages. First stage is represented only by the offshore HES part, Scenario I. Scenario I is merged with the onshore grid demand, creating a system with higher complexity, Scenario II. Further expansion of the wind farm to the currently proposed size of 1500 MW [29], gives the HES a third scenario, Scenario III. Hence there were developed three scenarios based on the three HES stages of complexity. Each Scenario has three modifications in form of cases, giving a total of nine cases for the HES power balance simulation. The following section gives a more detailed description of the scenarios and an overview of parameters used in the cases.

- Scenario I: Offshore Part of Hybrid Energy System

  This scenario concerns balancing the power and heat needs of the Ekofisk platform with only 2 wind turbines representing 20 MW of intermittent wind power capacity. In addition comes 250 MW of constant thermal power produced by a small modular reactor. Thermal power is either stored as heat or converted into electricity. Energy Storage System consists of thermoelectric energy storage (TEES) and vanadium redox flow battery (VRFB). This is a fairly realistic scenario given that ConocoPhillips ended up after much deliberation on the decision to install 2 wind turbines in Ekofisk proximity [86] and the power barge project from Seaborg is approaching being a shelf product [69]. Parameters of the individual cases of Scenario I are summarized in table 3.1.

  Case 1 setup is following: HES produces both intermittent wind power and dispatchable nuclear power using 2 generators. ESS consists of 1 TEES and 5 VRFBs. Demand is represented by variated power and heat demand of Ekofisk, described in section 3.3.7.

  Case 1A setup is using the same HES as in Case 1, but power production is limited to nuclear power.

  Case 1B setup is using the same HES as in Case 1, but power production is limited to wind power.

Table 3.1: Overview of parameters used in cases of Scenario I.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 1	1	2	5	1	2	0	1
Case 1A	1	2	5	1	0	0	1
Case 1B	0	2	5	1	2	0	1

- Scenario II: Offshore Hybrid Energy System Balancing Onshore Power demand

  Scenario II is an extension of Scenario I. In addition to power demand of the Ekofisk platform this scenario also attempts to balance power demand of the NO2 area, shown in Figure 2.4. This is done using a HVDC cable sending any eventual excess of offshore power production to NO2 area, or the other way around - excess of onshore production is sent to the offshore part of HES.

  Parameters of the individual cases of Scenario II are summarized in Table 3.2.

  Case 2 is an extended version of Case 1 included onshore demand.

  Case 2A has no MSR power production and tenfold VRFB capacity compared to Case 2.

  Case 2B has no MSR power production and tenfold TEES capacity compared to Case 2.

Table 3.2: Overview of parameters used in cases of Scenario II.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 2	1	2	5	1	2	1	1
Case 2A	0	2	50	1	2	1	1
Case 2B	0	20	5	10	2	1	1

- Scenario III: Expansion based on plans for future

  Scenario III is an extension of Scenario II. It attempts to balance the system II where the installed wind power scaled up to 1500 MW. Wind farm of this magnitude is in accordance with licenses that the government has released for the Southern North Sea this spring [29].

  Parameters of the individual cases of Scenario III are summarized in Table 3.3.

  Case 3 is an extended version of Case 2, having wind power capacity increased from 2 to 150 wind turbines.

  Case 3A has no MSR power production and tenfold VRFB capacity compared to Case 3.

  Case 3B has no MSR power production and hundredfold VRFB capacity compared to Case 3.

Table 3.3: Overview of parameters used in cases of Scenario III.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 3	1	20	50	10	150	1	1
Case 3A	0	2	50	1	150	1	1
Case 3B	0	2	500	1	150	1	1

3.5 Power States

For the purpose of evaluation of power balance in the HES there are defined following four power states indicating ESS capacity, i.e. combined capacity of both TEES and VRFB:

- State I: Charging
- State II: Full ESS
- State III: Discharging
- State IV: Empty ESS

These power states are determined by an algorithm that analyses the output of the simulation. This algorithm is programmed in MATLAB. Its code is shown in Figure 7.10.

This code defines two key variables, value and *SOC_actual*. Value represents per hour value of simulation output *out.State_Difference*, which is called "Power Difference" in the graphical results. *SOC_actual* represents per hour value of simulation output *out.Total_Storage*, which is called "Total Energy Storage" in the graphical results.

In addition there is defined value of full ESS, *SOE_TotalCap*. Minimum and maximum storage capacity, i.e. *SOE_min* and *SOE_max*, are defined as 5% margins of zero ESS and full ESS, *SOE_TotalCap*.

The algorithm first sorts values into two groups - one of positive values, representing States I and State II, and the other of negative values, representing State III and State IV. Then the algorithm sorts these two groups by checking for extreme values, *SOE_min* and *SOE_max*. These steps are repeated during every iteration of the simulation, which results in output in form of distribution of the four groups representing State I - IV in simulation, defined by parameters of the specific case.

These power states are shown in Figure 3.6.

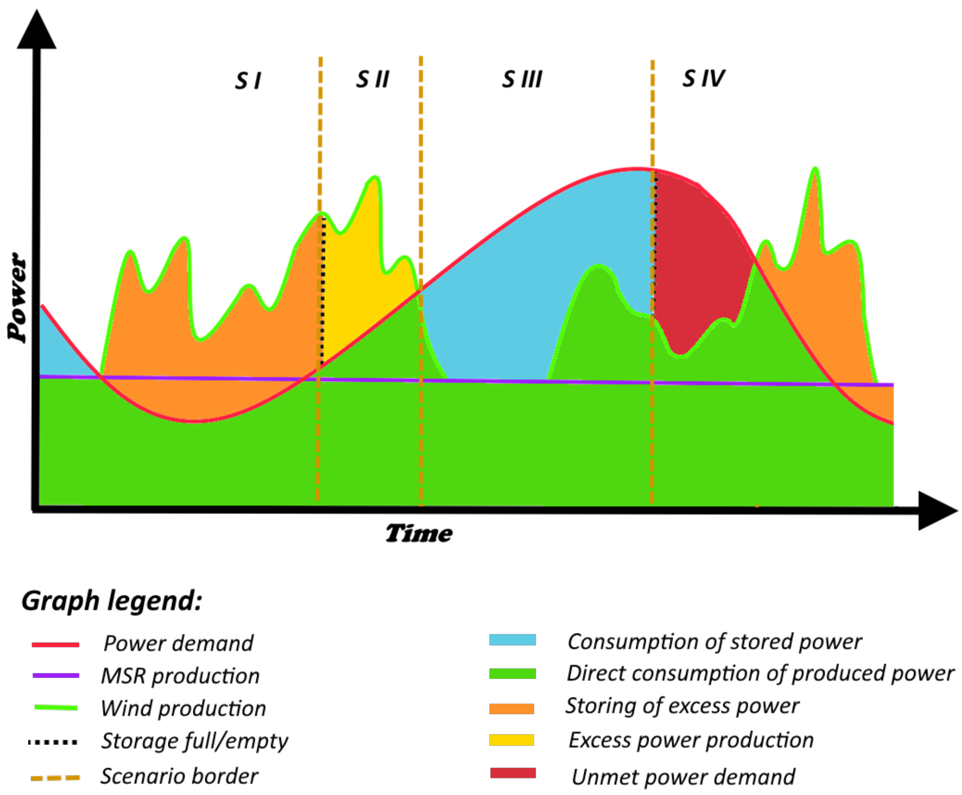

Figure 3.6: Power states: Charging (S I), Full ESS (S II), Discharging (S III) and Empty ESS (SIV).

4 Results and Discussion

The following section presents results of the three scenarios, giving nine cases, presented in Subsection 3.4.

As mentioned in Section 3.4, cases er determined by parameters of the HES simulation. Results of simulation of each case are documented in form of a pie chart and a graph.

Pie chart shows distribution of power states in the specific case. Categorization of power states, used for generation of pie charts, is explained in Subsection 3.5.

Graphs show hourly values of power production, power demand and their difference. In addition to that, graphs of Scenario II and Scenario III, include hourly values of total ESS capacity.

Simulation and algorithm providing graphical output are described in subsections 3.3 and 3.5.

Each scenario is followed by a short reflection.

4.1 Scenario I: Offshore Part of Hybrid Energy System

Scenario I focuses on simulation of power balance in the offshore part of the HES. Case 1 represents base case of this scenario. Cases 1A and 1B demonstrate outcome of domination of either dispatchable or intermittent power production on power balance and its effect on total ESS capacity.

Scenario I is described in detail in Section 3.4.

4.1.1 Offshore Base Case - Case 1

Case 1 is a base case of Scenario I. Both types of power production provide power and both types of energy storage contribute to the total ESS capacity. Table 4.1 recapitulates values of parameters specific to Case 1. Figure 4.1 shows distribution of hours spent across power states. Figure 4.2 shows hourly values of power demand, power production and their difference.

Table 4.1: Overview of parameters used in Case 1.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 1	1	2	5	1	2	0	1

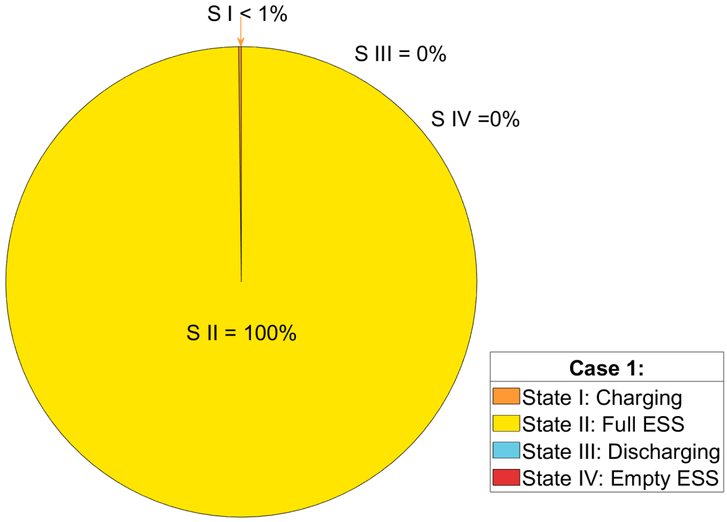

Figure 4.1: Distribution of power states in Case 1, characterised by dominated by State II.

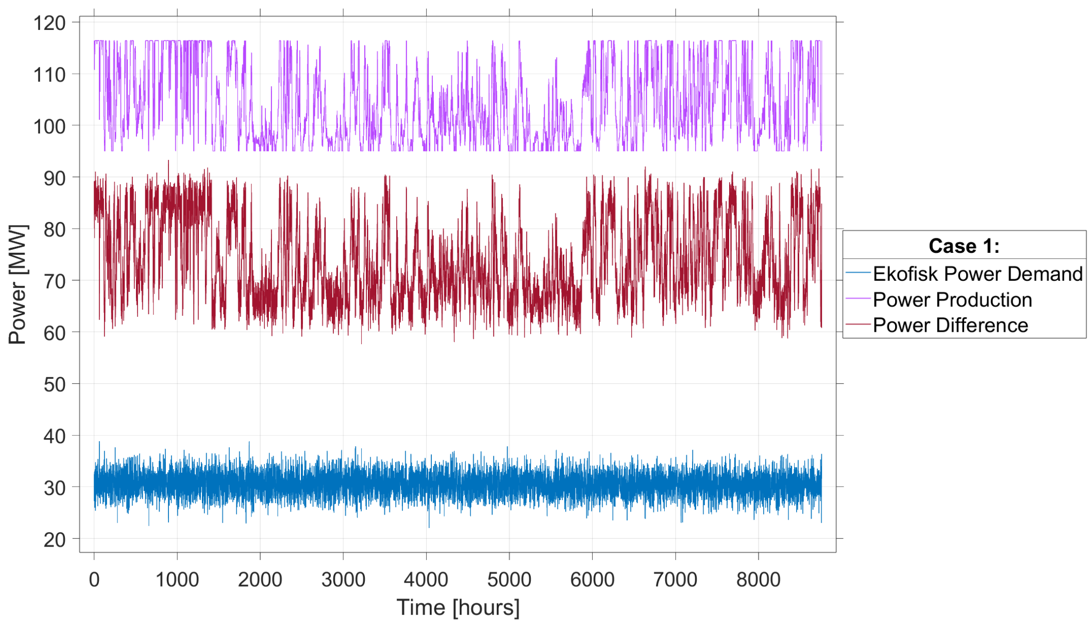

Figure 4.2: Hourly graph of Case 1, showing excess of power production, resulting in positive power difference. The spiky signal of power production is caused by intermittency of wind power production.

4.1.2 Offshore Demand balanced by Molten Salt Reactor - Case 1A

Power production in Case 1A is provided only by dispatchable nuclear power. Table 4.2 recapitulates values of parameters specific to Case 1A. Figure 4.3 shows distribution of hours spent across power states. Figure 4.4 shows hourly values of power demand, power production and their difference.

Table 4.2: Overview of parameters used in Case 1A.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 1A	1	2	5	1	0	0	1

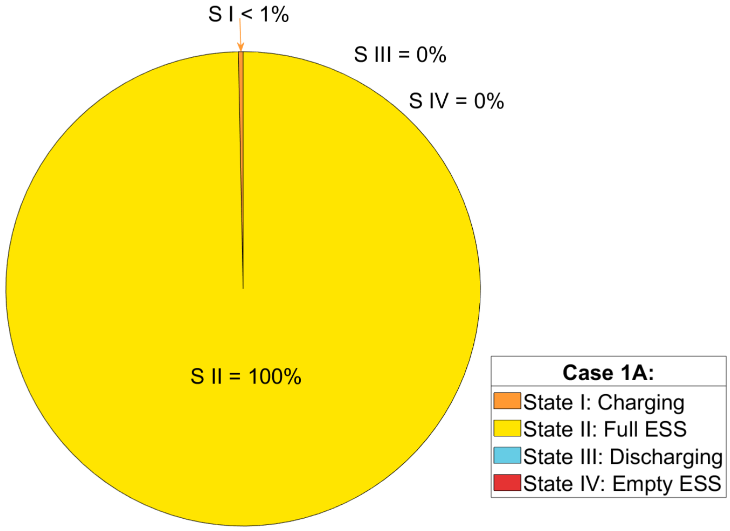

Figure 4.3: Distribution of power states in Case 1A, characterised by domination of State II, i.e. full Energy Storage System (ESS).

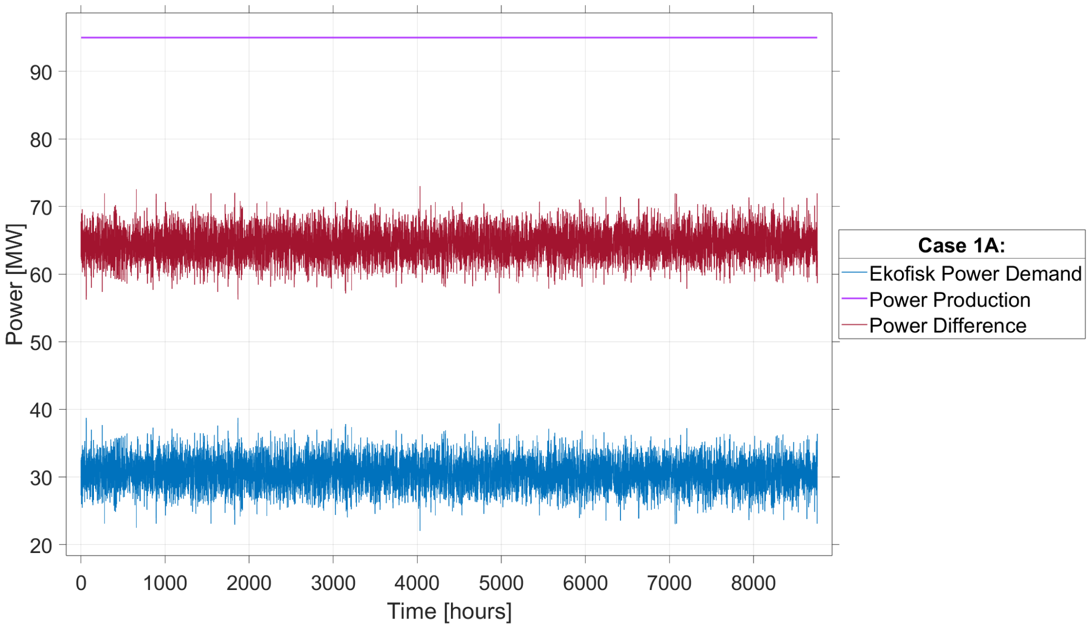

Figure 4.4: Hourly graph of Case 1A showing constant excess of power production resulting in positive power difference. The smooth signal of power production is caused by constancy of nuclear power.

4.1.3 Offshore Demand balanced by Wind Power - Case 1B

Power production in Case 1B is provided only by intermittent wind power. Table 4.3 recapitulates values of parameters specific to Case 1B. Figure 4.5 shows distribution of hours spent across power states. Figure 4.6 shows hourly values of power demand, power production and their difference.

Table 4.3: Overview of parameters used in Case 1B.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 1B	0	2	5	1	2	0	1

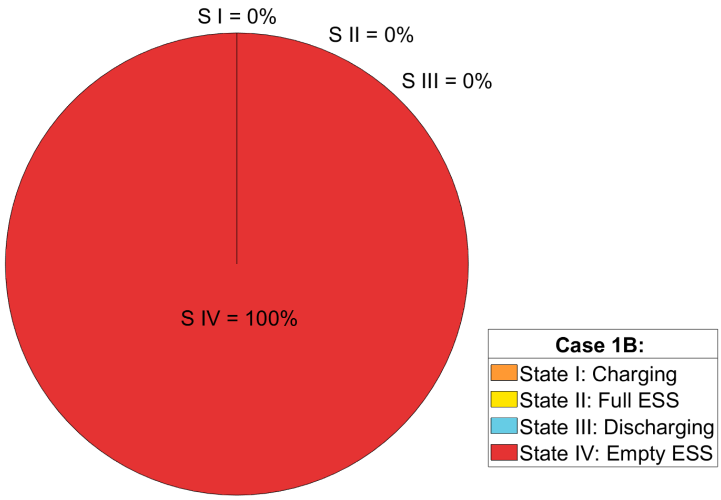

Figure 4.5: Distribution of power states in Case 1B showing domination of State IV, i.e. empty Energy Storage System (ESS).

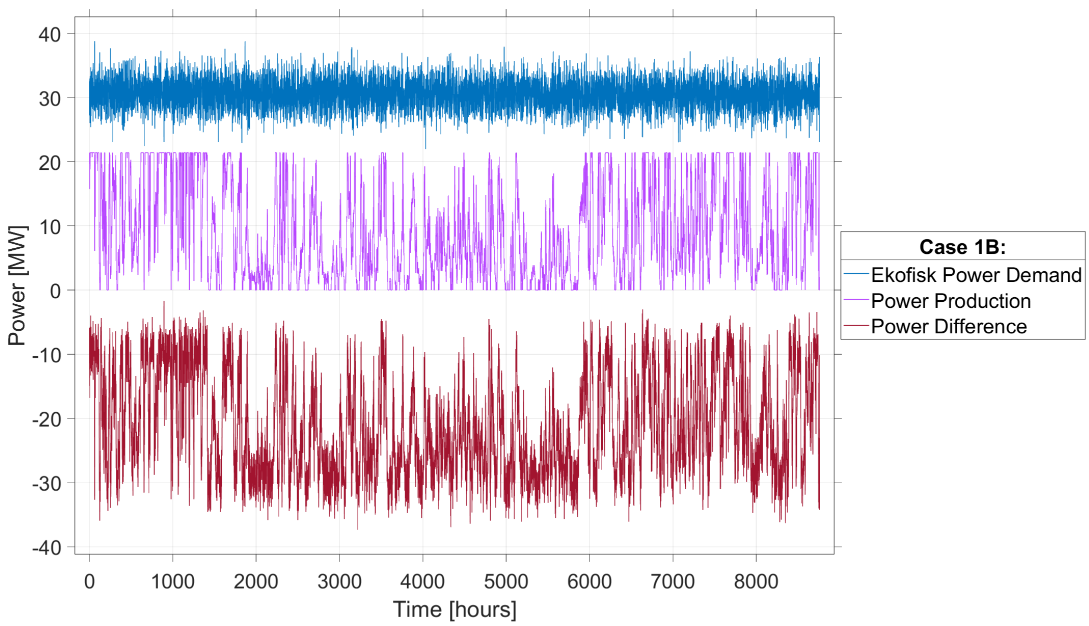

Figure 4.6: Negative value of signal for Power Difference indicates constant power imbalance in Case 1B.

4.1.4 Discussion of Results of Scenario I

Following comes a short overview of results of Scenario I, that are presented in the previous part of this section.

Results of the three cases of Scenario I in form of pie charts demonstrate imbalance between dispatchable and intermittent power production in the HES. Such situation leads to minimal utilisation of ESS.

This is demonstrated either by domination of State II, apparent in results of Case 1 and Case 1A, or domination of State IV, apparent in results of Case 1B. Even the combination of both types of power production, nuclear and wind power, specific for Case 1 doesn't result in a better distribution of power states. This means that both the dimensioning and the utilisation of ESS capacity aren't optimal.

Graphs of cases 1 and 1A, characterised by domination of State II, i.e. full ESS, show positive value of power difference. This is shown in figures 4.2 and 4.4. The opposite applies for graph of Case 1B in figure 4.6. This case is characterised by domination of State IV, i.e. empty ESS. This means that the results for power difference correspond with the results for state distribution.

4.2 Scenario II: Balancing of Onshore Power Demand

Scenario II includes onshore power demand in the HES. Case 2 represents a base case of this scenario. Cases 2A and 2B eliminate nuclear power production.

This adjustment makes the VRFB and the TEES signal separated from the constant charging effect of the MSR. As a result, it makes it easier to visualise and examine them through upscaling of their capacity in cases 2A and 2B.

Case 2A uses tenfold of VRFB capacity compared to Case 2 and Case 2B.

Case 2B uses tenfold of TEES capacity compared to Case 2 and Case 2A.

Scenario II is described in detail in Section 3.4.

4.2.1 Onshore Base Case - Case 2

Case 2 is a base case of Scenario II. Both types of power production provide power and both types of energy storage contribute to the total ESS capacity. Table 4.4 recapitulates values of parameters specific to Case 1. Figure 4.1 shows distribution of hours spent across power states. Figure 4.2 shows hourly values of power demand, power production and their difference.

Table 4.4: Overview of parameters used in Case 2.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 2	1	2	5	1	2	1	1

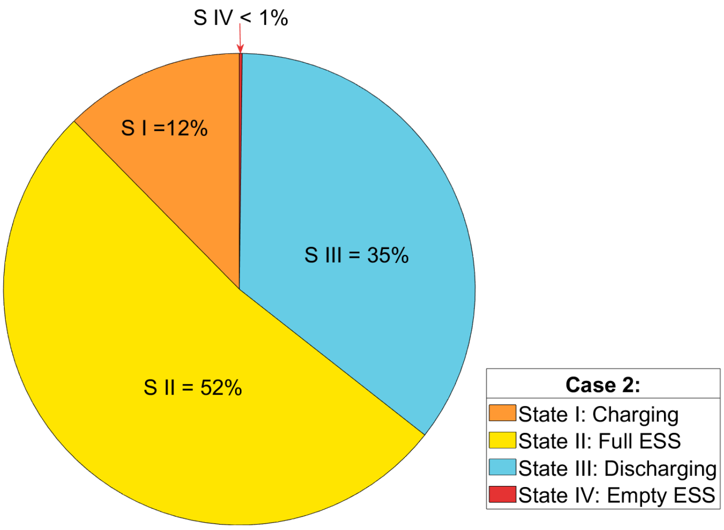

Figure 4.7: Power states in Case 2 are more evenly distributed than in cases of Scenario I. Case 2 thus presents an improved utilisation of the ESS capacity.

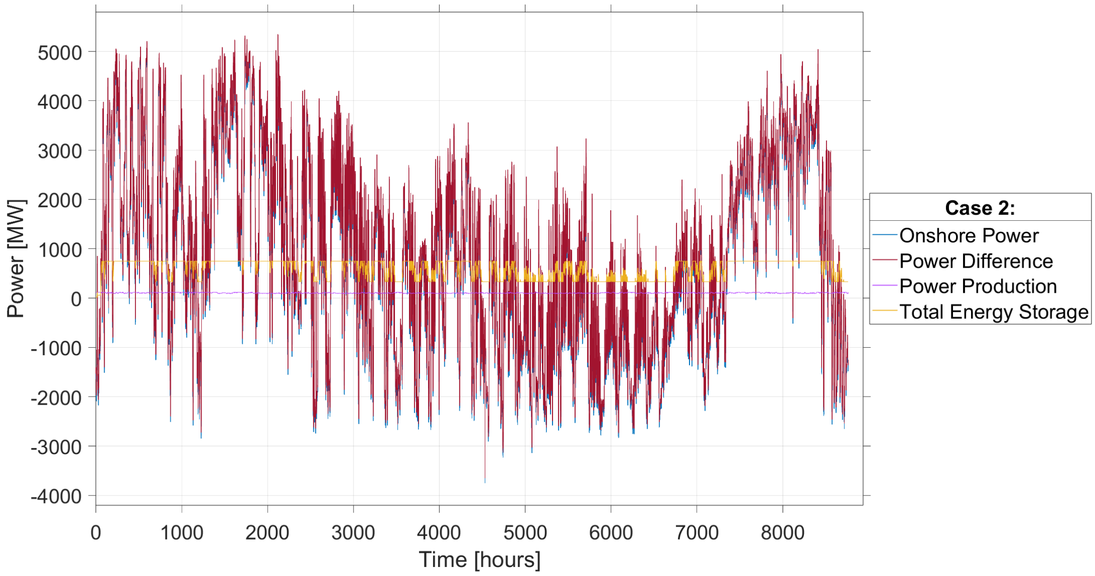

Figure 4.8: A closer look reveals peak shaving effect in form of blue tips of Onshore Power spiky signal, hidden under Power Difference signal. Compared to these seem signals of Total Energy Storage and Power Production considerably shrunk. Power Production can be spotted just above the x-axis.

4.2.2 Demand Balanced by Vanadium Battery - Case 2A

Power production in Case 2A is provided only by intermittent wind power. Energy storage is dominated by VRFB with tenfold capacity compared to the base case, Case 2. Table 4.5 recapitulates values of parameters specific to Case 2A. Figure 4.9 shows distribution of hours spent across power states. Figure 4.10 shows hourly values of power demand, power production and their difference.

Table 4.5: Overview of parameters used in Case 2A.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 2A	0	2	50	1	2	1	1

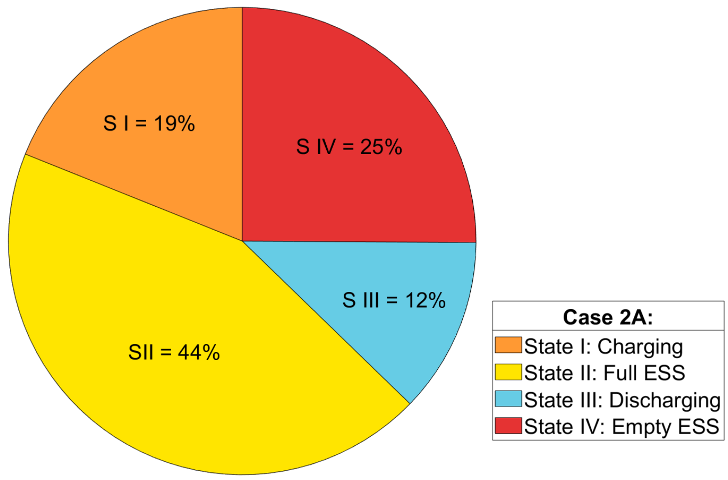

Figure 4.9: Power states in Case 2A are more evenly distributed than in Case 2, including a significant portion of State IV.

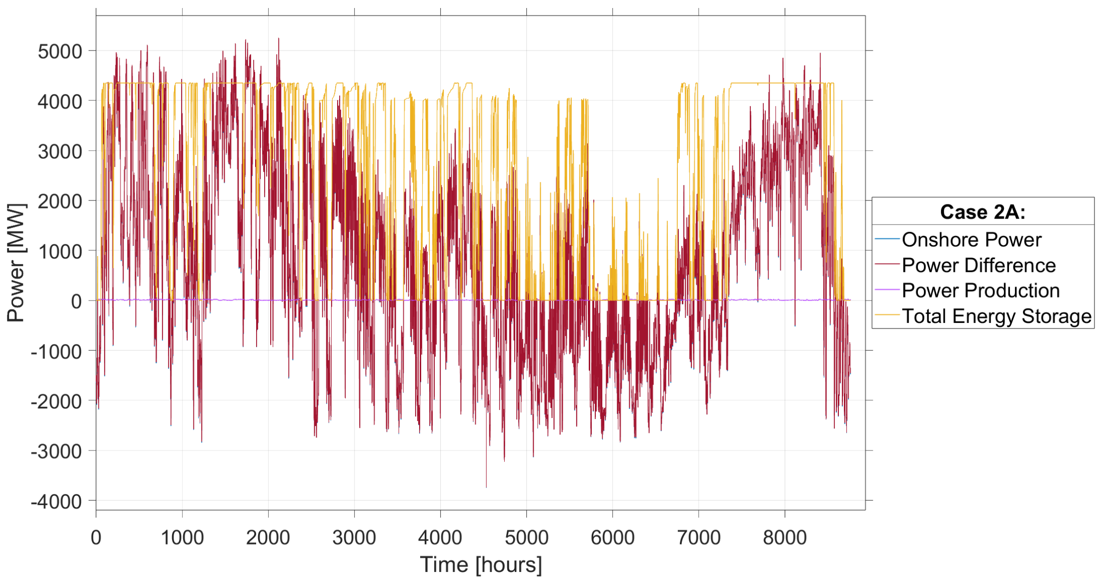

Figure 4.10: Signal of Total Energy Storage, consisting mainly of VRFBs, reaches same magnitude as power difference. Peak shaving effect in form of blue tips of Onshore Power peeking behind Power difference production is slightly visible with zoom in. Power Production can be spotted just above the x-axis.

4.2.3 Demand Balanced by Thermal Storage - Case 2B

Power production in Case 2B is provided only by intermittent wind power. Energy storage is dominated by TEES with tenfold capacity compared to the base case, Case 2. Table 4.6 recapitulates values of parameters specific to Case 2A. Figure 4.11 shows distribution of hours spent across power states. Figure 4.12 shows hourly values of power demand, power production and their difference.

Table 4.6: Overview of parameters used in Case 2B

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 2B	0	20	5	10	2	1	1

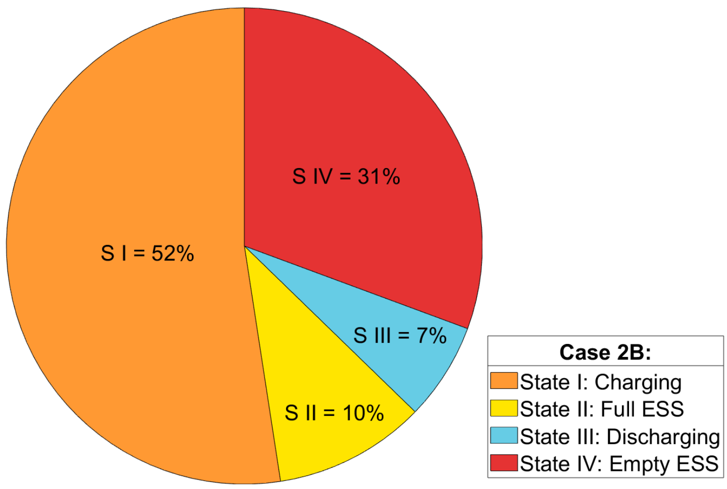

Figure 4.11: Power states in Case 2B have significantly higher proportion of State I than any other scenario. Large proportion of State IV reveals an unbalanced power system.

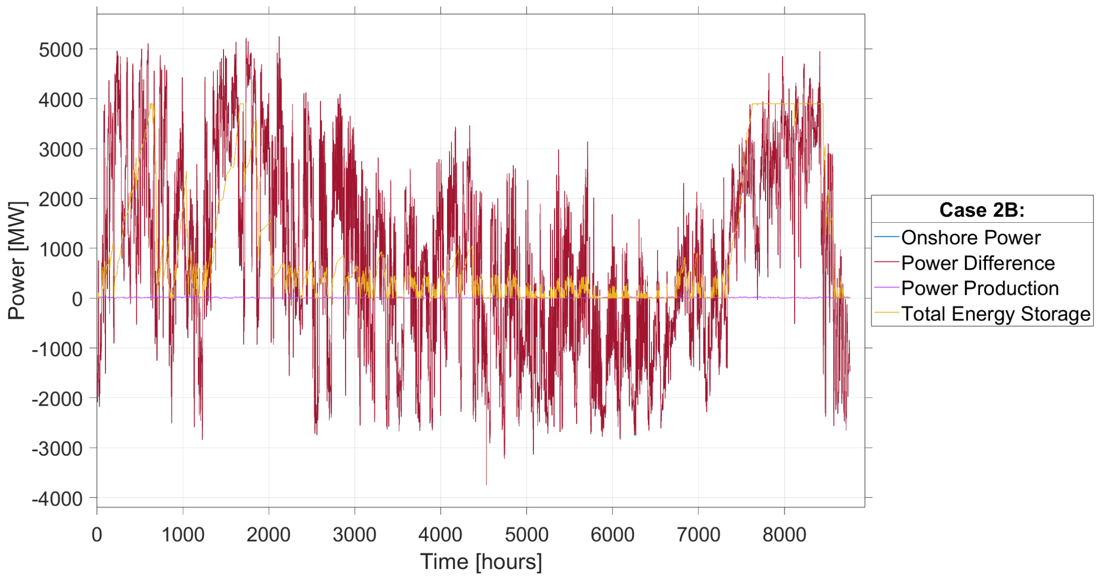

Figure 4.12: Signal of Total Energy Storage, consisting mainly of TEESs, is varies between the shrunk size of Case 2 and Power Difference magnitude of Case 2A. Peak shaving effect in form of blue tips of Onshore Power peeking behind Power difference production is barely visible even with zoom in. Power Production can be spotted just above the x-axis.

4.2.4 Discussion of Results of Scenario II

Power states in Case 2 are more evenly distributed than in cases of Scenario I, thus demonstrating a better utilisation of ESS. Based on distribution of power states could be the Case 2 considered as a stable power system. However, a closer look at the graph 4.8 reveal an issue with TEES, that doesn't discharge fully during power deficit in the HES. Detailed description of this phenomenon and it's consequences can be found in section 4.11.

Both cases 2A and 2B show charging followed by complete discharging. In Case 2A, shown in the left graph in Figure 4.13, is this process quite steep, compared to charging and discharging process in Case 2B, shown in the right graph in Figure 4.13. This is caused by installed power output of fifty VRFB units (Case 1) with total power output 500 MW, compared to ten TEES units, giving just 200 MWh per a simulation step.

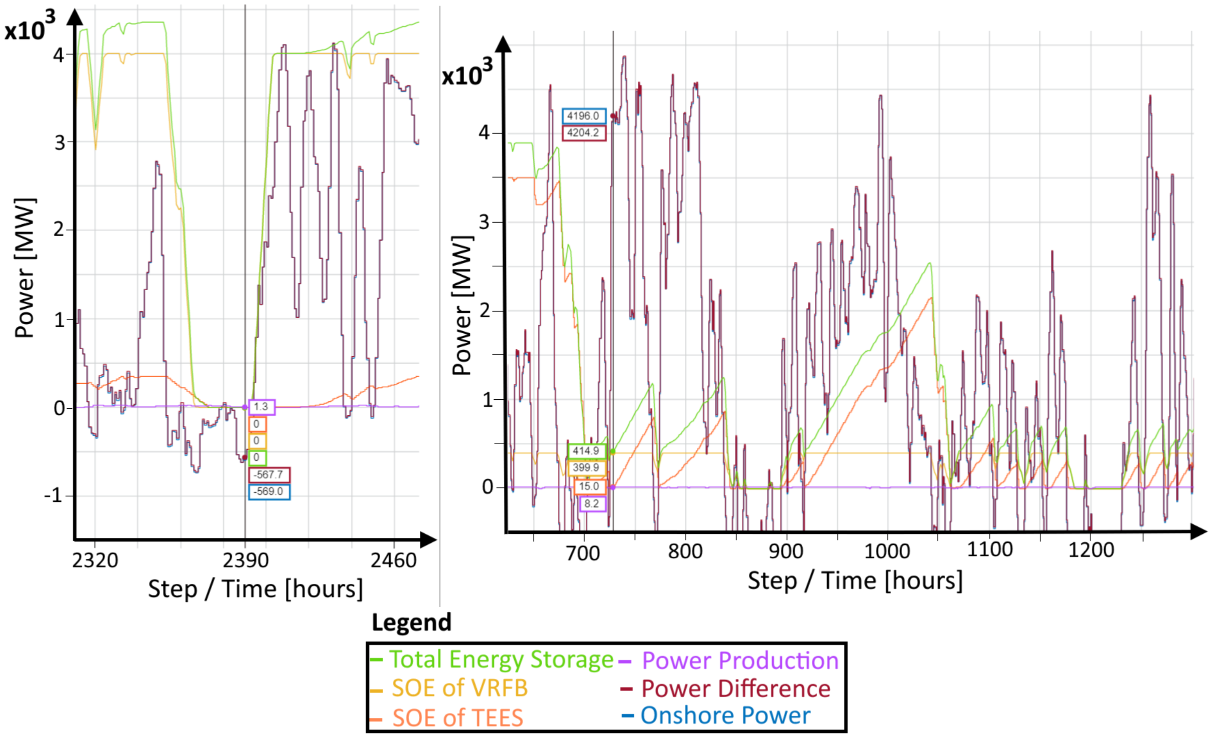

Figure 4.13: Graph of Case 2A to the left and Case 2B to the right, showing closeup of different charging and discharging depending on power output.

4.3 Scenario III: Wind Farm Expansion

Scenario III expands the installed capacity of offshore wind power in the HES according to the future plans to build a wind farm in the area of Sørlige Nordsjø II [29]. This wind farm is supposed to have installed power of 1500 MW. That represents seventy five fold increase in the wind power capacity compared to the other base cases, Case 1 and Case 2.

In order to balance the wind power expansion, the total ESS capacity needs to be slightly increased already in the base case. Therefore the total ESS capacity in Case 3 is tenfold compared to the other base case scenarios. As a result, the total installed ESS capacity size is quintuple compared to the installed wind power capacity.

Scenario III is described in detail in subsection 3.4.

4.3.1 Wind Farm Base Case - Case 3

Case 3 is a base case of Scenario III. Both types of power production provide power and both types of energy storage contribute to the total ESS capacity. Table 4.7 recapitulates values of parameters specific to Case 3. Figure 4.14 shows distribution of hours spent across power states. Figure 4.15 shows hourly values of power demand and production, their difference and total capacity of the ESS.

Table 4.7: Overview of parameters used in Case 3.

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 3	1	20	50	10	150	1	1

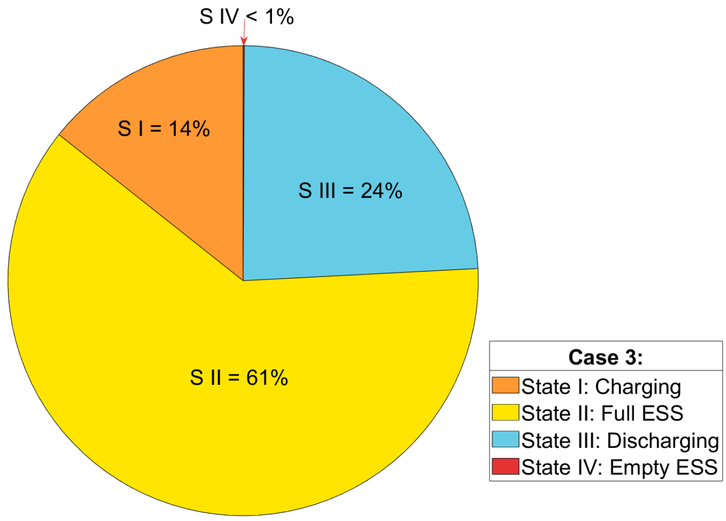

Figure 4.14: Distribution of power states in Case 3 less even but similar to the Case 2.

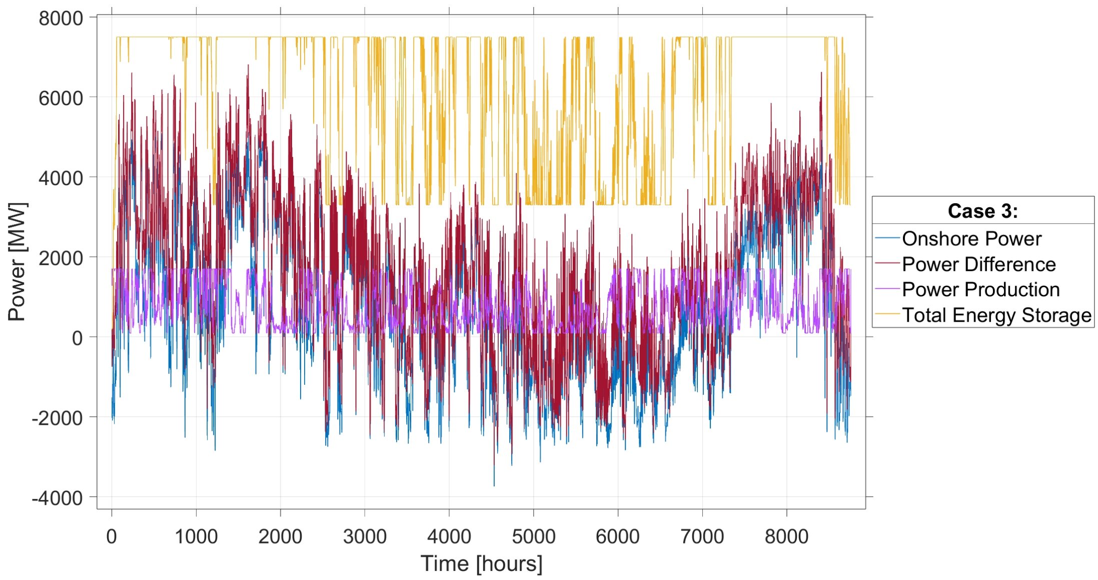

Figure 4.15: Signal of Total Energy Storage is delimited by TEES installed capacity on the bottom and by the total installed ESS capacity on the top. This graph also shows several well apparent and prolonged periods of full ESS capacity.

4.3.2 Wind Farm without Molten Salt Reactor - Case 3A

Power production in case 3A is provided only by the intermittent wind power. This change is made in order to bring forward the effect of VRFB capacity, which is otherwise difficult to distinguish from the constantly full TEES. Table 4.8 recapitulates values of parameters specific to Case 3A. Figure 4.16 shows distribution of hours spent across power states. Figure 4.17 shows hourly values of power demand and production, their difference and total capacity of the ESS.

Table 4.8: Overview of parameters used in Case 3A

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 3A	0	2	50	1	150	1	1

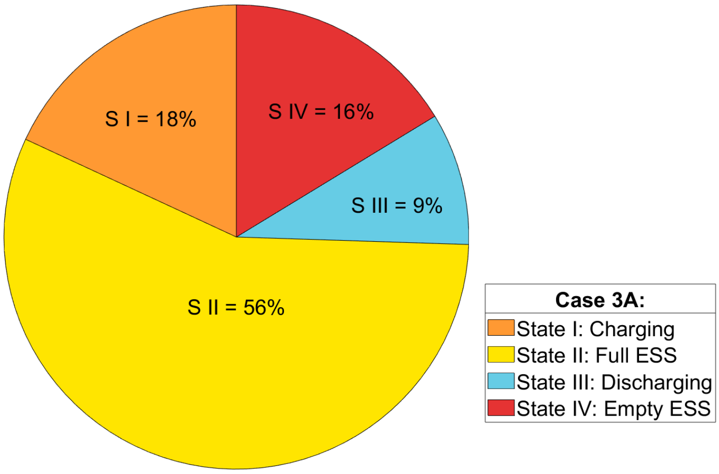

Figure 4.16: Distribution of power states in Case 3A shows an unbalanced power system with a significant portion of State IV.

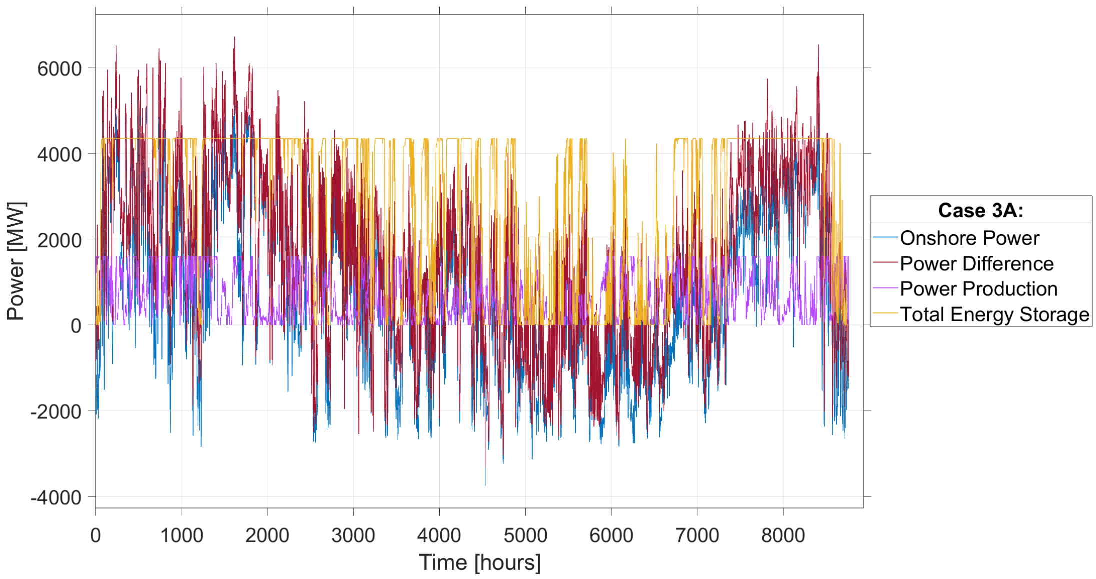

Figure 4.17: Signal of Total Energy Storage shows improved utilization of the ESS capacity, compared to Case 3. ESS consists of 4000 MWh of VRFB and only of 350 MWh of TEES, which corresponds with the signal maximum. Contrary to the Case 3, this graph shows that the ESS signal reaches minimum of 0 MW at several occasions. Their frequency corresponds with the portion of Case IV in the pie chart 4.17.

4.3.3 Wind Farm Balanced by Tenfold of Vanadium Batteries - Case 3B

The VRFB capacity in Case 3B is increased tenfold compared to Case 3A, making the Case 3B a modification of Case 3A. Similarly to Case 3A, the power production in case 3B is provided only by the intermittent wind power. Table 4.9 recapitulates values of parameters specific to Case 3A. Figure 4.18 shows distribution of hours spent across power states. Figure 4.19 shows hourly values of power demand, power production, their difference and total capacity of the ESS.

Table 4.9: Overview of parameters used in Case 3B

Simulation	MSR	Generator	VRFB	TEES	Wind Turbine	Onshore Demand	Ekofisk Demand
Case 3B	0	2	500	1	150	1	1

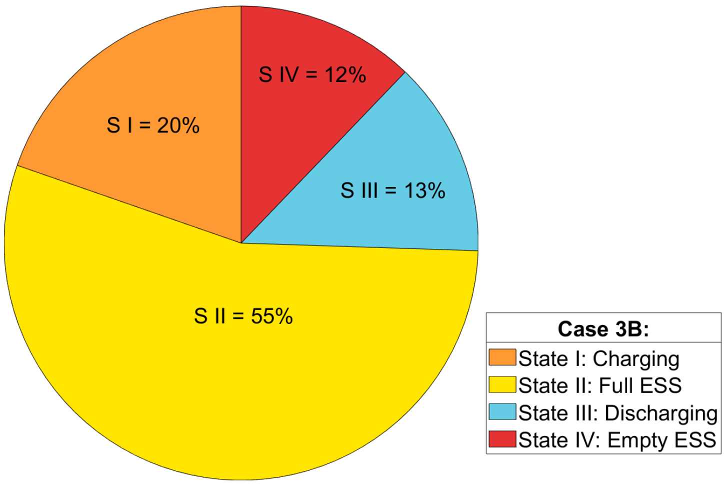

Figure 4.18: Distribution of power states in Case 3B shows a slight, 4% reduction in share of State IV compared to Case 3A.

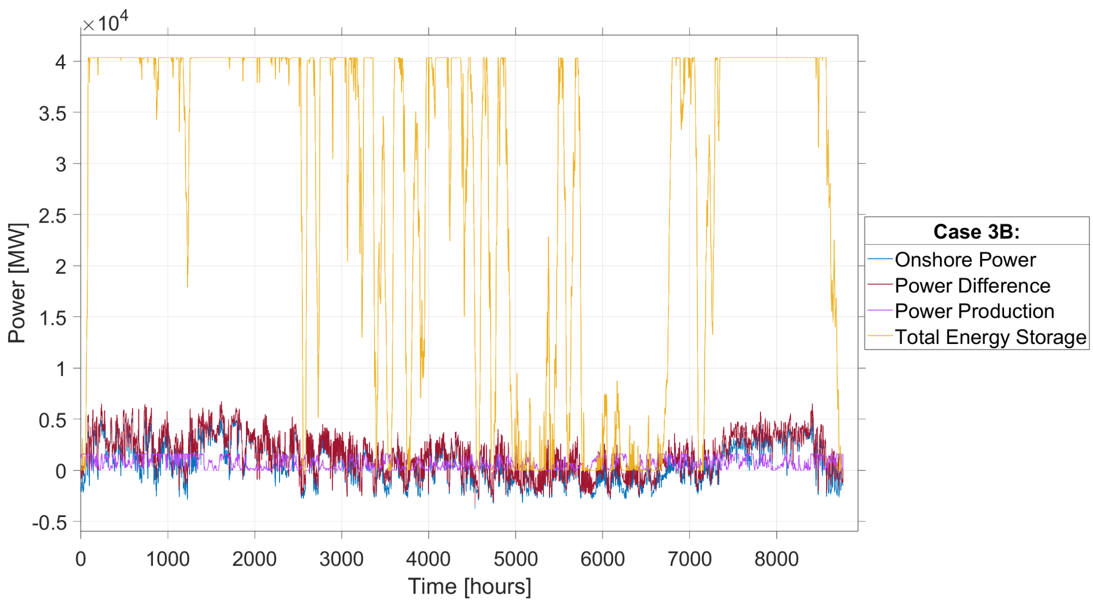

Figure 4.19: Hourly graph of power balance during Case 3B displaying dominating signal of Total Energy Storage. The total ESS capacity consists of 40 GWh of VRFB and only of 350 MWh of TEES.

4.3.4 Discussion of Results of Scenario III

Results of Cases 3A and 3B in the table 4.10 show that tenfold increase in VRFB capacity gives only 4% reduction in State IV.

Table 4.10: Overview of installed battery and power production capacity, their ratio and share of State IV in the Power Distribution.

Simulation	MSR	TEES	VRFB	Wind Turbine	Installed Capacity ESS/Wind Power	Share of S IV [%]
Case 3	1	10	50	150	~ 5 x	< 1
Case 3A	0	1	50	150	~ 3 x	16
Case 3B	0	1	500	150	~ 27 x	12

Since Case 3B is using a significant amount of ESS capacity, a common misconception would lead to expectations of stable power system [2]. However, the fact is the opposite. A closer inspection of Figure 7.16 in Appendix 7.9 may give an explanation why. This figure shows annual variations of power demand, with long periods of either power surplus or power deficit. Currently there is no storage technology that could cover that prolonged periods of power deficit as Figure 7.16 shows.

4.4 Summary of Findings

The following section gives a summary of results presented in the previous section.

Table 4.11 lists parameters and results of the individual cases. This table is a result of both, an attempt to improve application of power states, and a search for correlation. The only correlation observed is the following: Equal value of combined share of State III and State IV between cases of the same Scenario.

Table 4.11: Overview of all cases and their results in context to their parameters.

Simulation	MSR	TEES	VRFB	Wind Turbine	Installed Capacity ESS/Power Plants	S IV + S III [%]
Case 1	1	1	5	2	~ 6 x	0
Case 1A	1	1	5	0	~ 7.5 x	0
Case 1B	0	1	5	2	~ 38 x	100
Case 2	1	1	5	2	~ 6 x	< 36
Case 2A	0	1	50	2	~ 218 x	37
Case 2B	0	10	5	2	~ 195 x	38
Case 3	1	10	50	150	~ 5 x	< 25
Case 3A	0	1	50	150	~ 3 x	25
Case 3B	0	1	500	150	~ 27 x	25

Regarding Scenario I, from the data in the table 4.11, it is clear that the only balanced cases are those with surplus of dispatchable power, Case 1 and Case 1A. Design of Case 1B, reflecting the current political ambitions to stabilise wind power with various types of ESS, failed completely [51].

Scenario II tested interaction of the offshore part of HES with an onshore power grid. The initial positive result, showing negligible share of State IV in Case 2, didn't make sense in context of the significant power deficit generated by the onshore part of HES. This contradiction led to detection of an issue with TEES charging.

Design of the TEES limits its discharging at the same rate as the MSR charges it. This creates an issue in Case 2, where the power demand is unable to empty ESS though it exceeds the installed combined battery and power capacity of the HES. This issue leads in cases with MSR power production to false indication of available TEES discharge capacity. After reaching full capacity the TEES does only partially discharge, being constantly recharged by the MSR. This phenomenon is documented in figure 7.11 in Appendix 7.7. This issue is avoided by removal of the MSR from the HES, resulting in TEES fully charging and discharging as shown in figure 7.12 in Appendix 7.7.

The TEES issue described above applies to the following cases: Case 1, Case 1A, Case 2 and Case 3. In these cases State IV isn't a reliable marker of potential power deficit, i.e. imbalance in the HES system. Potential power deficit can be found by including share of power distribution of both State III and State IV in the estimate. Such approach is shown in Table 4.11.

High share of State IV indicates higher risk of power deficit in the defined grid setup (case) and as an ultimate consequence an increased risk of grid collapse. High share of State II indicates less optimal utilisation of the ESS and a higher risk of power overload in the defined grid setup (case). Ultimate consequence of high share of State II is an increased risk of grid collapse. Contrary to power deficit caused by State IV, there are methods to alleviate power overload caused by State II. Excess of power can be used for example for hydrogen production or offshore fresh water production using desalination [9].

Scenario III is based on quite unrealistic amount of VRFB batteries. In addition, one VRFB battery pack of 80 MWh has according to its producer a footprint 131 meters x 27 meters [25]. Such parameters correspond to a deck area three times bigger than the biggest class of Platform Supply Vessel [87]. On the other hand, the proposed TEES may not be quite realistic either. Only the molten salt alone would according to the producers data weigh around 2.3 tonne [42].

5 Conclusion

Conclusion presented in this section may be more intricate than the presented results may have led up to.

Summary of Scenario III results in the table 4.10 indicate minimal effect of battery storage technology as a means of balancing a wind farm.

From the results of the simulations it may seem obvious that share of State IV in power distribution represents the total amount of power deficit hours. Unfortunately, as explained in section 4.11, design of the TEES creates a bug in evaluation using ESS capacity as an indication of power balance.

The suggested inclusion of State III in the state of power deficit could improve accuracy of the results to some extent. On the other hand, in systems with frequent excess of power production, it may give too high estimation of power deficit. However, such approach could give quite realistic estimates in systems with dominating share of intermittent power or in systems with high variation of power demand, frequently exceeding installed power capacity.

Both of these systems can be found in Scenario III. Scenario I represents only one of them, a power system with unstable power demand, exceeding installed power. It could be speculated that potential intervariation of wind power and power demand makes State III irrelevant for power deficit calculation. For the particular power demand, such argument can be contradicted by a reflection on it's spiky shape, as follows.

Power demand of Southern Norway shows same trend as wind power production for the same year, i.e. 2022 [26]. In addition the proposed Wind farm, Sørlige Nordsjø II, lies in geographically and climatic close area to Southern Norway. Such close proximity leads indirectly through correlation of wind speeds to correlation of wind power production. Given the fact that wind turbines are mostly land-based, the effective distance to wind farms in Southern Norway is roughly 200 km.[66] According to results of a relevant study in the North Sea [75] such a distance results in correlation between 0.7 and 0.75. Such a high correlation weighs rather in favor of recognition of State III as a significant contribution to power deficit in the given scenario of this project.

Based on the presented results of the dynamic simulation it can be concluded that the Norwegian weather dependent power system should be supported by other, weather independent, power systems. Such weather independent systems should have enough capacity to serve as auxiliary systems during periods of unfavorable weather.

6 Further Work

The HES design has plenty of room for improvement. The following section gives some suggestions on changes that might compensate for eventual imperfections.

As already mentioned, the presented HES model has an issue with TEES double function, making it constantly charged by MSR. This issue could be solved by more advanced modelling approach, using transfer functions to create a more flexible, TEES independent MSR.

Another HES part with a significant potential for improvement is the "Turbine/Generator" component. The linear approximation doesn't reflect the dynamic behaviour of the power conversion process. Also this component could be improved using a Simulink block with customised transfer functions. With a simulation running at a higher time resolution, load following abilities could be simulated and evaluated.

The option to adjust number of generators hasn't been tested. This parameter of "Turbine/Generator" controls power output and requires a corresponding adjustment of TEES parameters.

The logic control is programmed so that it can send an excess of power to the grid and thus create an oscillation in reaction of the HES system. That could be eliminated by an upgrade to a proportional-integral-derivative controller (PID controller), giving an precise and adaptable correction to the control function.

From the system point of view, there are still some unexplored system settings. For example, the HES design enables for variation of number of generators, a parameter indirectly controlling power output of TEES. Naturally, such changes in power output would have to be synchronized with adequate changes in TEES' MATLAB settings.

Analysis of HES simulation could be improved by telling apart power demand of the offshore platform and power demand of the onshore grid.

In order to provide a good foundation for an eventual economical analysis, the distribution should be extended with calculation of energy amount produced in each power state. In addition, input, in form of datasets of power demand and power production, should use average values obtained from longer periods, one decade at least. Longer time periods provide a better statistical foundation and thus better approximation.

The presented model of HES can be applied on the other power grid areas by setting up a simulation model where each power region is connected to their own instance of the offshore power system. In this simulation both regional and inter-regional power balance can be evaluated. Ultimately, a network of offshore power supply, here in form of HES, stretching in parallel with the Norwegian coast, can be simulated [75].

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7 Appendix

7.1 Appendix A

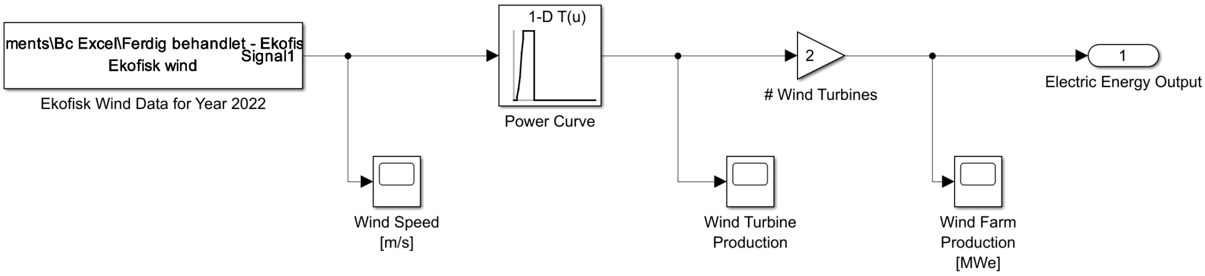

Figure 7.1: Component of the Simulink model of the HES system called "Ekofisk Wind Farm [MWe]".

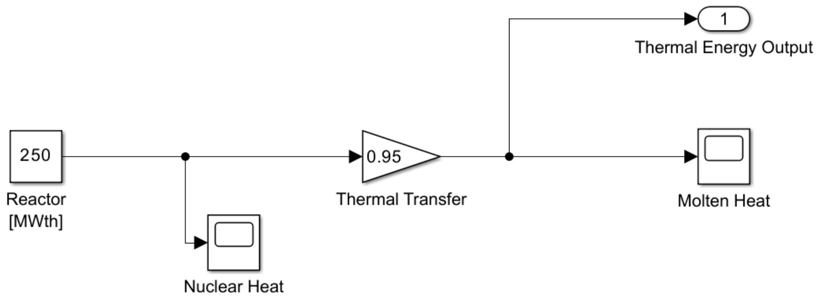

Figure 7.2: Detailed scheme of the "Molten Salt Reactor" component of the Simulink model of the HES.

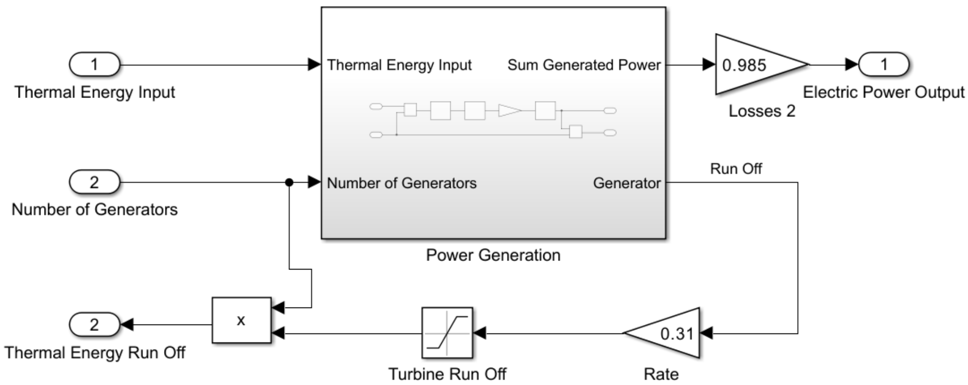

Figure 7.3: Detailed scheme of the "Turbine/ Generator" component of the Simulink model of the HES.

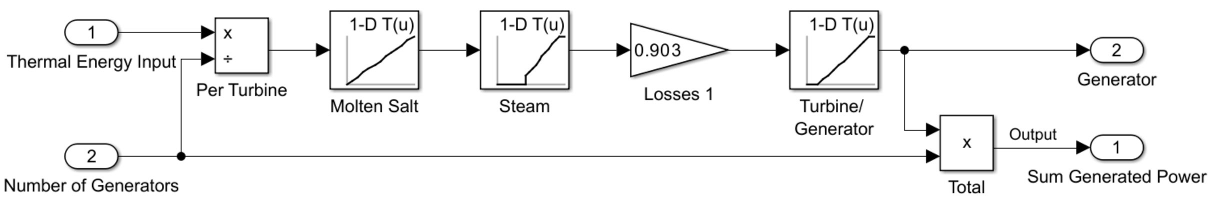

Figure 7.4: Detailed scheme of the "Power Generation" Component of the "Turbine/ Generator" component of the Simulink model of the HES.

7.2 Appendix B

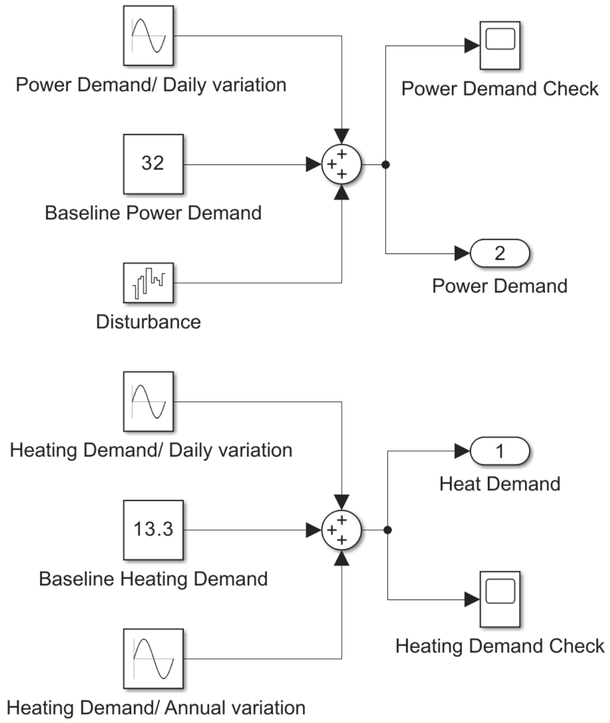

Figure 7.5: Component of the Simulink model of the HES system called "Ekofisk Platform [MW]"

7.3 Appendix C

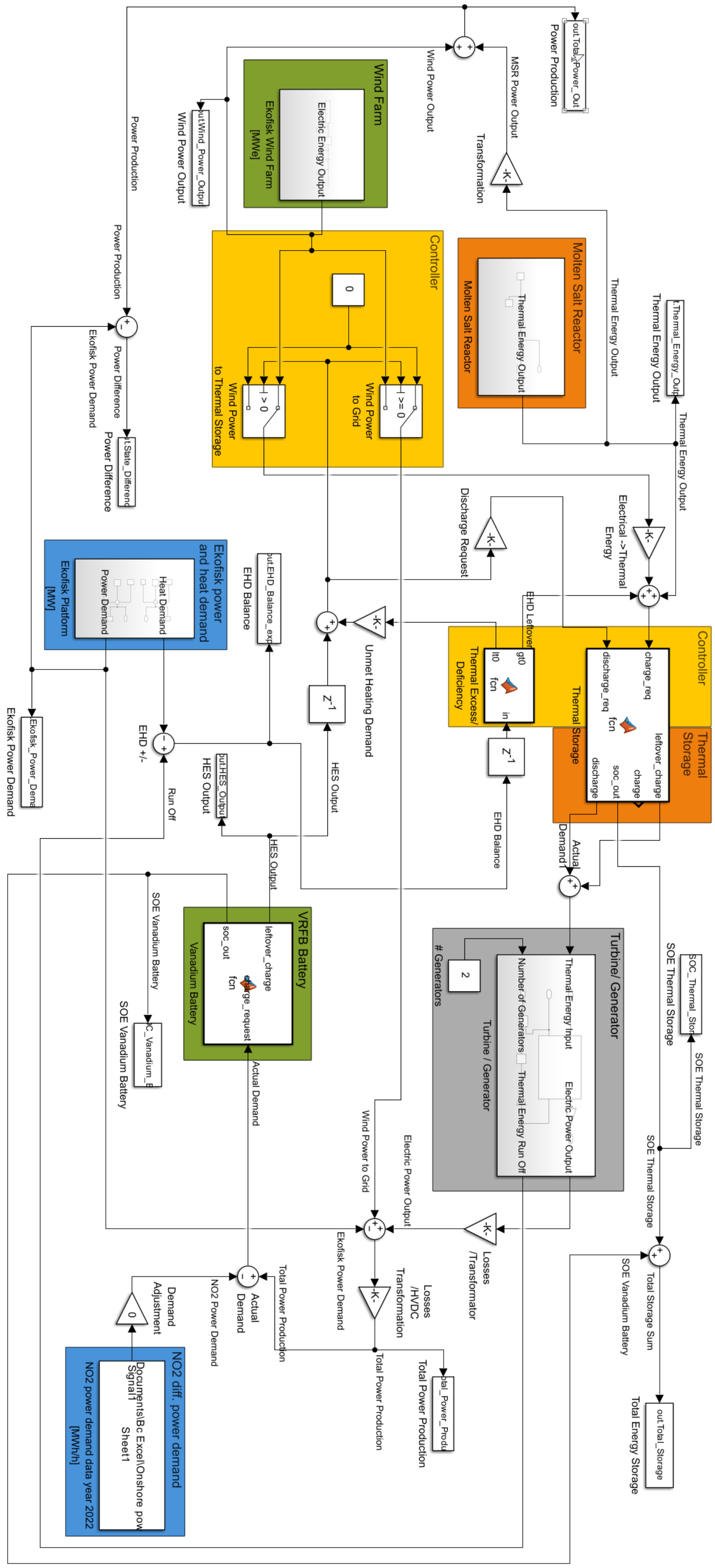

Figure 7.6: Simulink scheme of HES system used in cases of Scenario I.

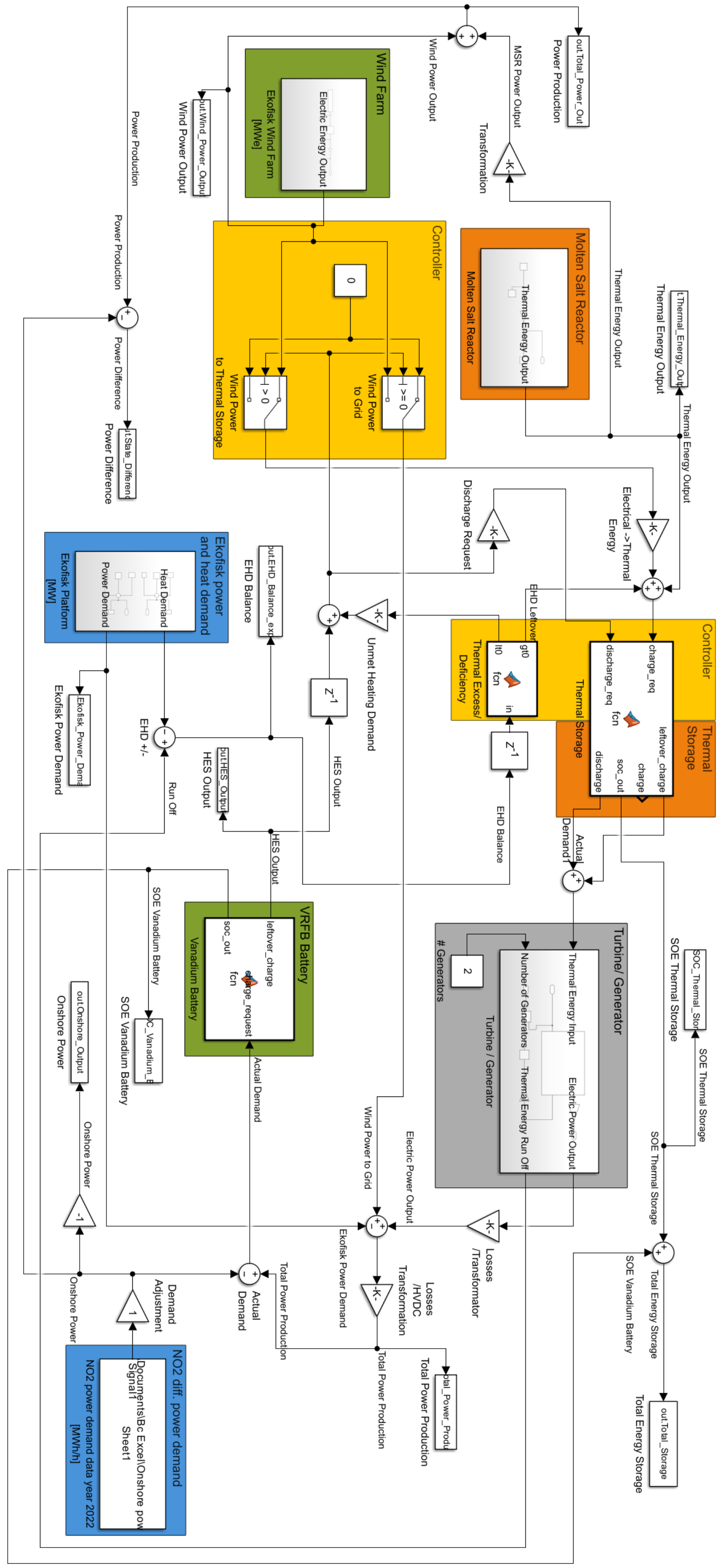

Figure 7.7: Simulink scheme of HES system used in cases of Scenario II and Scenario III.

7.4 Appendix D

```
Function: fcn
function [leftover_charge,soc_out] = fcn(charge_request)
    persistent soc % current state of energy [MWh]
    if isempty(soc)
        soc = 0;
    end
    no_batteries = 5;  % number of batteries in the block, i.e. scale factor
    efficiency = sqrt(0.75) ; % loss during charging and discharging
    max_char_in = 10 * no_batteries; % maximum charge capacity [MWh/h]
    max_char_out = 10 * no_batteries; % maximum discharge capacity [MWh/h]
    max_soc = 80 * no_batteries; % maximum battery capacity [MWh]

    avail_soc = max_soc-soc; % available battery capacity [MWh]

    if charge_request > 0
        charge = min([max_char_in,avail_soc,charge_request]) ; % change in state of energy [MWh]
    else
        charge = -1 * min([max_char_out,soc,-charge_request]) ;
    end
    charge = charge * efficiency;
    soc = soc + charge;
    soc_out = soc;
    leftover_charge = charge_request - charge; % % energy leftover after storage [MWh]

```

Figure 7.8: Matlab code of the "Vanadium Battery" HES component presented in section 3.3.6.

7.5 Appendix E

Function: fcn

```matlab
function [leftover_charge,charge,soc_out, discharge] = fcn(charge_req, discharge_req)
    persistent soc  % current state of energy [MWh]
    if isempty(soc)
        soc = 0;
    end
    no_batteries = 1; % number of batteries in the block, i.e. scale factor
    efficiency = 0.95; % loss during charging and discharging
    max_char_in = 20 * no_batteries; % maximum charge capacity [MWh/h]
    max_char_out = 20 * no_batteries; % maximum discharge capacity [MWh/h]
    max_soc = 350 * no_batteries; % maximum battery capacity [MWh]

    avail_soc = max_soc-soc; % available battery capacity [MWh]

    if charge_req > 0
        charge = min([max_char_in,avail_soc,charge_req]) ; % change in state of energy [MWh]
    else
        charge = -1 * min([max_char_out,soc,-charge_req]) ;
    end
    charge = charge * efficiency;
    soc = soc + charge;
    leftover_charge = charge_req - charge; % energy leftover after storage [MWh]

    discharge = 0;
    if discharge_req > 0
        discharge = min([max_char_out,soc,discharge_req]) ; % change in state of charge from requested discharge (e_out_req)
        discharge = discharge * efficiency;
        soc = soc - discharge;
    end
    soc_out = soc;

```

Figure 7.9: Matlab code of the "Thermal Storage" HES component presented in section 3.3.4.

7.6 Appendix F

```
states_ = zeros(length(out.State_Difference),1);
hours_surpluss = 0;
hours_deficit = 0;
hours_balanced  = 0;
full_empty_factor = 0.05;
SOE_TotalCap = max(out.Total_Storage); % assuming all storage is full at som point
SOE_min = SOE_TotalCap * full_empty_factor;
SOE_max = SOE_TotalCap * (1 - full_empty_factor);
hours_blackout_S4 = 0;
hours_discharging_S3 = 0;
hours_full_S2 = 0;
hours_charging_S1 = 0;


for i= 1:length(out.State_Difference)
    value = out.State_Difference(i);
    SOC_actual = out.Total_Storage(i);

    if value > 0
        hours_surpluss = hours_surpluss + 1;
        if SOC_actual >= SOE_max
            hours_full_S2 = hours_full_S2 + 1;
            states_(i) = 2;
        else
            hours_charging_S1 = hours_charging_S1 + 1;
            states_(i) = 1;
        end

    elseif value < 0
            hours_deficit = hours_deficit + 1 ;

            if SOC_actual <= SOE_min
                hours_blackout_S4 = hours_blackout_S4 + 1;
                states_(i) = 4;
            else
                hours_discharging_S3 = hours_discharging_S3 + 1;
                states_(i) = 3;
            end

    else
        hours_balanced = hours_balanced  +1;
    end

end

disp(hours_surpluss)
disp(hours_deficit)
disp(hours_balanced)

disp(hours_surpluss)
disp(hours_deficit)
disp(hours_balanced)

%counts = histcounts(states_);

counts = [hours_charging_S1, hours_full_S2, hours_discharging_S3, hours_blackout_S4];
figure
p = pie(counts);
%title('Distribution of States');
colormap([1 .6 .2;    %// orange
          1 .9 0;    %// yellow
          .4 .8 .9;    %// blue
          .9 .2 .2])   %// red
```

Figure 7.10: Matlab code using output data to create results in form of pie chart, shown in section 4.

7.7 Appendix G

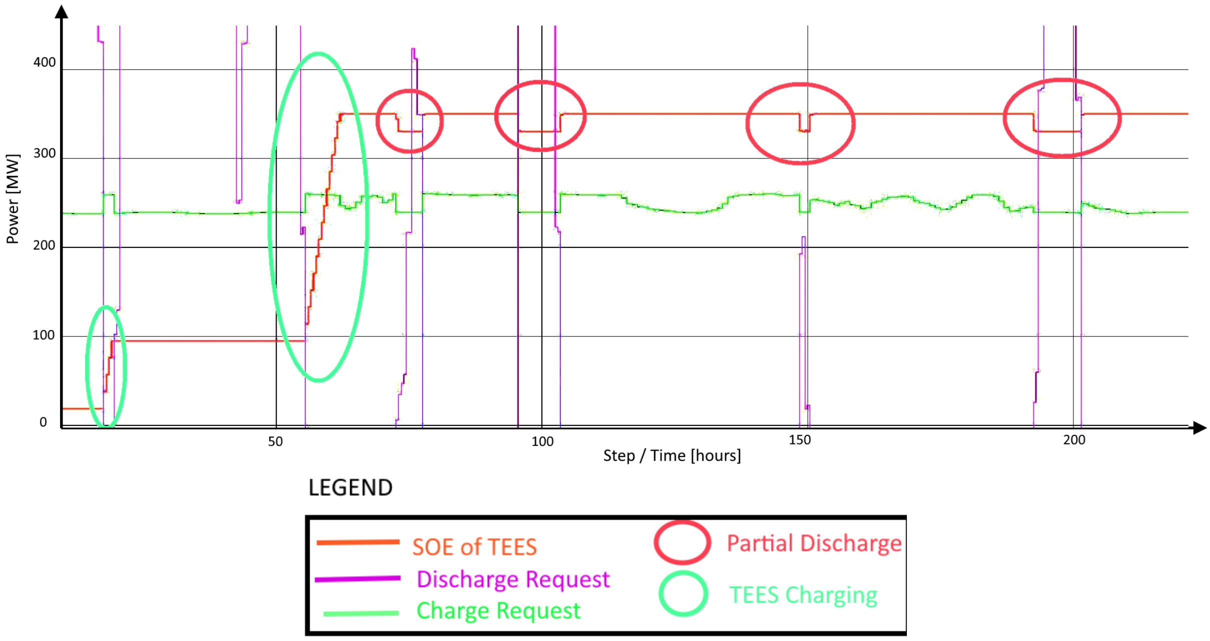

Figure 7.11: Graph of initial phase of TEES simulation, exposing an issue in TEES design that makes it unable to fully discharge.

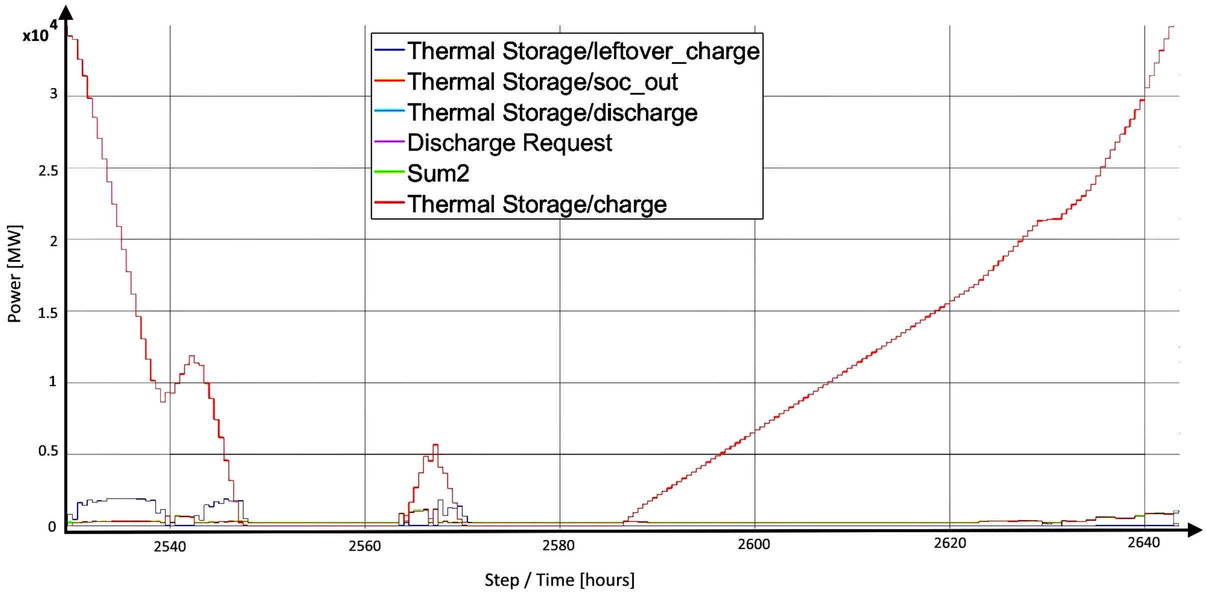

Figure 7.12: Stepwise process of charging and discharging of TEES in the absence of MSR.

7.8 Appendix H

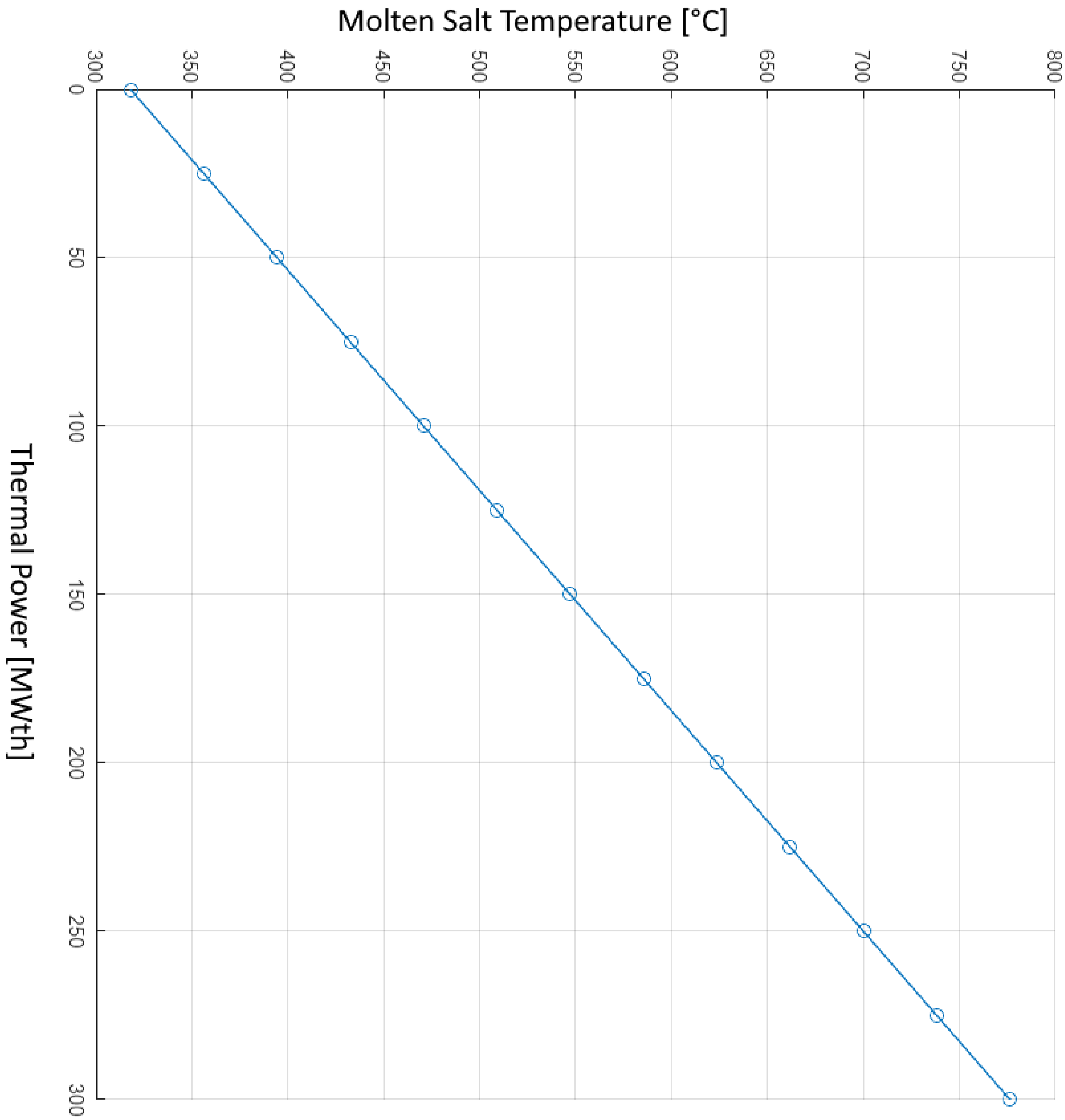

Figure 7.13: Linear conversions giving an approximation of heat exchange between MSR and TEES in "Molten Salt" block of the subcomponent "Power Conversion" of the HES component "Turbine/Generator".

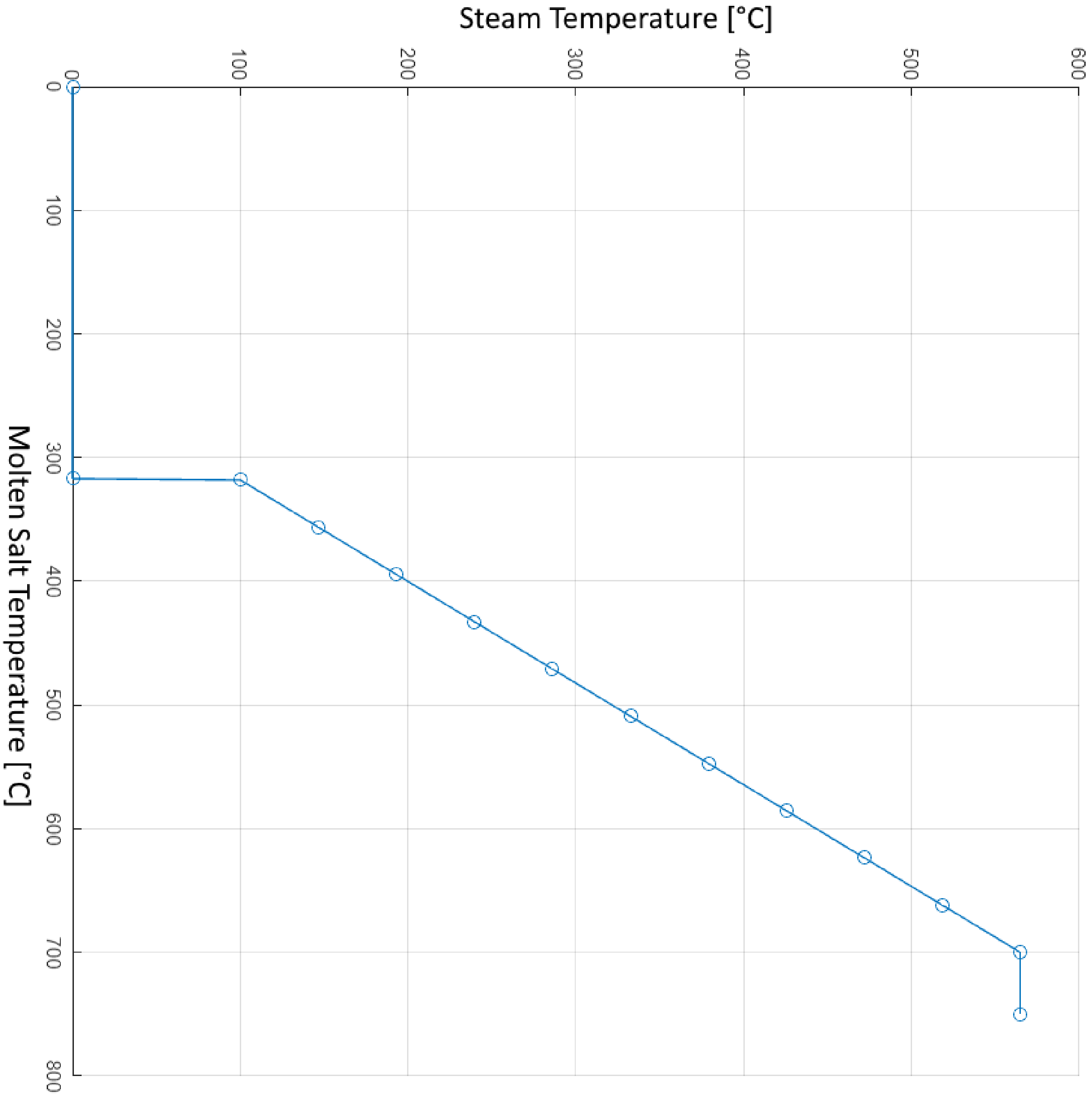

Figure 7.14: Linear conversions giving an approximation of heat exchange between TEES and steam in "Steam" block of the subcomponent "Power Conversion" of the HES component "Turbine/Generator".

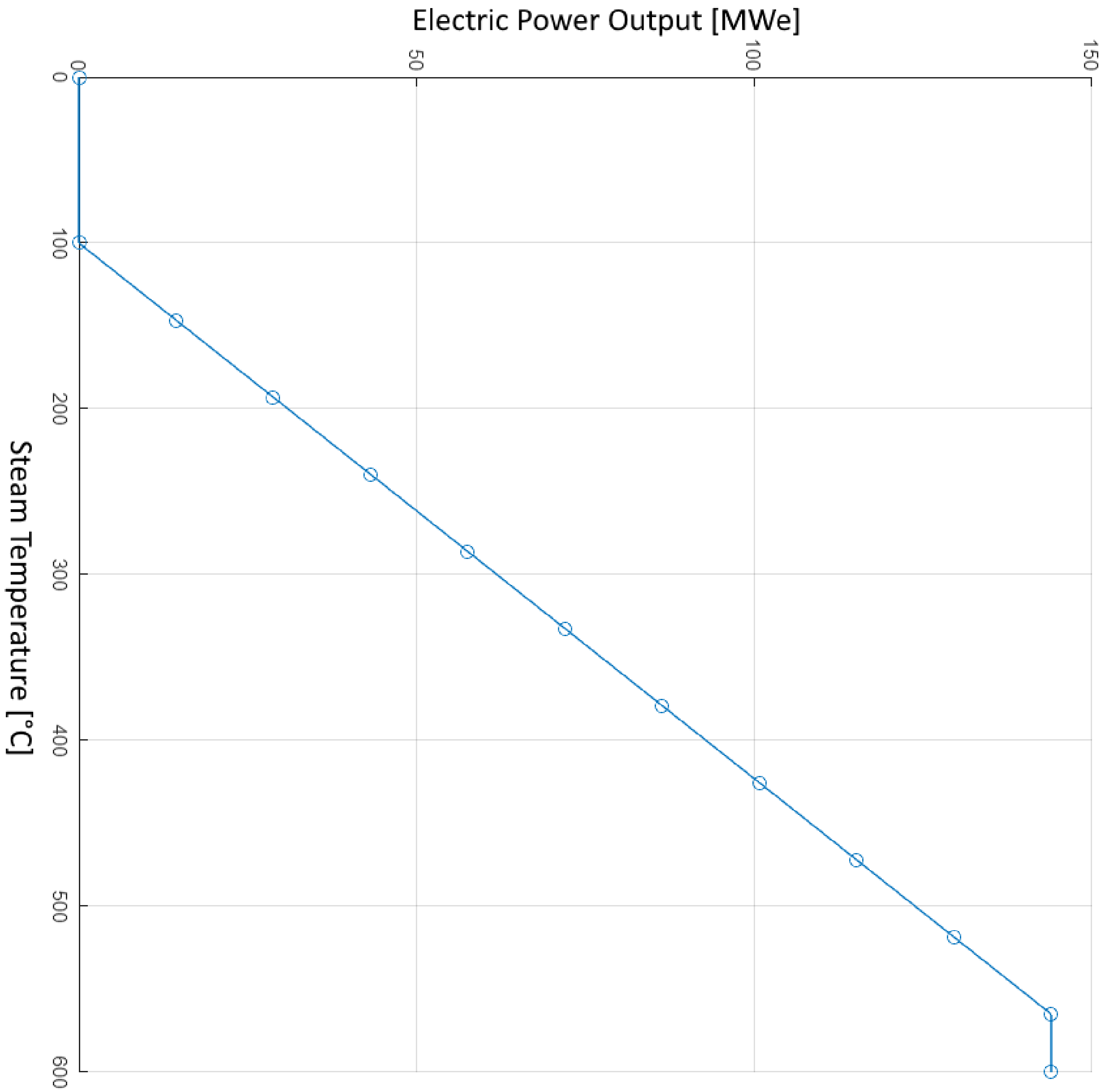

Figure 7.15: Linear conversions giving an approximation of power conversion in "Turbine/Generator" block of the subcomponent "Power Conversion" of the HES component "Turbine/Generator".

7.9 Appendix I

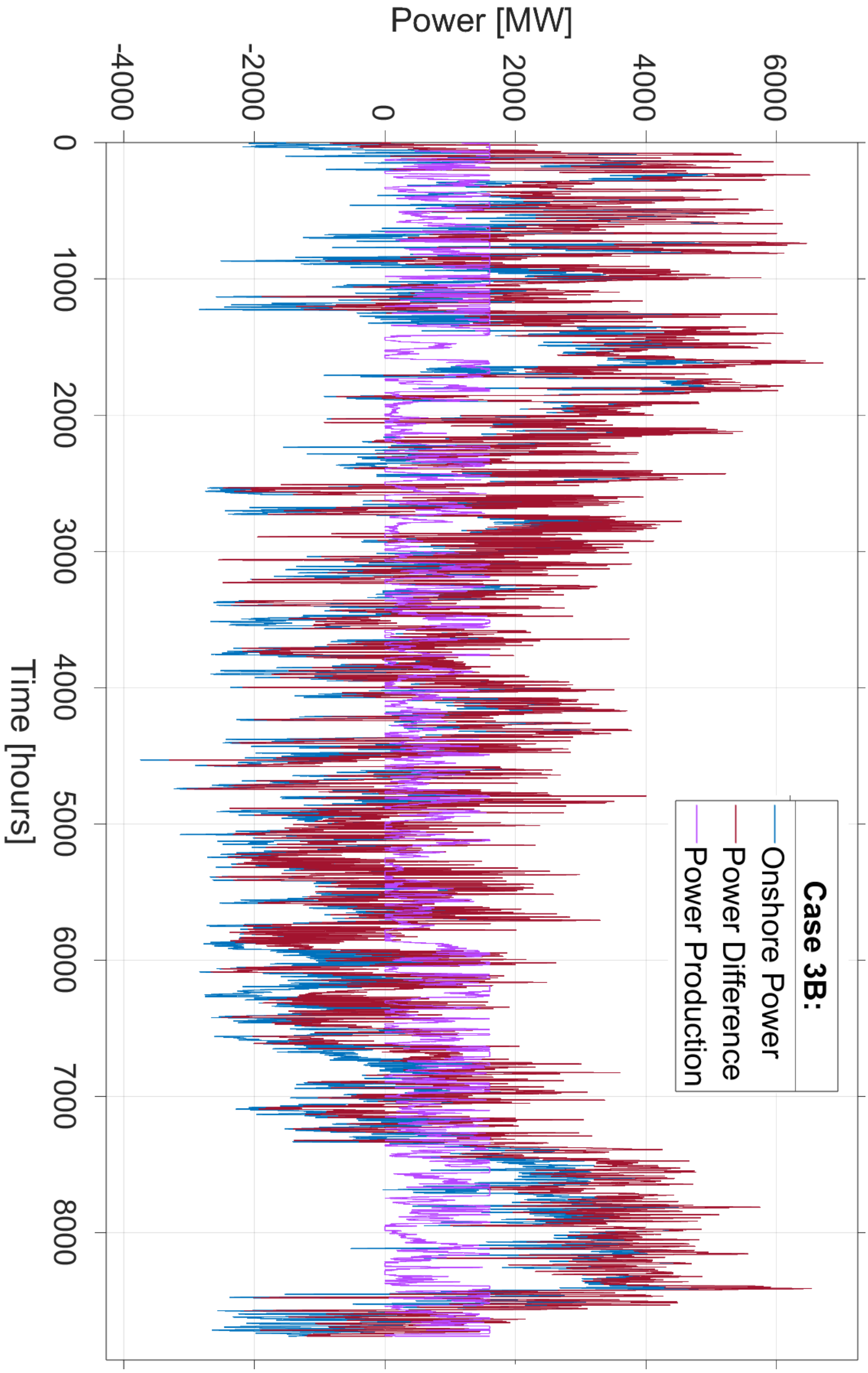

Figure 7.16: Hourly graph of power balance during Case 3B, displaying magnitude of annual changes in power demand. It shows a prolonged period of power deficit between 5000 and 7000 hours.

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