Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Andreas Ruud Jacobsen

Conceptual Design of Offshore Energy Storage Systems

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2021

NTNU
Norwegian University of Science and Technology

Andreas Ruud Jacobsen

Conceptual Design of Offshore Energy Storage Systems

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2021

Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

NTNU
Norwegian University of
Science and Technology

Abstract

Many renewable energy sources such as wind, solar and wave are intermittent energy sources. This often leads to an imbalance between energy demand and production. The reduced commercial capability of intermittent renewable energy production is enabling growth in the energy storage market. The main goal of this thesis is to create a product platform for the conceptual design of offshore energy storage systems and investigate the positive and negative aspects of the design method. The thesis aims to establish the feasibility of the platform and investigate its capability of efficiently configuring high-performance offshore energy storage systems. The thesis performs the necessary research to enable good decision making when developing the design approach. The main issue of a modular design approach for offshore energy storage systems is the poor accommodation for innovation, which is required to properly design such systems. The product platform obtained solves this issue by dividing the design process into two segments. The development of the modules and the configuration of these modules. The platform isolates the innovation to the development of the modules, enabling the benefits of downstream strategies for the configuration of the offshore energy storage systems. These development methods were derived using inspiration from Pahl and Beitz's Systematic Approach, Configuration-Based Design and Hazelrigg's Decision-Based Design. The product platform is deemed feasible and provides a number of benefits to the conceptual design of offshore energy storage systems. It enables the comparison and evaluation of a large number of design points, making it easier to identify the optimal system. The standardisation that modularity provides will according to theory benefit the cost-efficiency of the solution by lowering both the production and maintenance cost of the system. However, validation in terms of experimental and computational testing of the platform's efficiency is not performed.

Sammendrag

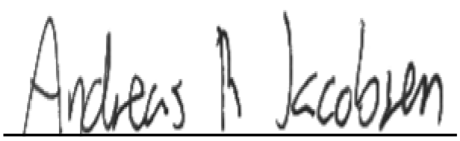
Mange fornybare energikilder som vind, sol og bølger er intermitterende energikilder. Dette fører ofte til en ubalanse mellom energibehov og produksjon. Den reduserte kommersielle kapasiteten til intermitterende produksjoner av fornybar energi muliggjør en fremtidig vekst i energilagringsmarkedet. Hovedmålet med denne oppgaven er å skape en produktplattform for konseptuell design av offshore energilagringssystemer og undersøke de positive og negative aspektene ved designmetoden. Oppgaven tar sikte på å etablere plattformenes gjennomførbarhet og undersøke dens evne til å effektivt konfigurere høytytende offshore energilagringssystemer. Oppgaven utfører den nødvendige undersøkelsen for å muliggjøre god beslutningstaking når man tar designtilnærmingen. Hovedproblemet med en modulær designtilnærming for offshore energilagringssystemer er dårlig akkommodering for innovasjon, som kreves for å utforme slike systemer. Den oppnådde produktplattformen løser dette problemet ved å dele designprosessen i to segmenter. Utviklingen av modulene og konfigurasjonen av disse modulene. Plattformen isolerer innovasjonen i utviklingen av modulene, noe som muliggjør fordelene med nedstrømsstrategier for konfigurering av offshore energilagringssystemer. Disse utviklingsmetodene ble hentet fra inspirasjon fra Pahl og Beitz Systematic Approach, Configuration-Based Design og Hazelriggs Decision-Based Design. Produktplattformen anses mulig og gir en rekke fordeler med den konseptuelle utformingen av offshore energilagringssystemer. Det muliggjør sammenligning og evaluering av et stort antall designpunkter, noe som gjør det lettere å identifisere det optimale systemet. Standardiseringen som modularitet gir, vil ifølge teorien være til fordel for løsningens kostnadseffektivitet ved å senke både produksjons- og vedlikeholdskostnadene til systemet. Imidlertid har validering i form av eksperimentell og beregningstesting av plattformers effektivitet ikke blitt utført.

Preface

This document constitutes the Master's thesis for the degree of Master of Science in Technology. It was conducted at the Department of Marine Technology at NTNU in Trondheim during the spring semester of 2021. The workload corresponds to 30 ECTS.

The scope of the thesis encapsulates my specialization of Marine Systems Design by applying a large variety of different engineering design theories. The scope also represents my interest in renewable offshore energy production. The topic was chosen after guidance from my supervisor Professor Stein Ove Erikstad, of which I would like to extend my gratitude for his valuable advice and expertise throughout the semester.

Due to time constraints the original scope of the thesis was altered. Although researched to a small degree, the question of when an offshore energy storage is deemed necessary and efficient has not been answered to a satisfactory degree, as the necessary cost estimates have not been performed.



Andreas R. Jacobsen

Trondheim, June 9th 2021

Contents

List of Figures

List of Tables

Abbreviations

AEL Alkaline Electrolyse.

AFC Alkaline Fuel Cell.

AHP Analytic Hierarchy Process.

ATO Assemble-to-Order.

BVGA BVG Associates.

CAD Computer Aided Design.

CAES Compressed Air Energy Storage.

CAGR Compound Annual Growth Rate.

CNESA China Energy Storage Alliance.

CODP Customer Order Decoupling Point.

DSM Design Structure Matrix.

EC Electrochemical Capacitors.

ETES Electric Thermal Energy Storage.

ETO Engineer-to-Order.

FES Flywheel Energy Storage.

FTO Fabricate-to-Order.

HOQ House of Quality.

HVAC High Voltage Alternating Current.

HVDC High Voltage Direct Current.

IEA International Energy Agency.

IRENA International Renewable Energy Agency.

LAES Liquid Air Energy Storage.

LHTES Latent Heat Thermal Energy Storage.

LNG Liquid Natural Gas.

MCFC Molten Carbonate Fuel Cell.

OTEC Ocean Thermal Energy Conversion.

PAFC Phosphoric Acid Fuel Cell.

PCM Phase Change Material.

PEM Proton Exchange Membrane Electrolyser.

PEMFC Proton Exchange Membrane Fuel Cell.

PHES Pumped-Heat Electricity Storage.

PSH Pumped-Storage Hydroelectricity.

ROI Return of Investment.

SBS System Breakdown Structures.

SMES Superconducting Magnetic Energy Storage.

SNG Synthetic Natural Gas.

SOFC Solid Oxide Fuel Cell.

TRL Technolgy Readiness Level.

Chapter 1

Introduction

1.1 Motivation and background

The last few years have seen a rapid development in renewable energy production. The global efforts to reduce greenhouse emissions and to limit the effects of climate change have accelerated the investments towards the production of clean energy. However, many renewable energy sources such as wind, solar and wave are intermittent energy sources due to the unpredictability of outside factors such as weather. The amount of energy produced at any given time is difficult to predict which often lead to an imbalance between energy demand and production.

The ocean contains a vast amount of energy and space for the construction of energy production technologies, and offshore energy production is expected to play a key role in the development of low-carbon energy. However, compared to their onshore counterpart, the offshore production sites are associated with a high cost in development, construction and maintenance.

The reduced commercial capability of intermittent renewable energy and the increased cost of offshore energy production negatively impacts its cost-competitiveness in the market. The offshore sites are dependent on a high cost-efficiency and need to fully take advantage of the increased energy production potential the offshore sites provide.

Energy storage systems can provide a number of useful applications to an energy production site that may solve the issues of intermittency. Although the industry has a lot of experience with energy storage systems, the implementation of such systems offshore requires innovation and finding an efficient solution can be resource-intensive. Implementing an energy storage system to an offshore production site can further reduce the cost-competitiveness if the solution is inefficient. This thesis will investigate how modern design approaches can enable an efficient conceptual design of high-performance offshore energy storage systems.

1.2 State of the art

Energy storage technologies have been developed by the industry for a long time, and there exist a vast number of different technologies today. However, there are little to no research on the opportunities of implementing such technologies offshore. The ocean provide different environments and boundaries for the energy storage technologies than onshore solutions, and researching how these characteristics can be used to develop efficient energy storage solutions have not been performed to a high degree. Although a few energy production technologies that attempt to take advantage of these ocean characteristics are in development, little research has been made on the potential opportunities offshore energy storage provides.

Engineering design methods have been in constant development and large amounts of research on many different design approaches are available. Modular design theory has been applied to many different industries for a long time and is a well-established design approach. For example, a modular approach has been used in the car industry for a long time and proven to provide many benefits for the cost-efficiency of the design process. Moreover, there is a lot of research available regarding how computational power and digitization can be used to improve the design of complex systems.

However, the implementation of such modern design approaches for offshore structures have only been investigated in recent years, and mainly for the development of ships. The high complexity of vessels makes it difficult to move away from the traditional design approaches based on integral structures and iterative processes. However, a lot of progress has been made during the last few years, applying digitisation and platform strategies in the conceptual phase of offshore ship designs. A lot of the research is focused on the conceptual design of ships, and there is little research regarding efficient engineering design methods for the development of offshore energy storage systems.

This thesis will research energy storage technologies to understand how such technologies can exploit the offshore environment. Further, the thesis will use inspiration from established engineering design methods to develop a structured approach for the conceptual design of offshore energy storage systems. The thesis will continue the work from a pre-project that was completed in the fall of 2020. The pre-project was a literature study on existing and upcoming energy storage technologies. Important literature is Pahl and Beitz Systematic Approach, Simpson's Engineering Modularity and Hazelrigg's Decision-Based Design.

1.3 Problem formulation

The goal of the thesis is to investigate modern design approaches and the use of these to enable a cost-efficient conceptual design of offshore energy storage systems. The thesis performs the research required to acquire a good basis for decision making. The approach is based on product platform technologies and attempts to provide a systematic approach to develop and exploit such a platform. After the product platform is developed its feasibility is evaluated, discussing the benefits and downsides of the design approach for offshore energy storage systems.

1.3.1 Scope of work

The main objective of the thesis provides an overall picture of the feasibility of using a product platform for the conceptual design of offshore energy storage systems. With such a wide objective, a few limitations are set to account for the limited amount of time in which this thesis will be written. Most of these restrict the in-depth analysis of some of the subjects.

The scope of the thesis is limited to the conceptual design phase of the energy storage systems design process, see figure 1.3.1. This will limit the amount of detail required for the designs derived from the design process. Moreover, as task clarification is considered outside the scope of the thesis, the mapping between customer needs and functional requirements is only performed to a limited degree, and is not meant to provide an in-depth understanding of how such mapping can be performed.

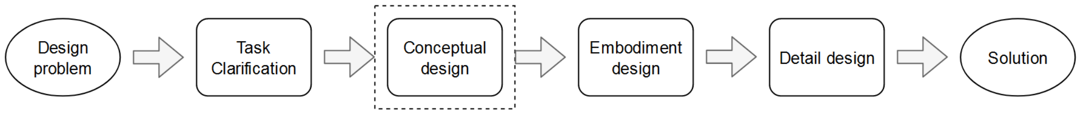


Figure 1.3.1: Phases of an engineering design process.

The design process considers the energy storage system without the transportation of the energy. Transportation solutions are researched to a minor degree, as understanding the basics of how the energy can be transported to shore and how this affects the energy storage system is important. However, energy transportation is not integrated into the system as this would require a more in-depth analysis of the supply chain for energy, which is considered outside the scope of this thesis.

Validation in terms of experimental and computational testing of the efficiency the platform provides is not in the scope of this thesis. The thesis will however include a mock-up of how the final system may function using a case study as an example. This is to illustrate the feasibility of the design approach.

The research phase of the thesis is considered important, as this provides the foundation of knowledge of which the design approach will be built upon. Deriving a design approach without understanding the fundamentals of energy storage systems or the benefits and downsides of engineering design approaches will lead to bad decision making and an inefficient design approach. The literature study is therefore performed in-depth, to provide a good information basis for further work.

1.3.2 Research objectives

The main objective of this thesis is reached by the fulfilment of the following secondary objectives:

- Gather information about energy storage technology and engineering design theory to enable good decision making throughout the thesis.
- Develop a method to identify and derive relevant modules for the product platform using inspiration from established engineering design methods.
- Establish a system architecture and the underlying theory and methodology that support the product platform.
- Develop a method to use the product platform to generate complete conceptual energy storage systems.
- Evaluate the design approach with respect to the design of offshore energy storage systems by discussing positive and negative aspects of the method.

1.4 Outline of thesis

The thesis aims to reach these objectives systematically by establishing general theory before moving on to developing the platform where this theory is applied. The outline of the thesis is provided in figure 1.4.1, where the arrows illustrate the flow of information from the research chapters to the development of the product platform. This is to visualise why the research was performed and where it was required.

1.4.1 Part I: Market analysis

The market research investigates the offshore energy production market and how energy storage can be used to improve the efficiency of renewable offshore energy production. The goal of the market research is to illustrate the needs in the renewable energy market for a cost-efficient energy storage system and the possible applications an energy storage system can provide to intermittent energy production.

1.4.2 Part II: Energy storage research

Energy storage technologies are researched to provide insight into what technologies that are currently in the market. Energy principles aim to establish the general physics and thermodynamic principles that govern energy storage and conversion principles. With this information, it is easier to understand how existing and upcoming energy storage technologies operate, and under what conditions and market needs they excel. Energy distribution technologies are also investigated to understand how energy can be transferred between two points, and what conditions that must be met for the transportation system to be viable. The information collected is used as inspiration when deriving the modules in the product platform and when estimating the performance of the designs configured in the case study.

1.4.3 Part III: Engineering design research

With a satisfactory understanding of energy storage technologies, the research phase ends by investigating different engineering design methods. The challenges of designing complex systems and how different engineering design methods tries to solve these challenges are investigated. Positive and negative aspects of traditional and modern approaches are established to understand how such methods can be applied to the product platform and what benefits they bring. The aim is to understand the benefits and challenges of using a product platform and how other engineering design problems can be applied to solve these challenges. This section provides a fundamental understanding of engineering design theory to create a good basis for decision making during the development of the product platform.

1.4.4 Part IV: The Product platform

The product platform is developed using the theory established in the research phase. The information obtained from the engineering design theory is applied to provide the structure of the product platform. Using this theory, methods for the development and exploitation of the platform that are based on engineering design methods are established. For the development of the platform, the energy storage technology previously researched will be used as a basis for the system breakdown when deriving the necessary functions and components in a storage system.

The aim of this part is to develop the product platform. This includes a method for developing the modules, defining the structure of the platform and developing a method for the configuration of offshore energy storage systems using the product platform. A case study is performed to provide an example of how the product platform can be used to configure conceptual designs of offshore energy storage systems.

1.4.5 Part V: Discussion and conclusion

The thesis includes a discussion of the thesis methodology and a discussion of the results obtained. The thesis methodology is discussed to provide information of limitations and simplifications to enable others to replicate and continue the work performed in the thesis. The aim of discussing the results is to evaluate the product platform as a design method for the conceptual design of offshore energy storage systems. The positive and negative aspects of the platform is discussed, along with its feasibility and how it solves the issues of designing complex systems.

The thesis will end with concluding remarks and a few recommendations for further work.

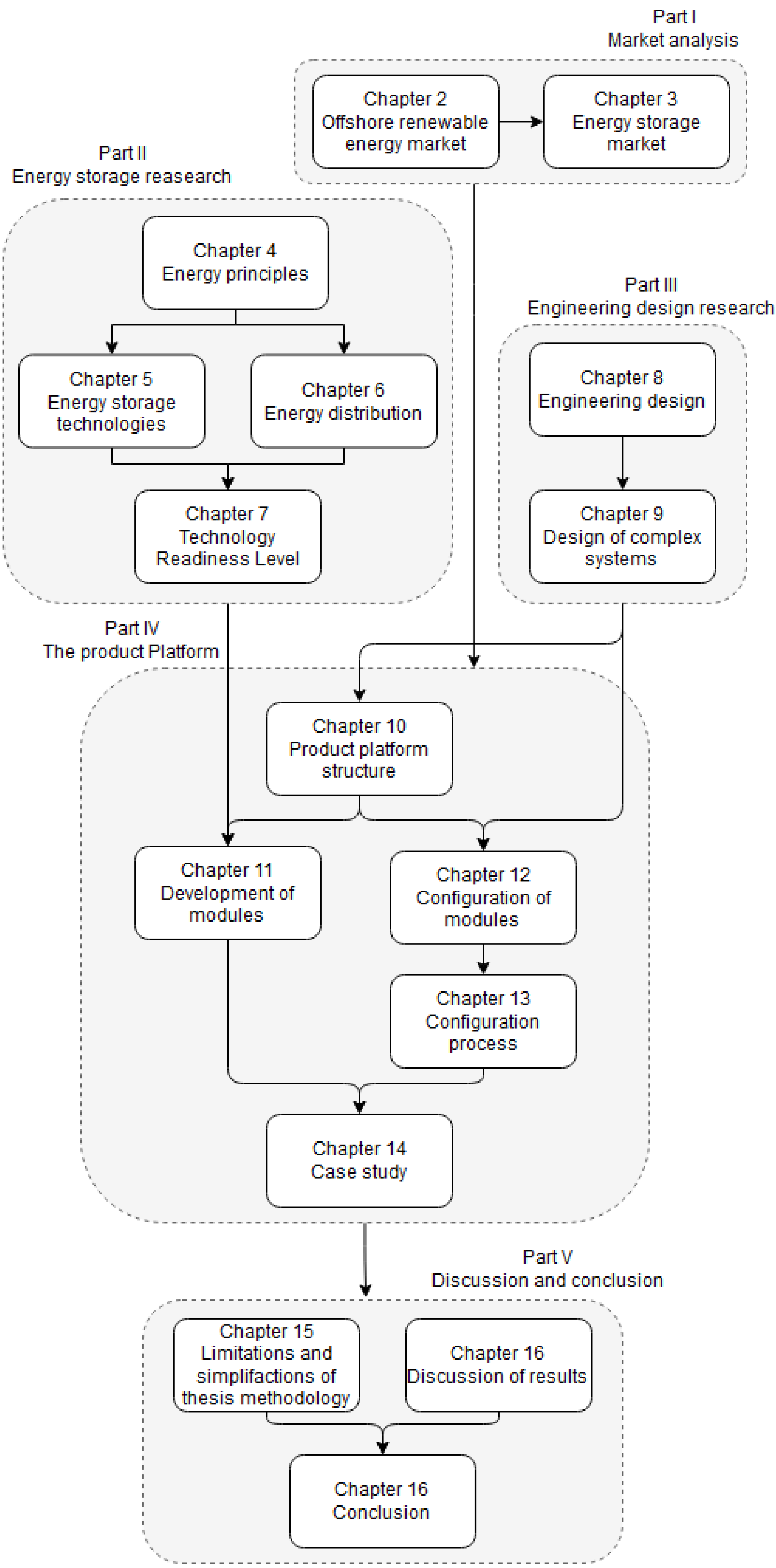


Figure 1.4.1: Outline of the thesis

Part I

MARKET ANALYSIS

Chapter 2

Offshore renewable energy market

2.1 Motivation

The Paris Agreement entered into force on the 4th of November 2016 with the signature of 55 countries that accounted for 55% of global emissions. As of today, 196 countries have signed the contract and are working together to reduce the effects of global warming. The agreement aims to strengthen the global response to climate change by uniting its members and accelerate actions and investments towards a sustainable low-carbon future. The goal is to restrict the global temperature increase to 2 °C, or preferably only 1.5 °C, compared to pre-industrial levels (UNFCCC, 2020).

To reach these goals, the countries need to cut their emissions drastically. Energy production is the single largest greenhouse emission contributor today and the decarbonization of the energy production sector has been a major focal point in the effort to reach the Paris Agreement's terms. As shown in figure 2.1.1, the global energy consumption was almost 159 000 TWh in 2019, where 89% of the energy was generated from fossil fuels (Ritchie, 2020).

According to DNV the world is reaching a peak in both energy production emissions and energy supply. The forecast toward 2050 shows a significant drop in coal energy that is replaced by solar and wind. This is much due to the increased demand for electricity generation, as shown in figure 2.1.2. As the industry is moving towards clean energy, fossil fuels will be used less in both combustion and electricity generation. Additionally, the efficiency of the electricity production systems is expected to increase. This efficiency increase is partly due to the benefits energy storage systems can provide to the energy production industry (DNV, 2020a).

The Paris Agreement and the potential cost of the consequence of an increase in global temperature is motivating the investment and development of renewable energy production. However, DNV's publication suggests that the development towards net-zero carbon emission is too slow, and the 2 °C budget will be exhausted by 2051. Although uncertainty applies to all forecasts, an estimated overshoot of almost 530 Gt of CO_2 indicates that there is an urgent need to further increase the investments and development of low-carbon

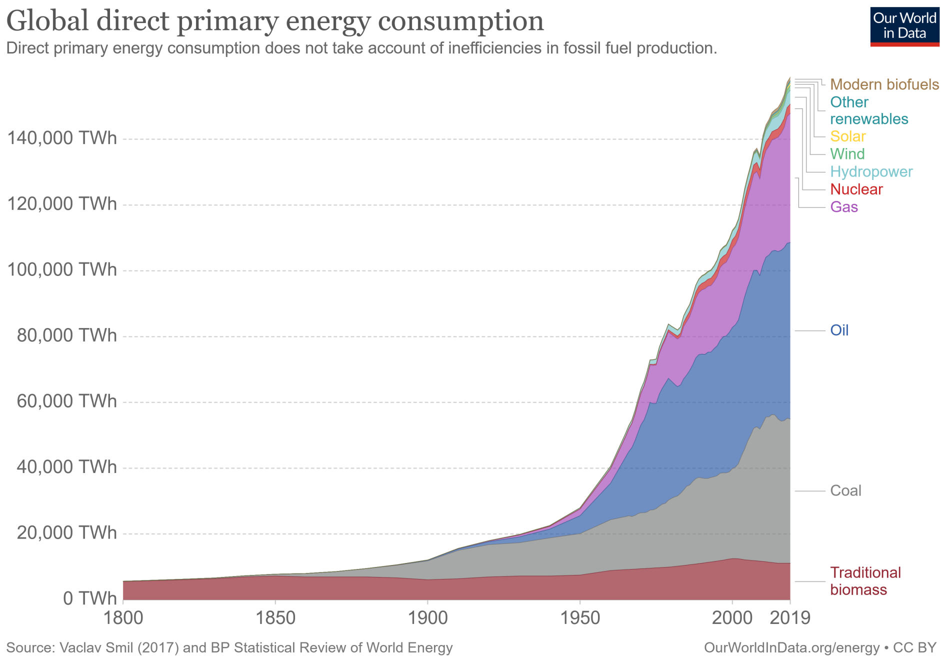


Figure 2.1.1: Global energy consumption (Ritchie, 2020).

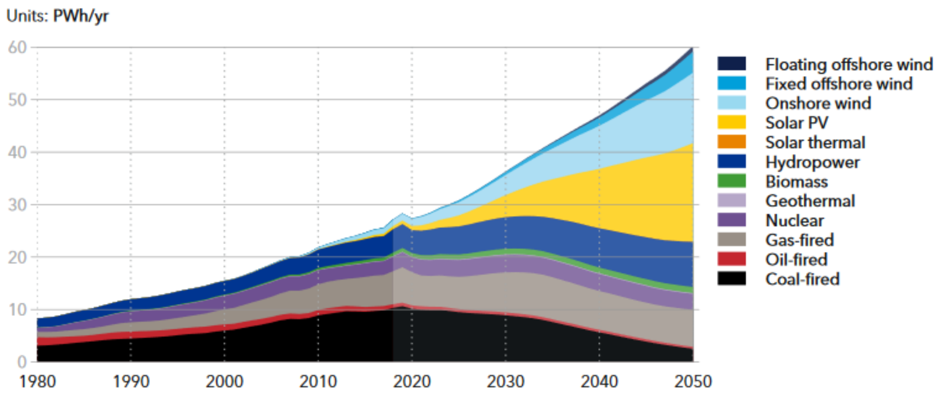


Figure 2.1.2: World electricity generation by power station type (DNV, 2020a).

energy solutions (DNV, 2020a).

2.2 Offshore energy production

The European Green Deal states that offshore renewable energy production will have a key role in the development towards a sustainable future (EC, 2020). The ocean contains an enormous amount of clean energy, and developing technology to harness this energy is crucial to reach the emission goals set by the Paris Agreement. This section introduces some of the energy production technologies that are growing in the market.

2.2.1 Wind energy

Offshore wind energy is the fastest-growing renewable power segment, reaching a global production capacity of 30 GW in 2019. The reduced regulation for offshore wind turbines enables the construction of larger turbines with longer rotor blades. A larger rotor diameter absorbs more energy from the wind, increasing the energy production and cost-efficiency of the system. Moreover, the higher wind speeds that are achieved offshore makes it suitable as a renewable energy source (DNV, 2020b). BVG Associates (BVGA) reports an expected global capacity of 84 GW by 2024 (BVGA, 2019). The International Renewable Energy Agency (IRENA) expects the offshore wind capacity to grow to 128 GW by 2030, corresponding to a cumulative investment of 350 billion USD (IRENA, 2018). Figure 2.2.1 illustrates the global cumulative offshore wind capacity as forecasted by IRENA.

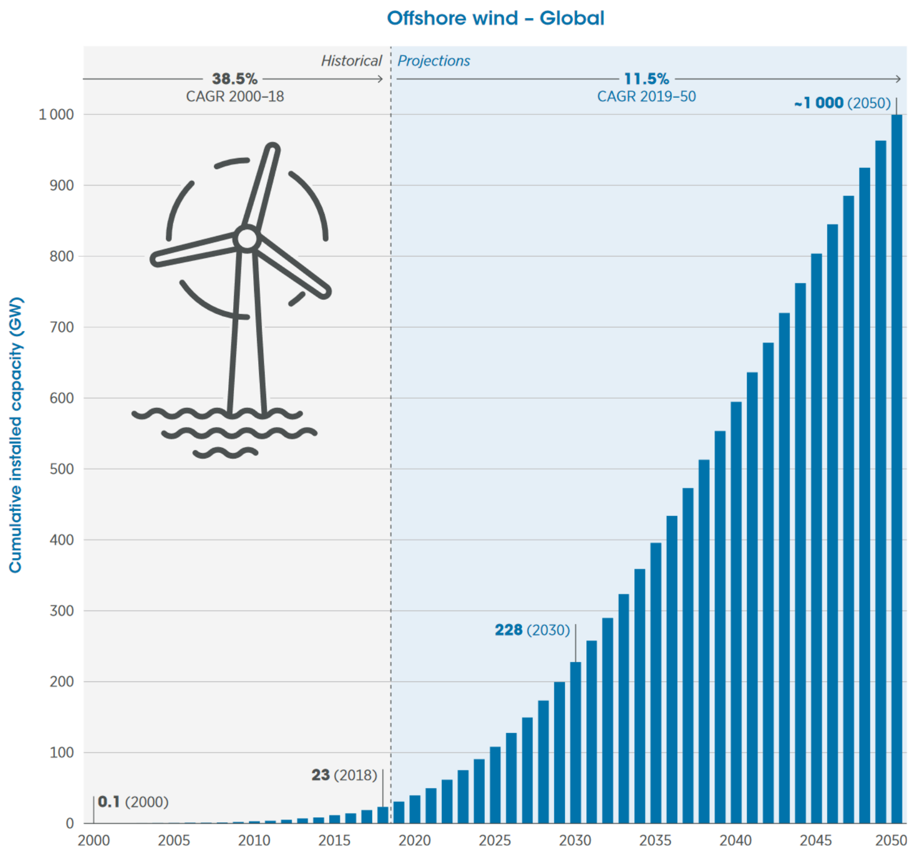


Figure 2.2.1: Global cumulative offshore wind capacity (IRENA, 2019).

Simultaneous with the rapid growth in capacity, the wind fields are also being constructed further away from the coast and grid entry points. This poses significant expenses and challenges to the industry, as the wind turbines must float with anchors instead of being fixed to the seabed. Moreover, high humidity and saltwater spray shortens service life and causes corrosion which becomes a significant expense due to the longer travel times for the maintenance crew. This results in a construction and maintenance cost far higher than land-based turbines (IRENA, 2018).

2.2.2 Wave energy

Absorbing wave energy have been tested for decades, but is not as well established as offshore wind power. These designs need to be robust to withstand the destructive power of storm waves. Although systems like this have been considered offshore, it is mostly relevant for coastal use, as they can be used in replacement of breakwaters (SUT, 2020).

2.2.3 Tidal energy

Tidal streams are generated by the gravitational interaction between the sun and the moon. Therefore, unlike wind and wave power, the energy created from tidal streams are entirely predictable. Several designs have been developed to absorb the energy from tidal streams, often resembling an underwater wind turbine. Energy can also be harvested from the differences in sea level between high and low tide, using conventional hydromechanical power principles.

The energy from tides is best exploited around ocean inlets and along the coast. These solutions are connected to the seabed and are not designed for far offshore use. However, predictable energy production works best in conjunction with an energy storage system, and plans to develop such systems are in motion (SUT, 2020).

2.2.4 Ocean Thermal Energy Conversion

Another promising offshore energy production method is Ocean Thermal Energy Conversion (OTEC). OTEC can produce electricity from the difference in temperature between deep water and surface water. OTEC can provide a predictable, steady stream of electricity every hour of the day. Large-scale OTEC plants are planned for use offshore and can produce up to 100 MW of power (Makai, 2020).

2.2.5 Floating solar

Floating solar PV systems are solar panels placed on a floating structure. The benefits of moving solar energy offshore are the amount of area available and fewer dust particles. However, there is an additional cost in maintenance due to saltwater spray. It is best applied along the coast and can be associated with existing grid connections, for instance in the case of a dam vicinity (IFE, 2021).

Chapter 3

Energy storage market

The motivation behind the increased focus on renewable energy production is determined and reveals a market that will grow in the coming decades. To be cost-competitive in the market the energy production technologies are reliant on a high cost-efficiency and to properly exploit the higher production potential the offshore sites can provide. This chapter investigates how the reduced commercial capability of renewable offshore energy production stimulates growth in the energy storage market, and how energy storage can be used to increase the efficiency of intermittent energy sources.

3.1 Current market and projections

The current energy storage market mainly consists of onshore systems. Although a few technologies for offshore energy storage have been developed, such as the FLASC project for floating PV solar systems, these are only in the conceptual phase and have not been deployed at a large scale (FLASC, 2021). This market analysis mainly provides information about the general growth of energy storage systems.

Pumped hydro energy storage systems are the dominating energy storage technology today, with a market share of over 90% globally. This amounts to a total capacity of 170 GW. Figure 3.1.1 illustrates the market share for other significant energy storage technologies. According to China Energy Storage Alliance (CNESA), the global growth of energy storage was 1.9% from 2019 to 2020 (CNESA, 2020).

There are many different segments of energy storage that are important to distinguish in the market analysis. Energy storage can be found in everything from small electronics to larger transportation vehicles. The application of energy production is segmented as stationary energy storage. According to Lux research, the total energy market forecast will experience Compound Annual Growth Rate (CAGR) in investments of 14.9%, going from a cumulative investment of 59 billion USD in 2019 to 549 billion USD in 2035. This represents a capacity growth from 164 GWh to 3046 GWh. The CAGR describes the mean annual investment growth rate over the time period (Holzinger et al., 2019).

Stationary energy storage only represents a fraction of this growth, but is estimated to

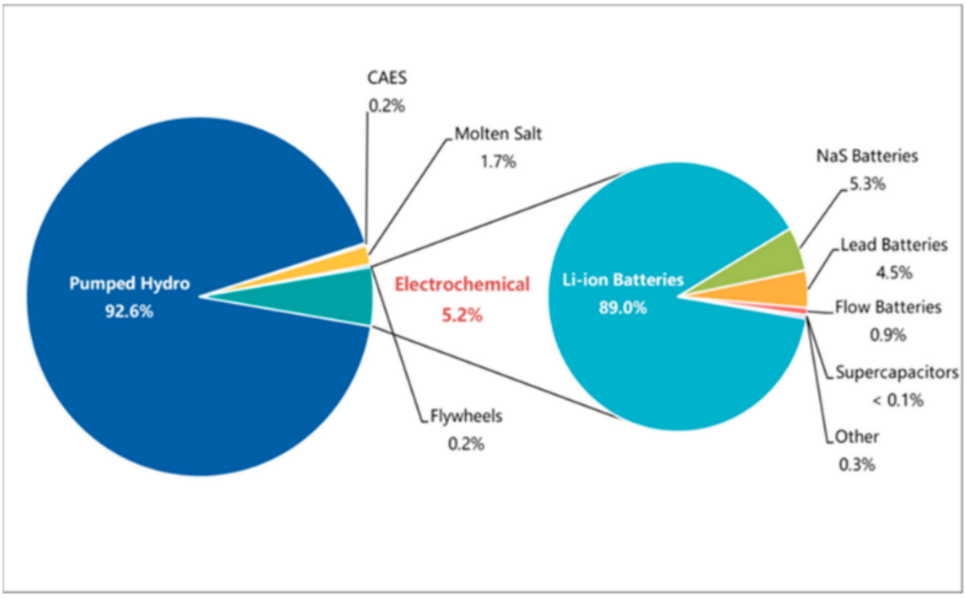


Figure 3.1.1: Market share of energy storage principles (CNESA, 2020).

experience a higher CAGR in investments of 17%. With a cumulative investment of 9.1 billion USD in 2019, the stationary energy storage segment is expected to increase to a cumulative investment of 111.8 billion USD by 2035, accounting for an increase from 15.2 GWh to 222.7 GWh. Figure 3.1.2 illustrates the expected annual revenue from energy storage systems projected by Lux Research (Holzinger et al., 2019).

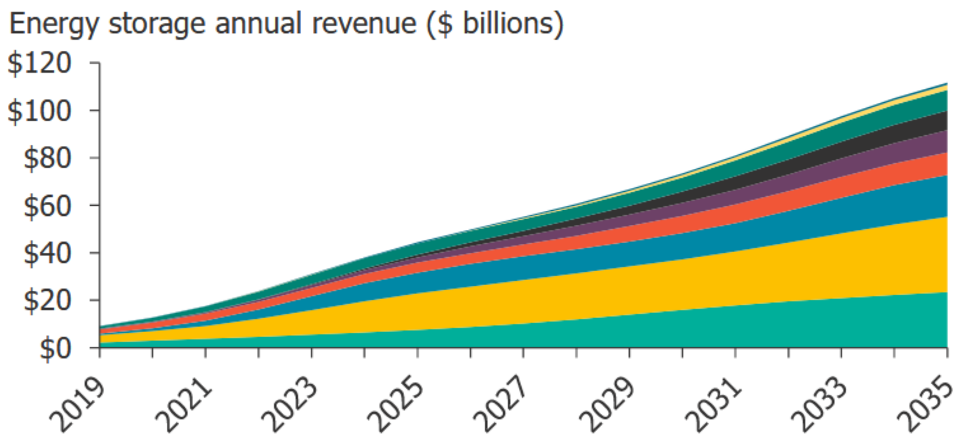


Figure 3.1.2: Annual revenue growth of energy storage systems (Holzinger et al., 2019).

3.2 Energy storage applications

It is not only the stabilization of the intermittent renewable sources that is compelling to the industry. An energy storage system that is properly integrated with the energy production system can improve the production efficiency and the overall quality of the grid by offering a range of different applications. Investigating such applications provides insight into what functional requirements an energy storage system must fulfil to deliver a grid service.

Table 3.2.1 provides a list over the applications of energy storage systems. The applications are segmented into three categories based on the required power rating that is necessary for the energy storage system to perform the application. Some of the applications will be explained in further detail (Behabtu et al., 2020).

Table 3.2.1: Energy storage system applications (Behabtu et al., 2020).

Segment	Application	Storage time	Power rating
Power quality and regulation	Fluctuation Suppression/Smoothing Dynamic power Response Low voltage Ride Through Line Fault Ride Through Uninterruptable Power Supply Voltage Control Support Reactive Power Control Oscillation Damping Transient Stability	≤ 1 min	Small scale (≤ 1 MW)
Bridging power	Spinning/Contingency Reserves Ramping Emergency Backup Load Following Wind Power Smoothing	1 min - 1 h	Medium scale (10-100 MW)
Energy management	Peak Shaving/Time Shifting	1-10 h	Large scale (≤ 300 MW)
	Transmission Curtailment Energy Arbitrage Transmission and Distribution Deferral Line Repair Load Cycling Weather Smoothing	5-12 h	
	Unit Commitment Load Leveling Capacity Firming Renewable Integration and Backup	Hours-days	
	Seasonal Storage Annual Smoothing	≥ 4 months	

3.2.1 Power quality and regulation

Power quality and regulation involve applications where the duration of the storage time is less than a minute and the power rating of the storage system is below 1 MW. These are applications that provide suppression or smoothing of the fluctuations of voltage in the system. The voltage fluctuations can be caused by the variation in energy production or by a fault in the energy system. Uncontrolled reactive voltage spikes can cause extensive damage to electrical equipment with shortages and fires. Energy storage systems that can deliver such applications to the grid will need a very fast response time to counter the voltage fluctuations (Behabtu et al., 2020).

3.2.2 Bridging power

Bridging power includes applications related to transmission and grid support services. Energy storage systems that can deliver these applications require a power rating of 10 to 100 MW with a storage time of one minute to an hour. These are services such as ramping control, where the fluctuation of power output per minute is controlled. These systems can also deliver energy as an emergency backup in the event of a sudden and unexpected fault that causes an imbalance between energy supply and demand. Figure 3.2.1 is a simplified figure that illustrates how stored energy can resolve an unexpected decrease in power production (Behabtu et al., 2020).

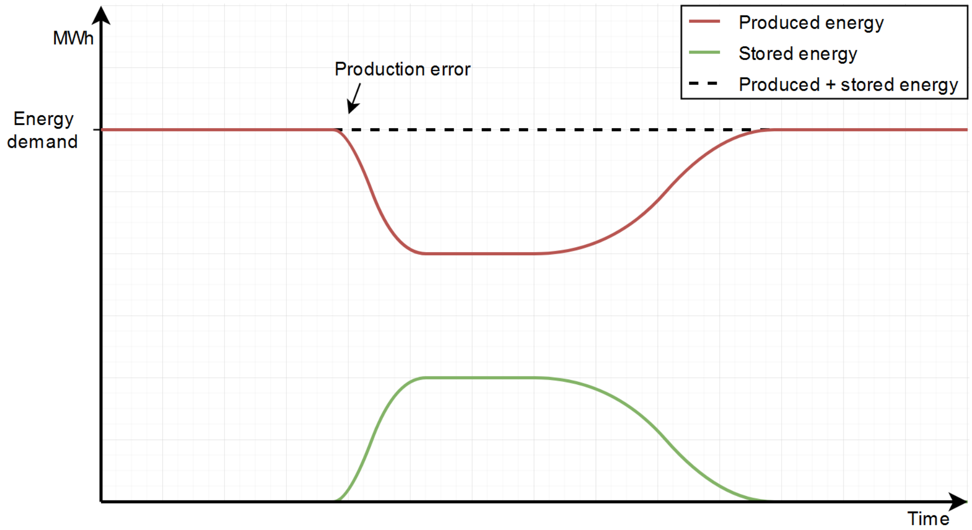


Figure 3.2.1: Power loss compensated by stored energy.

3.2.3 Energy management

The energy management segment includes applications regarding bulk power management. As such, these applications require a large scale energy storage system with a power rating above 300 MW. The storage duration varies from 1 h to 4 months, depending on what services the storage system is to provide (Behabtu et al., 2020).

Peak shaving, or time-shifting, store the excess energy produced at times with low energy demand and releases it back to the grid when the energy demand rises. This service can restore the balance between energy production and grid demand, and solve the issues related to the intermittency of renewable energy sources. Peak shaving can also improve the cost-efficiency of the system by increasing the profit of sold electricity. Instead of selling electricity at a low demand, it can be stored and sold for a higher price when the demand rises. Figure 3.2.2 illustrates the principle of peak shaving.

Other applications are capacity firming where fast response services are combined with a large scale energy storage system. A storage system capable of providing capacity firming will maintain the energy provided to the grid at a committed level for a period of time. Such a storage system is capable of controlling the ramp rate and the voltage fluctuations in the system. Such systems can store energy from a few hours to several days.

Finally, bulk power management with a storage time of over 4 months can provide seasonal storage. This uses the same principle as time-shifting, but over an extended period of time. The amount of energy produced from renewables is often fluctuating with the seasons. Using seasonal storage, the energy is stored during one season of high production, and

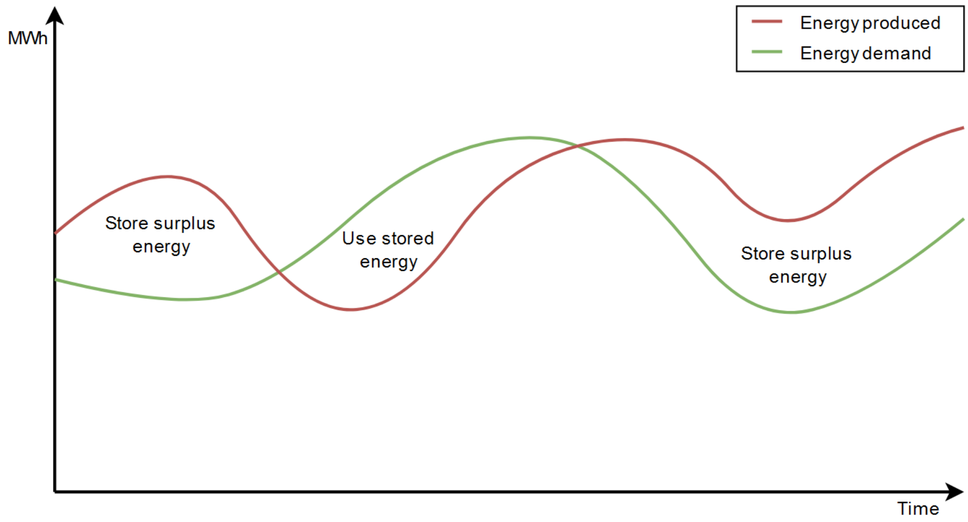


Figure 3.2.2: Peak shaving principle in energy production.

released to the grid at seasons of low storage. The cost-efficiency may also be improved, as the energy is sold at a higher price during the seasons of insufficient production.

3.2.4 Alternative energy markets

Additional to providing better grid services, an energy storage system can also increase cost-efficiency by offering more products. According to DNV, there will be an increase in demand for low-carbon liquid and gas (DNV, 2020a). This includes chemicals such as hydrogen, ammonia and synthesized methane. A storage system based on using these chemicals as energy carriers will have the flexibility of converting the energy back to electricity or selling the energy as a chemical. Since the market for low-carbon gas and liquids are increasing, this could potentially improve the cost-efficiency of the system.

DNV also estimates an increase in low-carbon transportation. The International Energy Agency (IEA) "ETP Clean Energy Technology Guide" show that engines based on the combustion of hydrogen, methanol and ammonia are under development, as well as fuel cell electric vehicles that use these chemicals as energy carriers (IEA, 2020).

3.2.5 Energy storage technologies

The functional demands of the storage system are dependent on what grid service it is expected to deliver. Figure 3.2.3 illustrates what grid services some energy storage technologies can provide with respect to their discharge time and rated power. Keep in mind that the segmentation of the power rating is different from table 3.2.1.

The use-cases for the different energy storage technologies are not only dependent on the storage duration or discharge time. To properly understand when energy storage systems are suitable for a case, the fundamentals of how they work need to be established.

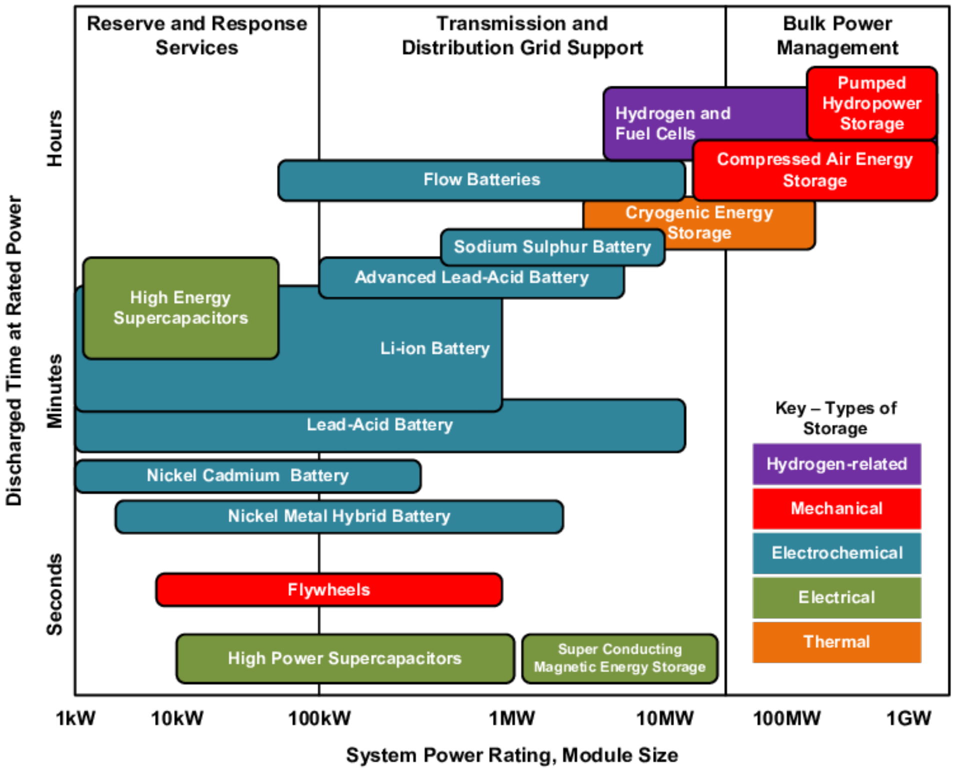


Figure 3.2.3: Energy storage grid support services (Sprake et al., 2017).

Part II

ENERGY STORAGE RESEARCH

Chapter 4

Energy principles

When energy is converted from one form to another, a certain amount of energy is lost. This is most often due to heat escaping the system. The amount of useful energy extracted from a system divided by the amount of energy input to a system is called round-trip efficiency. Round-trip efficiency is an important factor to determine the cost-competitiveness of a storage system.

The laws of thermodynamics govern the transition of energy systems. The first law of thermodynamics, the law of conservation of energy, states that the total energy in the universe is constant. Energy can neither be created nor destroyed, but rather converted from one form to another. This serves as the foundation of almost every energy conversion and storage principle. The amount of energy in a system and its round-trip efficiency can be determined by using this law (Gür, 2018).

Energy can be generally categorized as electrical, mechanical, chemical, thermal, radiant and nuclear. In this thesis, only the first four is considered. Gibbs free energy determines the maximum amount of electrical energy that can be extracted from a system. Its formula is given by equation 4.1, where G is Gibbs free energy, H is enthalpy, T is temperature and S is entropy. The maximum amount of electrical energy that can be extracted from a system is the sum of its internal energy subtracted by the amount of thermal energy per unit temperature that is unavailable for doing useful work.

$$G = H - TS \tag{4.1}$$

4.1 Mechanical energy

Mechanical energy is divided into potential and kinetic energy. Their respective formulas are given in equation 4.2 and 4.3, where f is force, d is distance, m is mass and v is velocity. For a mass hanging d meters above the ground, its potential energy would be mgd. When the mass is dropped, the potential energy will be converted to kinetic energy as the velocity, v, increases. This kinetic energy can be absorbed by a generator to produce electricity (Gür, 2018).

$$E_p = fd \tag{4.2}$$

$$E_k = \frac{1}{2}mv^2 \tag{4.3}$$

The kinetic energy in a rotating body is dependent on the bodies moment of inertia, I, and angular velocity, ω, see equation 4.4. The moment of inertia for a wheel can be calculated as described in equation 4.5 , where m is the mass and r is the radius. From these formulas, it can be derived that a high-density material combined with a larger radius will store more kinetic energy with rotation.

$$E_k = \frac{1}{2}I\omega \tag{4.4}$$

$$I = \frac{1}{2}mr^2 \tag{4.5}$$

Potential energy can also be stored in the tension of a spring or by compressing gas, referred to as elastic potential energy. Storing energy by compression relies on the gas law, see formula 4.6, where P is the pressure, V is volume, n is the amount of the substance, T is temperature and R is the ideal gas constant. The available work is given by integrating the pressure, P, over the incremental volume change, dV, see figure 4.1.1.

$$PV = nRT \tag{4.6}$$

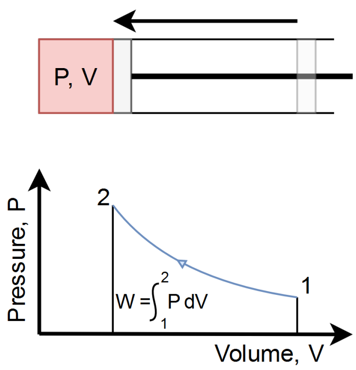


Figure 4.1.1: Available work from a compressed gas.

4.2 Thermal energy

The compression of a gas is closely related to thermal energy. Compressing a fluid pushes the atoms together causing friction, which in turn increases the temperature. The quantity of energy stored in the thermal vibrations of the molecules is called heat, q. Thermal energy relies on a materials ability to store heat, see formula 4.7. ρ is the material density, C_p is the specific heat, V is the material volume and ΔT is the temperature change (Gür, 2018).

$$q = \rho C_p V \Delta T \tag{4.7}$$

If a material changes phase during a thermal process, the latent heat energy should also be accounted for. Latent heat is the energy that is dissipated or absorbed by a material due to its phase change, see figure 4.2.1.

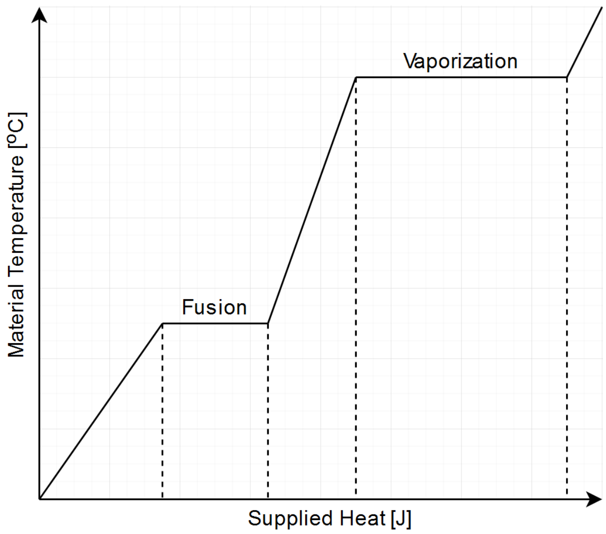


Figure 4.2.1: Supplied heat from each phase change of a material.

Heat can be transferred through advection, conduction, convection and radiation, see figure 4.2.2. Advection is the movement of a substance due to a bulk motion of a fluid, where the properties of that substance, such as its heat, is moved with the fluid. Conduction is the transfer of heat through direct contact. The molecules collide with each other, where the molecule with the highest internal energy transfer some of its heat to the other molecule. Thermal radiation transfers heat through electromagnetic radiation. This heat transfer is very slow, but is also the only method that works in a vacuum.

Convection is a combination of advection and conduction. This is the dominant method of transferring heat in systems. Convection transfer the heat by mass transfer, causing heat conduction within the fluid and heat transfer by bulk fluid motion. The motion of the fluid is often induced by a density gradient caused by temperature or pressure differences within the system.

Figure 4.2.3 illustrates an example of a thermal cycle for refrigeration, where Q is heat and W is work. An isothermal process is a thermal cycle where the temperature remains

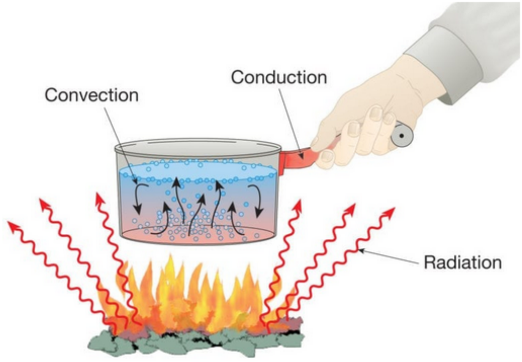


Figure 4.2.2: Heat transfer principles (SimScale, 2021).

constant, and therefore its internal energy is constant. This means that the amount of energy put into the system must be equal to the heat escaping the system at any given time. This provides a process with an energy efficiency of 100%. However, the heat escaping the system dissipates slowly, meaning that the energy input to the system also has to be slow. In reality, near-isothermal will be more suitable for energy storage. An adiabatic process is when the thermal cycle only loses energy to work, and not heat or mass. In such a process, the temperature is allowed to change with the compression and expansion of the gas.

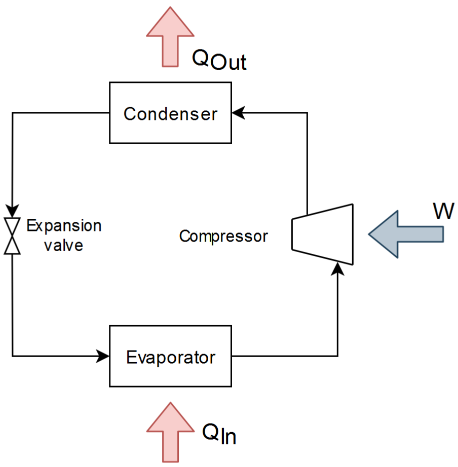


Figure 4.2.3: Working principle of a refrigeration cycle.

4.3 Chemical energy

Chemical energy stores energy in the chemical bonds in molecules. These bonds are very strong and can therefore store large amounts of energy, giving chemical storage solutions a high energy density. The general principle is to create energy by breaking these bonds and rearranging the atoms to form new molecules. These new molecules have a more stable bond that requires less energy. As a result, energy is released. Equation 4.8 illustrates the chemical reaction that occurs by burning methane. By looking at the required heat to form each molecule one can calculate the expected energy produced from the reaction (UIUC, 2020).

$$CH_4 + 2O_2 + spark \rightarrow CO_2 + 2H_2O + Heat \tag{4.8}$$

The amount of energy that can be extracted from chemical storage is dependent on the material used and is governed by equation 4.1. Common materials that are used to create energy are fossil fuels like diesel and gasoline. Table 4.3.1 provides the energy densities of some common chemical energy carriers in liquid form (Gür, 2018).

Table 4.3.1: Energy densities of common liquid fuels (Gür, 2018).

Material	**Energy density[Wh/kg]**	**Energy density[Wh/L]**
Gasoline	12 330	9060
Diesel	12 700	10 700
Propane	12 870	7490
Butane	12 700	7190
Ethanol	7490	5890
Methanol	5620	4470
Liq. Hydrogen	33 570	2200
Liq. Ammonia	6250	3194

To be used as a storage system the process needs to either be reversible or the chemical needs to be produced at the site. The synthesis of fuels is typically performed with fuels that contain atoms that can be absorbed from air or water, like hydrogen, carbon and nitrogen. There are several different ways to synthesise high energy density fuels. However, few of the mature technologies are carbon emission-free. As this report focuses on offshore energy storage solutions for renewable energy sources, the storage solution should be as low-emission as possible. This needs to be taken into consideration when deciding which chemical storage technologies that are interesting to investigate.

4.4 Electrical energy

Electrical energy can either be stored using electrochemical methods or by the use of electrical and magnetic fields. Electrochemical storage is based on the principles of storing charge. The theoretical round-trip efficiency of electrochemical storage is defined as presented in equation 4.9, where η is the energy efficiency, G is Gibbs free energy and H is enthalpy. This results in a very high round-trip efficiency for electrical based storage systems (Gür, 2018).

$$\eta = \frac{\Delta G}{\Delta H} \tag{4.9}$$

Electrochemical energy storage can be divided into three processes. Separation of charge, transport of charge and recombination of charge. These steps govern the basic principle of electrochemical technologies such as batteries, fuel cells and capacitors. However, the mechanisms involved in performing these steps are different between the technologies. For example, batteries store the charge within electrodes while capacitors store the charge on electrochemical surfaces. Depending on the technology and material choices, electrochemical storage has different characteristics like operating temperature, energy density and resilience. It is therefore very important to consider which materials to use to get the most out of the energy storage system (UIUC, 2020).

Electrochemical storage converts the chemical energy stored in the bonds of fuels into electrical energy. If the process is reversible, i.e. expending electrical power to synthesise the fuel, the system is rechargeable. This is very important for an energy storage solution to be viable. Generally, electrochemical storage consists of two electrodes, cathode and anode, that are separated by an electrical insulating electrolyte capable of transporting ions. Figure 4.4.1 depicts the fundamental principle of electrochemical energy storage. At the rightmost illustration, electrical power is introduced to the system and stored as ions. At the leftmost illustration the electrical power is absorbed from the system and introduced back into the grid. The electrolyte of ions completes the circuit by transporting the electrons between the electrodes.

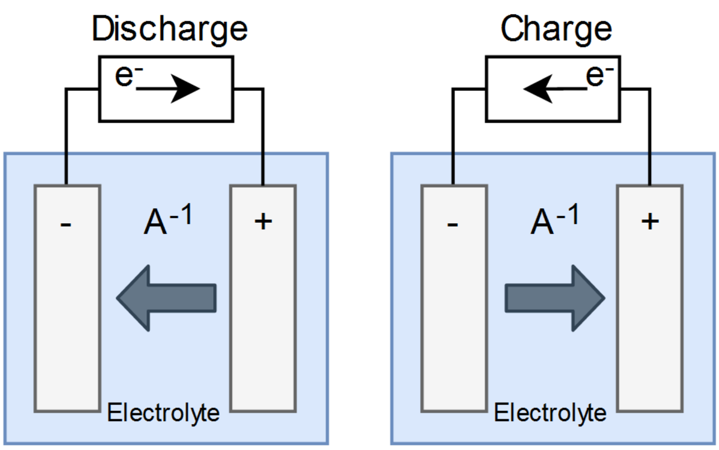


Figure 4.4.1: Working principle of electrochemical storage.

Chapter 5

Energy storage technologies

The fundamental understanding of the physical principles that govern energy conversion and storage technologies have been investigated. This chapter further expands on this knowledge by investigating how these principles are applied to energy storage technologies. The aim of the chapter is to provide an understanding of how such technologies work, what components they are made up of and what functions these components provide to the system. Moreover, comparing the technologies can provide information on their strength and weaknesses, which can be used to identify where they are the most applicable and efficient. The data collected can be found in Appendix A.1, table A.1.1 and A.1.2.

5.1 Electromagnetic storage

Superconducting Magnetic Energy Storage (SMES) uses cryogenically cooled superconducting coils to store energy in magnetic fields, see figure 5.1.1. Once the coil is charged there is very little decay, and the energy can be stored almost indefinitely. However, the self-discharge rate depends on how cold the coils are stored, which for modern SMES systems vary between 30-40 Kelvin, and can potentially be as low as 4 Kelvin. SMES loses the least amount of electricity during a charge/discharge cycle than any other storage solution, with a round-trip efficiency of over 95%. However, the refrigeration unit has a high power demand, and the superconducting wire is costly. Therefore the SMES system is mostly used to improve power quality with short term storage (EERA, 2019).

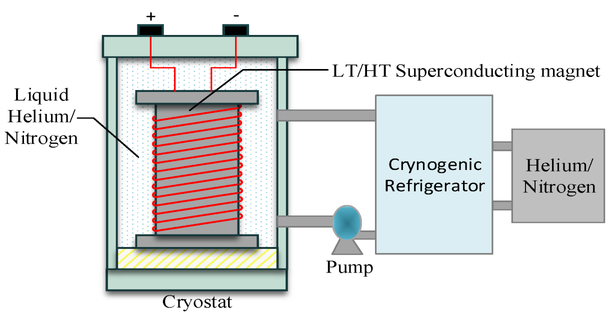


Figure 5.1.1: Working principle of a SMES system (Mutarraf et al., 2018).

5.2 Electrochemical storage

There are many different types of electrochemical batteries like flow cells, galvanic and electrolytic cells. It is important to consider the batteries characteristics when choosing which type that is most suitable for an application. To be applied to a storage system the batteries have to be rechargeable, called secondary cells. Other characteristics that may be interesting to consider are energy density, self-discharge rate, resilience and environmental effects.

5.2.1 Supercapacitors

Electrochemical Capacitors (EC) are composed as illustrated in figure 5.2.1. Two porous electrodes soaked in a liquid electrolyte are separated by a membrane that allows ions to flow through it. When a voltage is applied to the electrodes the ions in the electrolyte form an electric double layer of opposite polarity than the electrode. This separation of charge is how the energy is stored. The choice of electrodes highly influences the characteristics of the capacitor. An EC can typically reach energy efficiencies of around 92% with an annual efficiency decrease of 0.14%. The capacitor has a high response time of 0.016s, and is therefore suitable for grid stability (Mongird et al., 2019)(Victanis, 2020).

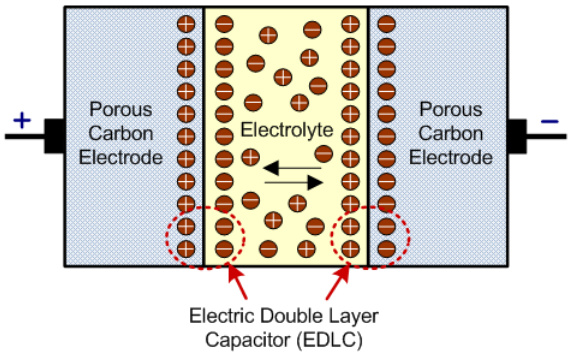


Figure 5.2.1: Working principle of a EC (Molina, 2010).

5.2.2 Hydrogen-bromine flow battery

The key difference between flow batteries and regular batteries is that the electrolytes are stored in a tank outside the cell stack, see figure 5.2.2. This enables the power and energy produced by the system to be scaled independently by modifying the cell stack and the amount of electrolyte stored in the tanks (Haile, 2015).

During operation, the electrolytes are pumped to the cell-stack. The cell stack separates the positive and negative electrolytes by using an ion-selective membrane. This membrane prevents the transfer of reactant materials. However, the ions which maintain charge neutrality can pass through. Electricity can then be produced or stored, with the same principle as described in figure 4.4.1.

Hydrogen-bromine is a flow battery that provides a low cell voltage, but a high energy density compared to dry cell batteries such as Lead-Acid. This type of flow battery is

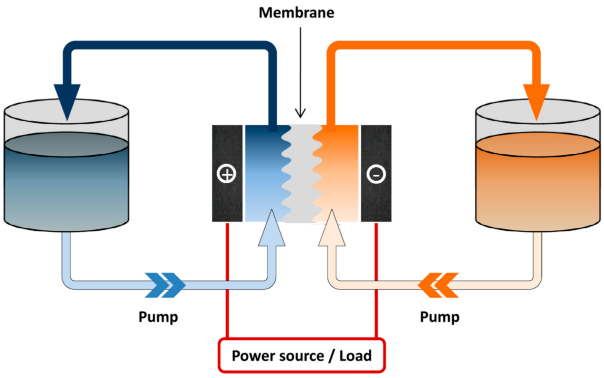


Figure 5.2.2: Working principle of a flow battery (Pan & Wang, 2015).

best suitable in situations that require a long discharge duration of 6 to 12 hours. The flow battery is very durable and can last for 10 to 20 years. It can be fully charged in a short amount of time and provides higher design flexibility than solid-state batteries. Hydrogen-Bromine has an energy efficiency of 70%, and an annual efficiency decrease of 0.4% (Mongird et al., 2019).

Although bromine is a naturally occurring element, it does pose an environmental hazard. It is toxic for the local ecosystem and can have very negative effects on animals such as algae, daphnia, fish and lobsters. However, the system tolerates overcharging and can operate at ambient pressure of 25 °C. This reduces the risk of it being damaged. Hydrogen-bromine flow batteries are preferred over other flow batteries like Iron-Chromium and Vanadium due its higher energy density and efficiency, better resilience and safety, and a lower total cost (Haile, 2015)(Lenntech, 2020).

5.2.3 Lead-Acid battery

Lead-Acid is the earliest type of rechargeable battery. The energy is stored in the potential difference between pure lead and lead dioxide, and the aqueous sulfuric acid between them. The battery produces energy by reacting H^+ ions in the acid and O_2^- ions from the lead dioxide, producing water molecules, see figure 5.2.3 (Mongird et al., 2019).

Although it has a rather low energy density, both in terms of weight and volume, it has a very high power density. The lead-acid battery is capable of delivering high surge currents compared to other battery types and is very cheap to produce. For a storage system, these batteries would therefore need to be used in conjunction with other technologies that are more suitable for large scale storage.

The battery is highly recycled compared to other battery technologies. However, lead can be extremely toxic and dangerous to the environment. An overcharge of the battery also poses the risk of explosion, as it releases hydrogen and oxygen to the atmosphere. Lead-Acid batteries also have a relatively low life span compared to other storage technologies.

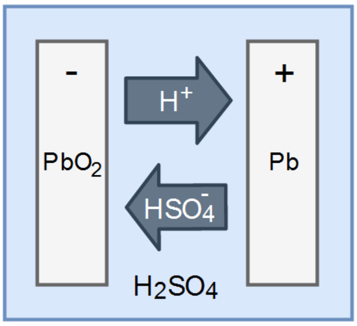


Figure 5.2.3: Working principle of a Lead-Acid battery.

5.2.4 Lithium-ion battery

Lithium-ion batteries are dry-cell batteries that utilize the most electropositive element, lithium, to achieve a very high energy density compared to other battery technologies. Lithium is a very light metal, making it an excellent battery material. Lithium-ion batteries have a lithiated metal oxide as a cathode and a layer of graphite or silicon wafer as an anode. The electrolyte used in such batteries is dissolvent lithium salts in organic carbonates. During charging the lithium ions on the cathode side move to the anode side and form a lithium-ion between the carbon layers of the graphite. During discharge, the process is reversed. Lithium-ion batteries are very expensive compared to other technologies and may explode or catch fire if damaged (Gustavsson, 2016).

5.2.5 NaS battery

In a sodium sulphur battery the electrodes are made from molten sulfur and molten sodium, and therefore have a very high operating temperature of over 300 °C. The molten electrodes are separated by a solid ceramic electrolyte. The working principle of a NaS battery is illustrated in figure 5.2.4. These batteries have long life cycles and high charge efficiency of 75%, with an annual decrease of 0.38%. However, the battery is very corrosive, operates at a high temperature and is costly to produce (Mongird et al., 2019)(Gustavsson, 2016).

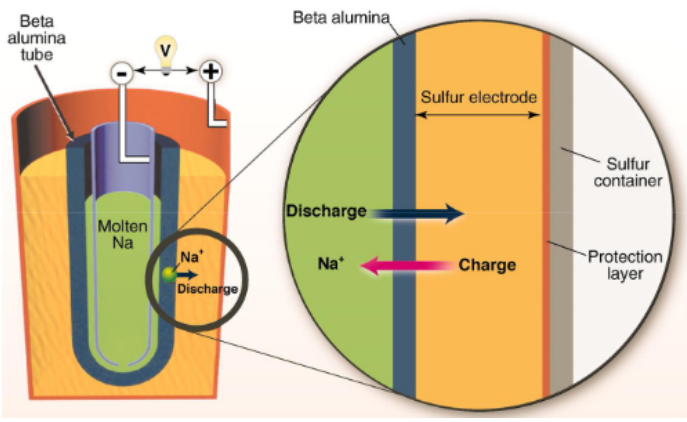


Figure 5.2.4: Working principle of a NaS battery (Wang et al., 2017).

5.3 Power-to-Hydrogen

Hydrogen is the most common element in nature and has been deployed as an industrial gas for decades. Stored hydrogen can hold large amounts of energy that can be used directly as fuel, or to generate electricity with very low emissions. However, compressing the hydrogen to achieve a suitable volumetric energy density is a challenging and energy-consuming process.

5.3.1 Conversion technologies

An electrolyser consumes electricity and stores is it the chemical bonds of an energy carrier. For hydrogen production, the general concept is to apply an electrical current to a pair of conductive electrodes placed inside a dissolution of ions. The cathode will attract the positive ions and the anode attracts the negative ions. The electrical current is providing electrons to the hydrogen ions, creating hydrogen. The oxygen ions are releasing electrons at the anode, creating oxygen. Some common electrolysers are Alkaline Electrolyse (AEL) and Proton Exchange Membrane Electrolyser (PEM) (Haile, 2015)(Kumar & Himabindu, 2019).

A fuel cell is a device that converts energy from chemical bonds to electricity. When the energy is needed, the fuel cell produces electricity from the hydrogen by consuming oxygen from the atmosphere and create water, see figure 5.3.1. A fuel cell therefore reverses the process of an electrolyser. The most common fuel cells are Alkaline Fuel Cell (AFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). Table A.3.1 in Appendix A.3 provides some of the characteristics of common electrolysers and fuel cells (Haile, 2015)(Kumar & Himabindu, 2019).

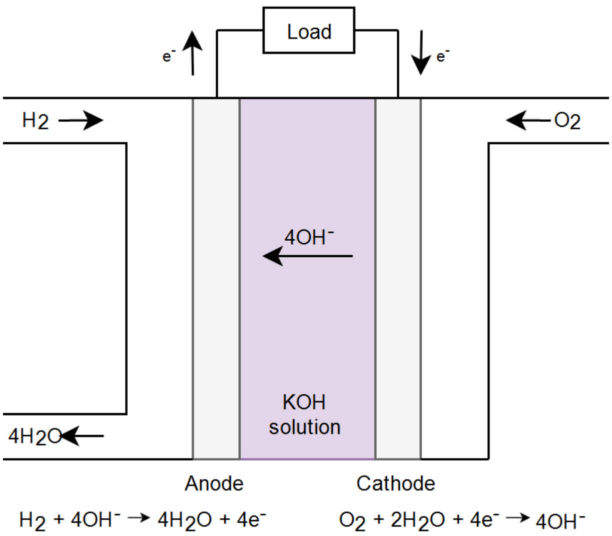


Figure 5.3.1: Working principle of an alkaline fuel cell.

5.3.2 Production

The electricity generated at the production site can be transformed into hydrogen through the electrolysis of seawater. There are several options on how to perform this electrolysis, ranging in efficiency and pollution. The most common hydrogen generator is alkaline. An illustration of the working principle of this electrolysis is provided in figure 5.3.2.

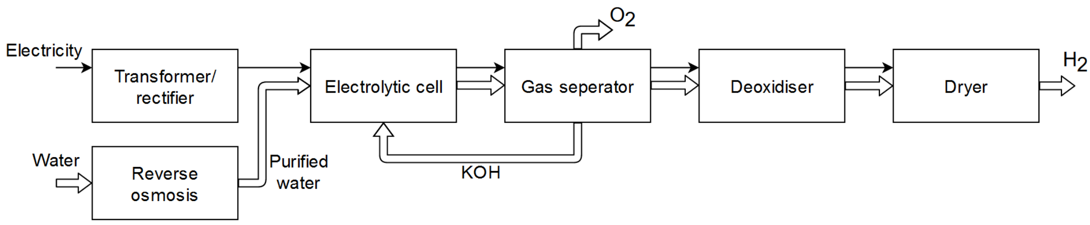


Figure 5.3.2: Flow diagram of alkaline electrolysis.

This method has an efficiency of 70% and operates from 30-80 °C. Two litres of water can produce hydrogen with the energy of one litre of gasoline. The round-trip efficiency of hydrogen using electrolysis and a fuel cell is 34-44%, depending on how the hydrogen is stored. The oxygen formed as a bi-product from the electrolysis can be stored and used for pure combustion of the fuel in a combustion engine (Blanco & Pérez-Arribas, 2017).

There are several other methods of producing hydrogen. However, these methods are considered outside the scope of the project for various reasons. Photobiological and photoelectrochemical water splitting is an environmentally friendly method that uses biological microbes and sunlight to produce hydrogen. This method will not take advantage of the excess energy produced by intermittent energy sources and is therefore not relevant to the study. Methods using thermochemical conversion requires fossil fuels, and will not be further investigated (HydrogenEurope, 2020a).

5.3.3 Physical based storage

Hydrogen storage is divided into material-based and physical-based methods, see figure 5.3.3. The physical approaches are the most conventional and involve storing hydrogen as a gas or liquid. Hydrogen gas stored in steel tanks can be compressed to increase its energy density. An energy density of 833 Wh/L is achieved if the gas is compressed to a pressure of 35 MPa. Increasing the pressure to 70 MPa provides an energy density of around 1250 Wh/L. The pressurization process requires 9 to 12% of the energy made available in the form of hydrogen to perform the compression.

Hydrogen can also be stored as a liquid, increasing the energy density significantly to around 2200 Wh/L. However, the solution requires a cryogenic temperature of -253 °C and is a lot more complex and costly. The liquid storage solution requires approximately 30% of the energy made available in the form of hydrogen (HydrogenEurope, 2020b) .

When the energy is required, the hydrogen is either converted back into electricity by using a fuel cell or used directly as a combustion fuel. Table A.3.1 shows that SOFC and MCFC requires fossil fuels that may not be available at the site, and is toxic to

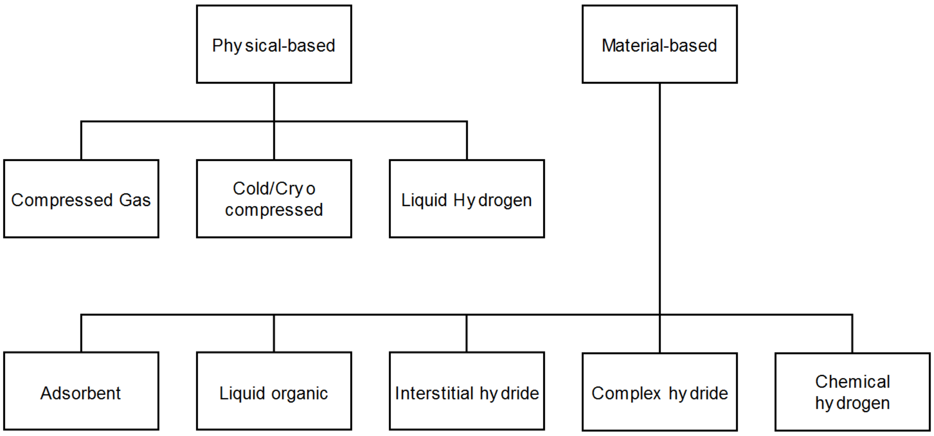


Figure 5.3.3: Hydrogen storage methods.

the environment. PEMFC or AFC seems more suitable as a hydrogen fuel cell. If the hydrogen is used for combustion it needs to be transported to shore, either by using ships or pipelines.

5.3.4 Material based storage

Material based hydrogen storage is the practice of storing hydrogen in solids, liquids or on surfaces of other materials. This method is in early development and the performance achieved is often not superior to physical-based hydrogen storage (Blanco & Pérez-Arribas, 2017).

Rechargeable hydrides utilize hydrogens property of reacting with transition metals. Given the right temperature and pressure conditions, this reaction is reversible, and a mass of metal can charge and discharge hydrogen atoms almost indefinitely. There is no leakage and the solution can operate under moderate pressure. It is not harmful to the environment, safe to operate and provides a higher energy density than liquid hydrogen. However, due to low hydrogen retention levels, the storage solution does have a substantial weight.

Storing hydrogen in carbon nanotubes provides an energy density twice the amount of liquid hydrogen storage. It is a lightweight solution with high mechanical resistance and therefore low maintenance. However, there is a significant cost involved, and the storage solution is only efficient at -192 °C.

5.4 Power-to-Methane

Methane is the most common Synthetic Natural Gas (SNG). The hydrocarbon has a simple molecular formula and can be produced from hydrogen. After electrolysis, the hydrogen is reacted with carbon dioxide in a Sabatier process, creating methane and water. See chemical formula 5.1. The Sabatier process operates at about 300-400 °C (Vogt et al., 2019a).

The methanation process absorbs carbon dioxide from the atmosphere. However, the emissions will be net-zero if the carbon dioxide released in the methane combustion is allowed to escape. Recycling the carbon dioxide can boost the Sabatier process to increase the round-trip efficiency of SNG energy storage.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{5.1}$$

Methane storage and transportation is very mature in the industry, and the technology is more established than hydrogen. Storing energy as methane is also reported to be as much as ten times cheaper than hydrogen. However, it has a lower energy density at 15 444 Wh/kg, and the Sabatier process reduces the round-trip efficiency of SNG storage to 30-38%, see figure 5.4.1 (Thurber, 2020). Methane is also dangerous to the environment, and should not be leaked into the atmosphere. A PAFC fuel cell can be used to convert the methane back into electricity, or the methane can be used directly as fuel to substitute costly diesel in transportation vehicles.

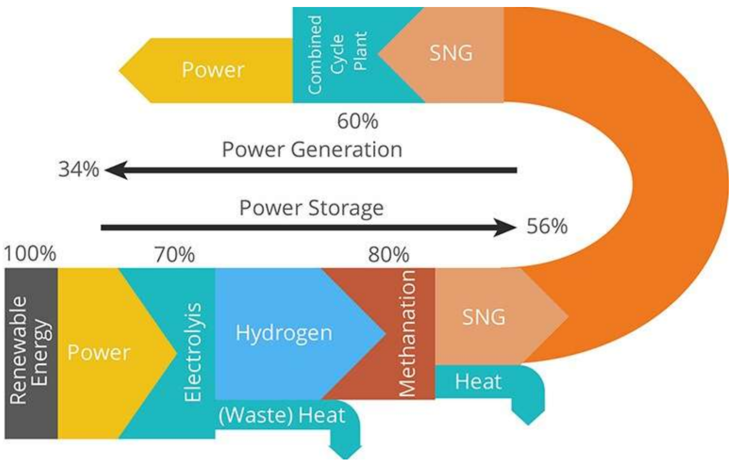


Figure 5.4.1: Methane energy storage round-trip efficiency (Vogt et al., 2019b).

5.5 Power-to-Ammonia

The hydrogen can also be used to produce ammonia. After the electrolysis, the hydrogen is combined with nitrogen from the atmosphere under high temperature and pressure, see figure 5.5.1. Reaction conditions are typically 200 to 400 bar, with temperature ranging from 400 to 650 °C (ESRU, 2020).

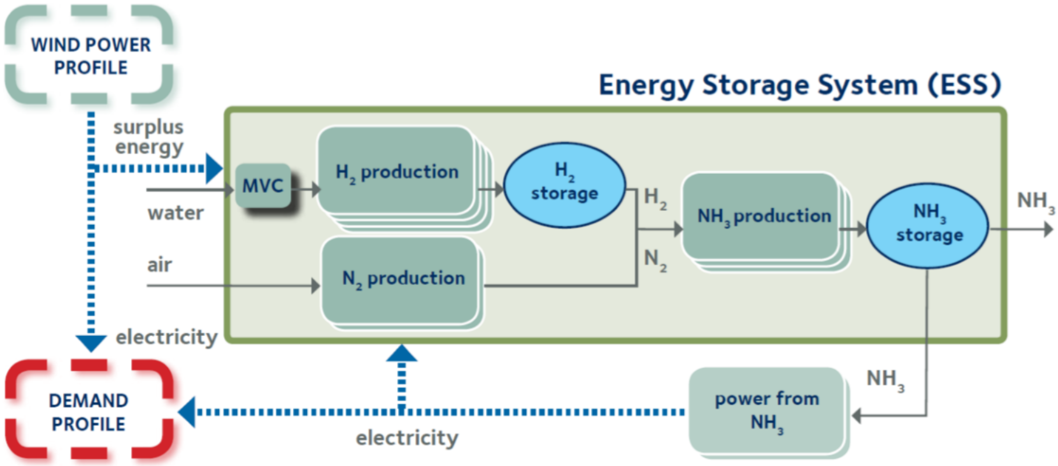


Figure 5.5.1: Ammonia production flow chart (ESRU, 2020).

Unlike hydrogen and methane, ammonia has a much higher boiling temperature at -33 °C. The ammonia is therefore easier to store at 25 °C and 10 bar. Ammonia is a good hydrogen carrier in terms of volumetric energy density, with a density of 3194 Wh/L or 6250 Wh/kg. Being one of the most produced chemicals in the world it is already well established in the industry. With a lot of experience handling the toxic gas there is less risk to the environment, as leaks are less likely to occur. If a leak occurs the ammonia will dissipate quickly, and only affect people in its immediate surrounding. The ammonia can be used directly as fuel without any release of carbon dioxide. The NOx emissions can be avoided by using a lower combustion temperature. Ammonia has a round-trip efficiency of 23-41%.

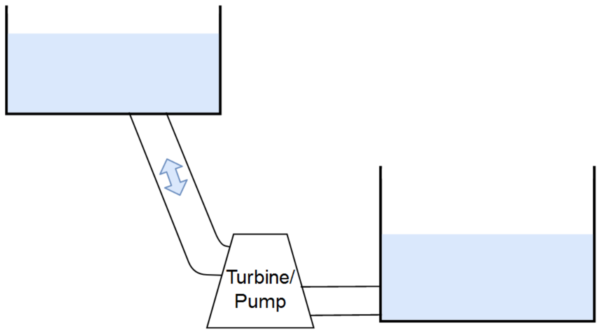
The chemical reaction creating ammonia is provided in equation 5.2. Comparing the chemical formula of methane and ammonia there are some interesting observations. One mole of CO_2 yields one mole of methanol, which only uses two-thirds of the available hydrogen, as the rest is lost to water. However, one mole of N_2 produces two moles of ammonia, without wasting any hydrogen. Given that the electrolysis to produce hydrogen is the most energy-intensive of the synthetic fuel process, the hydrogen waste of methanol is a significant energy burden (Brown, 2017).

$$3H_2 + N_2 \rightarrow 2NH_3 \tag{5.2}$$

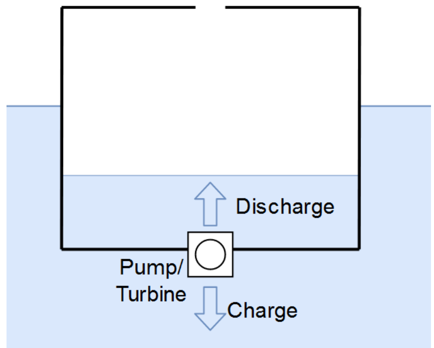
The ammonia can be converted back into electricity by first converting it back into hydrogen using thermal decomposition and then using a conventional hydrogen fuel cell.

5.6 Hydromechanical

Hydroelectricity generates electricity using turbines that are pushed by the movement of water. This could either be hydroelectric dams with reservoirs that are able to reduce or increase their power generating by adjusting the amount of water passing from one reservoir to the other. Pumped-Storage Hydroelectricity (PSH) is based on the same principle, but is a lot more suitable for energy storage. It is capable of using surplus energy to pump water back into the upper reservoir, see figure 5.6.1a. It is the oldest large scale energy storage solution and a well-established practice. Over 90% of the worldwide energy storage capacity is provided by PSH facilities, some of them reaching a round-trip efficiency of above 80%. The technology has a very long lifetime, but a low energy density at 0.28 kWh/m^3 at a reservoir elevation of 100 m (Letcher, 2016).



(a) Working principle of a PSH system.



(b) Working principle of buoyancy energy storage.

Figure 5.6.1: Hydromechanical energy storage systems

Although this method is currently only developed on land, its basic principles can be applied offshore. The concept of using turbines and pumps to move and store water is applicable in a wide range of configurations. One of them a buoyant energy solution that utilises the buoyancy of a floating structure to store energy. By letting water into the structure through a turbine it can generate electricity. A pump can push the water out of the structure with surplus energy. An illustration of the concept is provided in figure 5.6.1b.

5.7 Compressed air

Compressed Air Energy Storage (CAES) stores energy using pressurized air in a storage tank. By releasing the air through a turbine it generates electricity. In times of low demand, the excess energy can be used to pump air back into the pressure tank. By laws of thermodynamics, the air temperature will increase as it is compressed and decrease when expanded. If the energy from the heat generated can be stored and used during expansion, the efficiency of the system can improve significantly. The CAES system can perform the cycle using adiabatic or near-isothermal processes. The adiabatic CAES systems have a typical round-trip efficiency of 70-80%, and the near-isothermal can be expected to reach as high as 90% round-trip efficiency (Elmegaard & Brix, 2011).

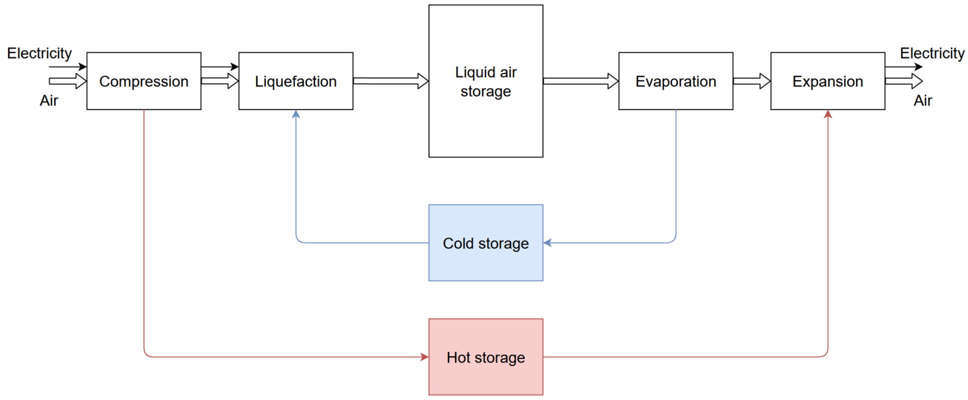


Figure 5.7.1: Working principle of a LAES system

The air can also be stored as a liquid at cryogenic temperature, known as Liquid Air Energy Storage (LAES). The principle of the solution is the same, however, more energy can be stored as the liquid has a higher energy density than compressed air, see figure 5.7.1. The air is cooled to a cryogenic temperature of -190 °C. The liquid air can then be stored with a density of more than 700 times the density of ambient air. The round-trip efficiency of the LAES solution is around 70%, by reusing air cooling and compression heat.

5.8 Flywheel

Flywheel Energy Storage (FES) stores energy as rotational energy by accelerating a flywheel to a high speed. Due to the conservation of energy the rotational speed decreases as the energy is extracted from the flywheel using a generator, see figure 5.8.1. The most common flywheel uses carbon fibre rotors suspended by magnetic bearings in a vacuum. This reduces drag on the rotor, providing a round-trip efficiency of over 90%. The system is very low maintenance and has a specific energy of 100-130 Wh/kg. However, the system is up to five times more expensive than a flywheel using mechanical bearings (Amiryar & Pullen, 2016).

Although the FES systems are the quickest to charge up to their capacity, they also have the fastest self-discharge than any other energy storage system. Therefore the most popular use cases are when high power bursts are required, like voltage regulation.

5.9 Solid gravitational

Gravitational energy storage stores and release energy by changing the altitude of solid masses, see figure 5.9.1. The potential energy is increased by using a winch that elevates the mass. The energy can be recovered by dropping the mass and using a generator to create electricity. Such a system has the potential to generate electricity with a one-second warning, making it useful to balance load surges in the grid. The round-trip efficiency depends on the set-up of the system, but can be as high as 85%. The concept has been under development since 2013, and several methods have been proposed. Among them is

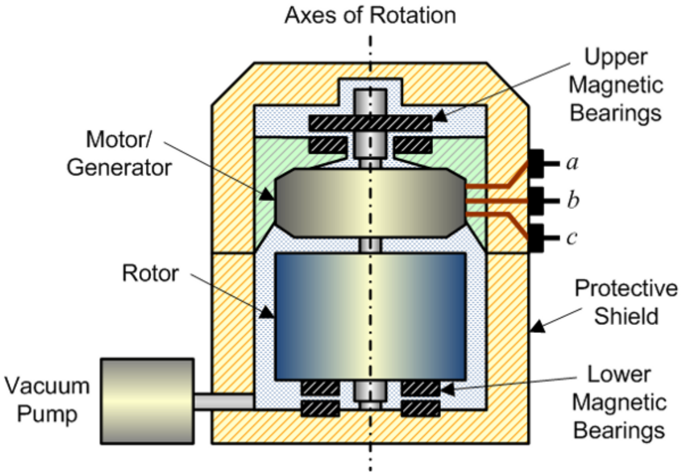


Figure 5.8.1: Working principle of a FES system (Molina, 2010).

the use of cranes and rails to slide weights up and down, and exploiting the deep ocean to lower and raise weights from the seabed to the ocean surface (Rathi, 2018).

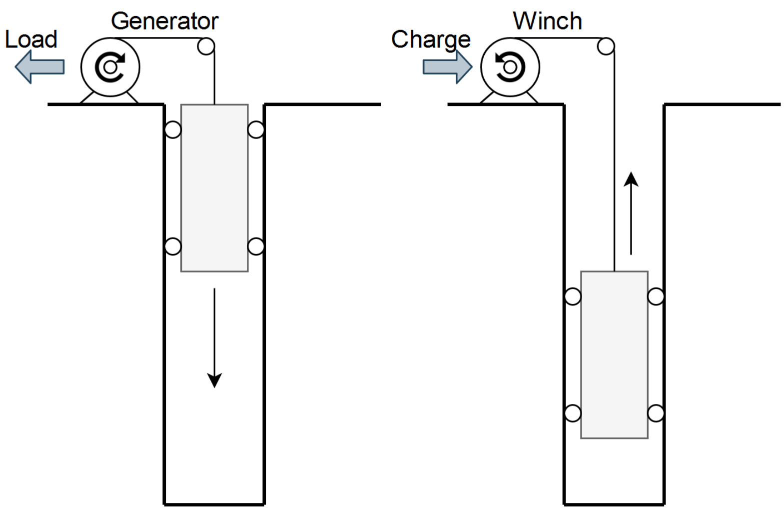


Figure 5.9.1: Working principle of gravitational energy storage.

5.10 Electric thermal energy storage

Electric Thermal Energy Storage (ETES) uses surplus energy to heat volcanic stones to over 600 °C. By the use of water and a conventional steam turbine, that heat can be converted back into electricity with a round-trip efficiency of 45%, see figure 5.10.1. With a heat storage efficiency of 95%, the system can store the energy long term. It can also be used for grid stability. The system is easy to maintain as the components are readily available, with 80% of them being off-the-shelf (Siemens, 2020).

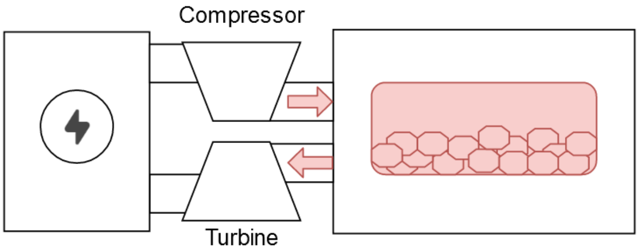


Figure 5.10.1: Working principle of a ETES system.

5.11 Pumped-heat electricity storage

Pumped-Heat Electricity Storage (PHES) uses a reversible heat-pump system to store energy as a temperature difference between two heat stores, see figure 5.11.1. The inert gas Argon transfers the heat through the system, warming up the heat store and cooling down the cold store using convection during charging. The system uses surplus energy to drive a compressor, adding heat to the system. When the energy is required the gas flow is reversed to obtain the electricity with a turbine. A PHES system has a round-trip efficiency of 70-75% and can be used for both long term storage and to improve grid stability (EASE, 2020).

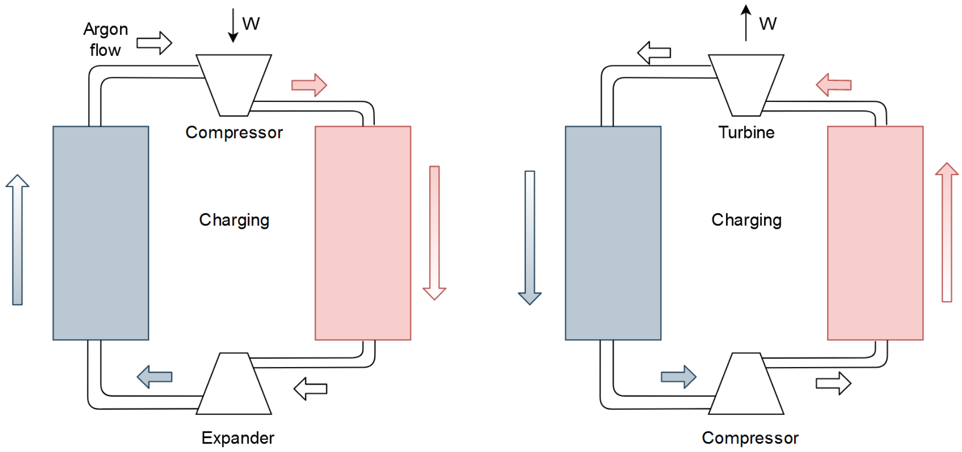


Figure 5.11.1: Working principle of a PHES system.

5.12 Latent heat thermal energy storage

Latent Heat Thermal Energy Storage (LHTES) utilises the energy released from a material that is changing its phase. It is a promising method due to its high energy storage density and near-isothermic phase changes. A Phase Change Material (PCM) is used as an energy carrier and these often have a high latent heat. An example of an LHTES system is the vaporization of water, using a steam accumulator (Letcher, 2016).

Chapter 6

Energy distribution

The energy needs to be transported over large distances with rough conditions. This chapter will introduce the energy distribution technologies that are capable of performing this task. The chapter aims to provide a basic understanding of how the different distribution technologies operate and how they affect the energy storage system. Some cost comparisons between the technologies will also be provided. However, how these costs affect the offshore energy storage system is not established as the supply chain of energy has not been researched.

6.1 High voltage transmission

As of today, renewable offshore energy production sites are transferring their energy through underwater high voltage transmission lines. Low voltage underwater cables direct the produced power towards a substation on site, that converts the electricity to High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC) in order to transport the electricity to shore. The voltage conversion is required to reduce the amount of lost energy during transmission (Mueller, 2019).

The HVAC is the preferred technology as this is a cheap and simple solution. However, as the production sites are moved further offshore the HVAC transmission experiences a significant loss in energy. The subsea HVDC cables are cheaper and can provide a higher current, but the power converters needed both offshore and onshore is a significant cost. An HVDC system is also much more complex and may cause control interaction issues with other control systems. However, as a result of the cheaper cable, HVDC systems may be the less expensive option for far-offshore production sites, as well as providing a higher energy transmission efficiency. Figure 6.1.1 illustrates the break-even distance between an HVDC and HVAC system.

The cost of these systems can be estimated from two factors. Distance from shore, and energy production capacity. A production site that is moved far away from shore will have a higher cost with respect to the cable installation process. There will also be an increased energy loss and a higher likelihood of a fault along the cable line. The necessary

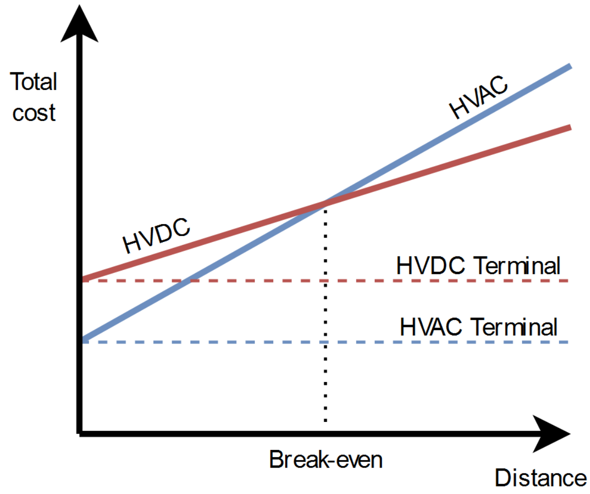


Figure 6.1.1: Cost comparison of HVAC and HVDC systems.

capacity of the site can be based on the local power demand and be used to estimate the cost of the substation.

With a direct transmission line, the opportunity for an onshore energy storage solution is made possible. It is important to keep these costs in mind, as an onshore energy storage system is much cheaper than an offshore solution. It requires less innovation and is less complex. Therefore, if the storage system does not take advantage of the offshore environment and transmission lines are used as transportation, an onshore energy storage system may be more suitable. This is important to consider when deciding which offshore production sites that can benefit from an offshore energy storage system, contrary to an onshore storage system.

6.2 Shipping

If a chemical is produced as an energy carrier it needs to be transported to shore. Given that the chemical is not converted back to electricity using a fuel cell at the production site, high voltage transmission cables can not be used. The chemical can rather be transported as an energy carrier by using ships. The maturity and costs of this transportation method depend on which chemical that is transported (IEA, 2020).

Ammonia and methane are already well-established in the industry. The transportation and storage of these chemicals is a mature technology, as they are already traded inter-country using ships. Implementing this method to distribute methane and ammonia from an offshore production site will therefore not be challenging. There may also be an opportunity to have ammonia or methane driven ships to transport the chemicals. Methanol engines already exist and have been deployed commercially, although at a small scale. Ammonia engines are still in the early development phase. Since there is a general focus on reducing emissions, utilizing the clean energy produced at the site to power the ships would help reduce the emissions from the offshore storage system.

Hydrogen ships will also require more research and testing before being commercialised.

Both liquid and compressed gas hydrogen storage are well established in the industry, but applying these technologies to ships is an immature technology. Both capital expenditures and operational costs can be expected to be higher than high voltage transmission lines. However, this transportation method enables the chemical to be sold in physical form, or converted back into electricity, depending on what is most profitable at any given time. The chemicals can also be transported to other parts of the world where they can be sold for a higher price. This increase in profit may overcome the increase in capital and operational expenditures. Moreover, unlike the required capital expenditure for the construction of the transmission lines, the transportation ships can be chartered, thus not requiring an initial investment from the production field owner at all.

6.3 Pipeline

Using pipelines to transport chemicals is a well-established technology due to the oil and gas industry. There are several pipelines transporting hydrogen in gaseous form in Europe and America, reaching a combined length of over 4000 km. A pipeline can also be used as storage, as the diameter of the pipe over the length creates a significant volume. This may diminish the need for storage at the offshore production site. Moreover, this transportation system allows the chemical to reach shore instantly when needed, instead of having to be transported by a ship. The capital expenditures of such a solution can be expected to be significantly higher than for ships, however, the operational costs are lower. Although the maintenance costs are high, the cost of transporting the hydrogen would be very low (IEA, 2020).

The capital expenditures could be reduced if there is an already established network of pipelines at the site, as hydrogen can be mixed with Liquid Natural Gas (LNG) to a certain concentration. However, each pipeline network would require its own research to calculate how much hydrogen that can be mixed with the LNG, and therefore extensive and costly studies would need to be performed. Methane, ammonia and hydrogen pipeline technologies are mature in the market.

Chapter 7

Technology readiness level

The technologies maturity is important to establish as it can be used as a measure for how much innovation and research that is necessary to commercialize the technology. Moreover, a technology that is new to the market have less data regarding its efficiency and might be less reliable than mature technologies. These uncertainties are important to consider when developing an energy storage system.

The Technolgy Readiness Level (TRL) is a scale that represents how far a new technology is in its development process. The TRL value for each technology is determined based on a systematic analysis and ranges from 1 to 11. The value can indicate how well established the technology is in the current market, and if the solution is ready to be implemented. The TRL values from 1 to 11 and their respective definition can be found in table 7.0.1 (IEA, 2020).

Table 7.0.1: TRL value definitions (IEA, 2020).

TRL segment	**TRL value**	**Definition**
Concept	1	Initial idea
	2	Application formulated
	3	Concept needs validation
Small prototype	4	Early prototype
Large prototype	5	Large prototype
	6	Full prototype at scale
Demonstration	7	Pre-commercial demonstration
	8	First of a kind commercial
Early adoption	9	Commercial operation in relevant environment
	10	Integration needed at scale
Mature	11	Proof of stability

In this report, the TRL values assigned to the energy storage technologies will be taken from the IEA *ETP Clean Energy Technology Guide* released in July 2020 (IEA, 2020). This guide provides a technology maturity analysis for over 400 technologies related to emission reduction. The technologies not listen in this guide will be assigned a TRL value based on other cited sources. The TRL values for the technologies mentioned in this report can be found in appendix A.2, table A.2.1.

Part III

ENGINEERING DESIGN RESEARCH

Chapter 8

Engineering design

Design projects can be categorized into three groups based on the degree of innovation involved. Routine design is design processes that involve the customization of an existing design, where the main modules and their interrelationships are already known. Innovative design incrementally adjusts the boundaries of an existing design, while a novel design is a completely new design that is not based on any previous project. (Goel, 1997)

An offshore energy storage system can be regarded as an innovative design. The industry has a lot of experience with energy storage, but implementing it offshore is a modern problem and finding an efficient solution can be resource-intensive. To maintain the cost-competitiveness in the energy market the development process of the energy storage system must be able to find optimal solutions efficiently to reduce costs. To be able to create such a design process the different engineering design methods will be investigated to establish their benefits and downsides. However, before doing so the challenges of designing large and complex systems must be established.

8.1 Economy of a design process

A design process can be categorized into different phases, ranging from the conceptual design to a detailed finished product. These phases are often defined by their designated tasks, with the goal of increasing the detail of the design from one phase to the next.

As the project evolves through the design phases there is an inverse relationship between design freedom and design knowledge, see figure 8.1.1. Although the ability to make changes to a design is high at the early stages of a design process, the knowledge about the design is low. Hence, it is difficult to understand which changes that will have a positive impact on the design.

Design changes are always possible to apply to a design, but the costs of implementing the change increase with the amount of detail and complexity. This is due to the bounds and constraints that are applied to the system when a design decision is made. Making changes at a late stage of a design process also implies an inferred cost of discarding previous work. 80% of the life cycle cost is determined during the conceptual design phase, and increasing the knowledge in this early stage can be significant to the quality of the final design (S. O. Erikstad, 2007).

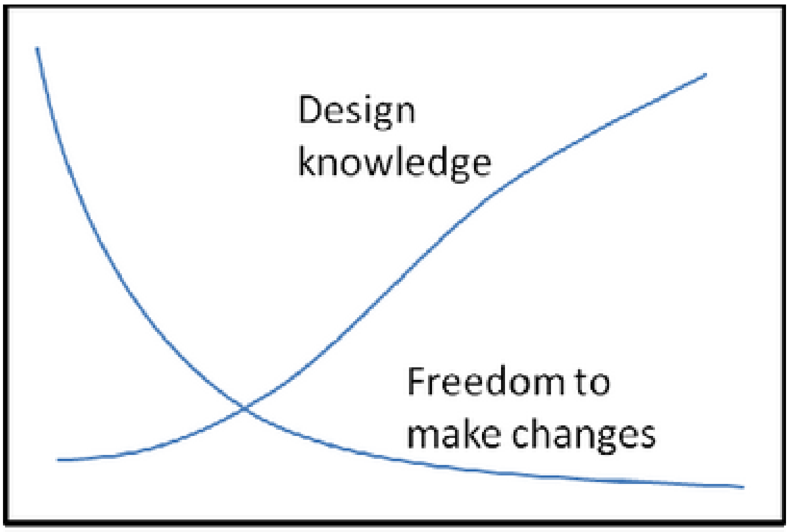


Figure 8.1.1: Design freedom and design knowledge relationship in a design process (S. O. Erikstad, 2007).

8.2 Complexity of a system

Complexity theory is the study of complex systems and aims to define the complexity of a system, often in an attempt to make the design process of complex systems manageable. However, complexity is a broad term that has many different interpretations, depending on the scientific field. In systems engineering, three seminal works can be used as a basis for a complexity definition (Gaspar et al., 2012).

Herbert Simon proposes that the complexity of a system is dependent on how it is described. As such, Simon introduces a hierarchical approach to managing the complexity of a system by decomposing it into subsystems until it can be understood. This approach is widely used in engineering design, however, it does not address to what degree a system should be decomposed. It is therefore often used in conjunction with another complexity theory introduced by Andrej Kolmogorov, called information theory. Kolmogorov argues that the amount of information that is required to describe a system or subsystem determines its complexity. From this description, it is derived that the hierarchical system should be decomposed to the point where the information required to describe its subsystems is manageable. Independence between the subsystems contributes to a lower complexity, as less information is required to describe them.

The third work is introduced by Nam-Pyo Suh and called Axiom theory. The theory describes complexity as the amount of necessary information required to describe a system and the number of dependent elements within that system. The theory provides a method of decreasing the complexity by introducing two axioms called the information axiom and independence axiom. The information axiom is similar to information theory and states that minimizing the information required to describe a system will lower its complexity.

The independence axiom further states that each subsystem should be independent of each other. Complexity theories such as these are often hard to implement for the design of large and complex systems, as it is difficult to find subsystems that satisfy both axioms simultaneously. However, engineering design methods use these theories as a basis with the aim to fulfil the requirements as good as possible in order to minimise the complexity of the system.

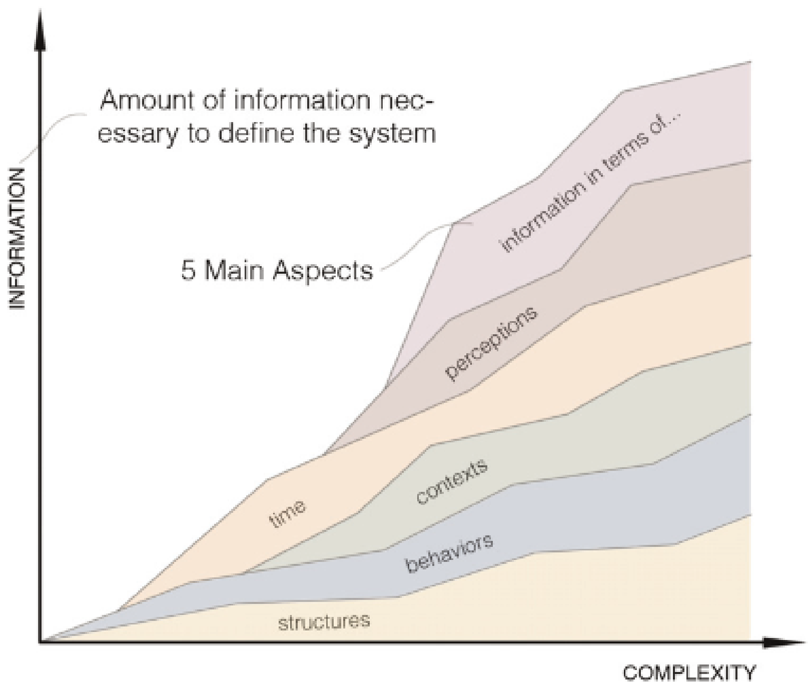


Figure 8.2.1: Complexity increases with the amount of information in a design (Gaspar et al., 2012).

Figure 8.2.1 illustrates the link between the amount of information used to describe a system and its complexity. According to Rhodes and Ross, the information can be divided into five main aspects. In engineering design, the structural and behavioural aspects are most focused on, as the other aspects are defined by uncontrollable factors such as market developments and regulations. However, the remaining aspects should not be ignored, as doing so may exclude important information.

Chapter 9

Design of complex systems

According to established complexity theory, the complexity of large systems is due to the amount of information necessary to describe the systems and the high number of dependent elements they consist of. The lack of design knowledge at the beginning of a design process provides a bad foundation for decision making, and changing a design at a later stage in the design process is more difficult and costly, as the amount of details in the design increase. This chapter investigates how traditional and modern engineering design methods aim to solve these challenges and how the use of a product platform can enable an efficient design method for offshore energy storage systems.

Engineering design methods aim to minimise the complexity of the design process. In general, the design theories divide the design process into three domains, needs, function and form, and describes the mapping between these domains, see figure 9.0.1. There are many different engineering design methods that apply a variation of design theories to achieve a solution. These methods have different characteristics and what is deemed efficient for one design problem, may be inefficient for another. Finding an optimal engineering design method for offshore energy storage will help maintain the cost-competitiveness by providing optimal solutions in a time-efficient manner (Pahl & Beitz, 1988).

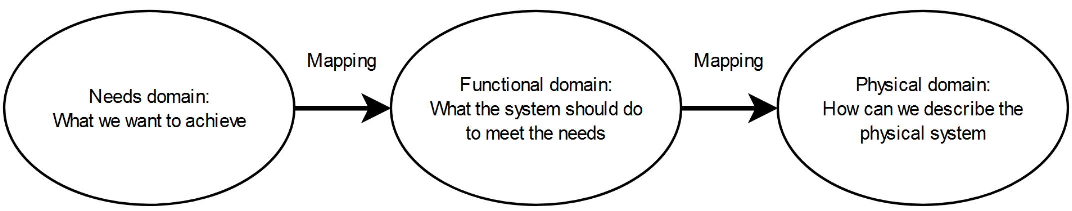


Figure 9.0.1: Mapping between needs, function and form domains in engineering design

9.1 Systems engineering

Systems engineering refers to the process of developing something that is too complex to be designed as a single monolithic entity and must rather be designed as a system consisting of several other subsystems or components. The size and complexity of the system increase the number of stakeholders that must cooperate in the design process. The project needs from these stakeholders are often conflicting, and favouring one over the other may lead to solutions that are inefficient and poorly optimized with respect to the customer requirements. For example, favouring the needs of the engineer specialists may lead to an efficient design that is not within the budget of the project. Systems engineering aims to guide the development process to find and maintain a balance between these needs, ultimately ensuring that the solution provided from the design process meets the customer requirements to a substantial degree. Such complex systems are designed using engineering design methods (Shea, 2019).

9.2 Traditional design approaches

Vessel design has traditionally been based on an iterative process, as illustrated by the ship design spiral in figure 9.2.1 that was introduced by Evans (1959) (Evans, 1959). Today, many of the engineering design approaches are still based on this spiral, and rely on this iterative and repetitive procedure. The traditional way to develop these designs has been to use an existing vessel and incorporate the necessary changes to fulfil the requirements of the customer. For every change made to the vessel, a new iteration is required to update the dependent systems that the change affects. The process will then keep iterating until the design satisfies the customer requirements to a substantial degree. This copy and edit method have proven to come at a considerable quality cost in terms of over-specifications, errors and omissions.

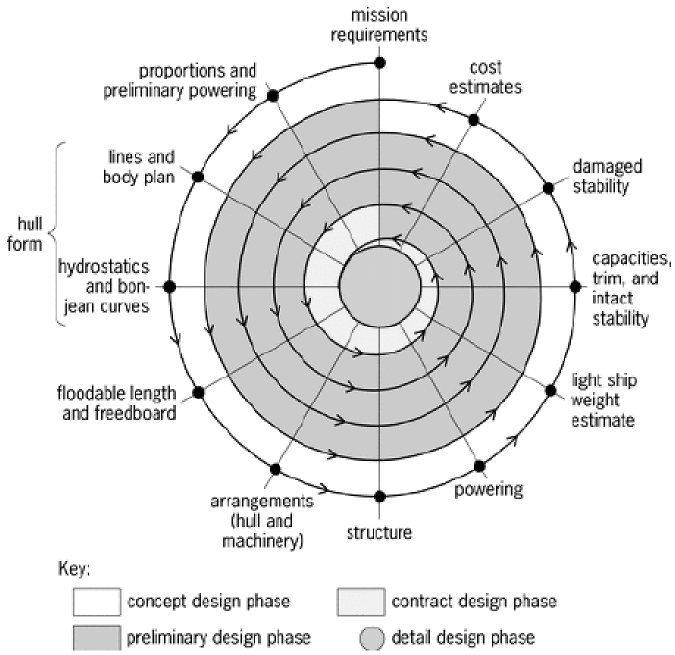


Figure 9.2.1: Ship design spiral (Evans, 1959).

Several engineering design methods that try to minimise the inefficiency of the design spiral have been developed. The methods approach the design problem systematically, providing a structure to the design process. An example of such a method is the System Based Design Approach. The approach describes the mission requirements using functions and uses statistical data from earlier designs to estimate the internal volumes and areas required for the ship to be able to satisfy each function. By doing so, the knowledge at the beginning of the design process is increased and much of the calculations can be automated, reducing the number of iterations (S. Erikstad & Levander, 2012).

Further expanding on the idea of using statistics to increase the efficiency of the design process, library-based approaches have been developed. Set-based design enables a wide exploration of possible design solutions by applying parametric analysis to a database of similar vessels. The approach postpones the decision making by generating a large number of possible designs using the results from the parametric analysis as a basis. These designs are evaluated and compared to each other by quantifying their functional requirements using utility theory. Methods such as these require a database of similar designs and are therefore poorly suited for creating innovative solutions (McDonald et al., 2012).

Although the methods have increased the efficiency using digitization and statistics, the design spiral they are built upon assumes a system with an integral structure. An integral structure is a system where the elements are highly dependent on each other. Changing an element in an integral structure affects one or several other elements in the design, which results in an iterative design process. As a result, many of the methods emerging from this spiral shares the same principle of creating a 'one-of-a-kind' solution through a high number of iterations, that is rarely applicable to other scenarios. The amount of information that must be handled simultaneously using these methods results in a complex and time-consuming design process. With project cost and time constraints, this may lead to a design process focusing on finding a feasible solution rather than an optimal one.

In recent years there has been a shift in the industry moving away from Evans design spiral and integral design structures. Recent developments have provided engineering design methods that exploit the benefits of modular design and standardisation.

9.3 Modularity in design

Modularity in design is the principle of dividing a large system into independent and self-sufficient subsystems called modules. The modules can be recombined to a wide range of different end products by following a set of rules provided by a system architecture (Mork et al., 2014).

9.3.1 Managing complexity

Modularisation enables a new method of managing complexity by moving away from the integral structure used in traditional design approaches. The designs based on an integral structure manages complexity by limiting the information required to describe the system, often using a hierarchical approach. A modular structure can further reduce the complexity by with the criteria of self-sufficiency of the modules. Thus, modularisation enables a designer to satisfy both of the design axioms proposed by Suh in Axiom theory.

However, as previously mentioned, it is difficult to identify such modules in a large and complex system (Mork et al., 2014).

For the hierarchical breakdown of the system structure, it is necessary to define the level of detail that is necessary for the modules. Large systems can be composed of thousands of different elements as a finished product. Addressing each element would minimise the amount of information required per module, but complicate the design process as a whole as many of these elements are dependent on each other. As modules are meant to be self-sufficient the dependency between them need to be minimised.

In modular theory, the level of detail required for the modules is different for each design phase, increasing the level of detail from one phase to the next. As such, detailed modules and sub-functions are derived from larger and less detailed modules that are manageable at an early design phase. This means that even though the modules are independent over the same design phase, they are dependent from one design phase to the next. This creates the foundation of product platforms and product architecture that provides a structure for how these modules can be recombined together into complete systems. The number of subsystems in the hierarchy should also be limited to keep the hierarchy simple and organized.

This method of managing complexity comes at a cost. The modules in early design phases, such as the conceptual design, have to satisfy detailed requirements from the customer without directly addressing them, as the detail of the modules is insufficient to address them directly. Moreover, a traditional design approach is able to create more tailored solutions by addressing every element in the design, where a modular approach will use standardized modules that are not optimized for the specific case. This may lead to a less optimized physical architecture or performance for the design. Moreover, the modules may need additional components to satisfy the criteria of self-sufficiency and to accommodate for the standardized interface used to connect the modules. It is therefore important to consider where a modular design approach is beneficial.

9.3.2 Configuration in early design phases

As mentioned previously it is necessary to increase the knowledge of a design at an early stage of the design process to accommodate for design changes without adding significant cost. Modularisation addresses this issue by drawing inspiration from the traditional copy and edit method. However, instead of gaining knowledge through existing complete designs, knowledge is by storing information about the developed modules in a product platform. The modules can be combined to create new systems that satisfy the requirements of the customer. The designed system is easily perceptible to change as modules can be added, removed or scaled without affecting the other modules in the system (S. O. Erikstad, 2009) .

The product platform and its modules will mature with time, as statistical information about the module performance in different contexts can be stored. Data such as reliability and cost can be gathered to estimate in which cases the module should be used or not.

As certain modules are preferred over others given a set of customer requirements, the modules can be categorized based on which design segment they perform well in and what economical boundaries they have. This creates the basis for product platform strategies.

9.4 Product platform

In engineering design, a product platform can be defined as a platform providing a collection of resources and an architecture describing how these resources can be used to create a wide range of customized product definitions. In other words, a product platform provides a general platform on which a range of products can be built upon. It consists of building blocks, or modules, that can be added, removed, replaced or scaled according to a set of rules to target specific markets or customer requirements (S. O. Erikstad, 2009).

9.4.1 Product platform strategies

Product platform strategies determine the subdivision of modules and module variants, and how these can be grouped together into product families. A product family is defined by Mork as a group of products that are derived from the same set of modules in the product platform. The product families therefore provide a set of modules and the platform architecture required to combine these modules into systems. Figure 9.4.1 illustrates the infrastructure of a product platform (Mork et al., 2014).

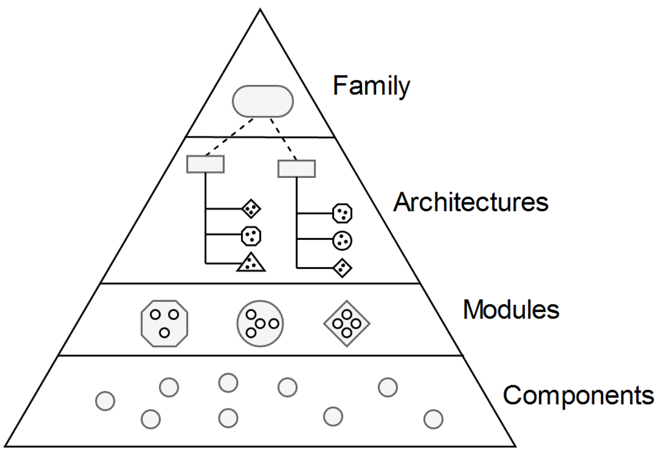


Figure 9.4.1: Infrastructure of a product platform

The product platform strategy determines how modules and product families can be leveraged, or categorized, to target specific markets or product niches. For example, product families and modules may be leveraged according to the cost and performance of the systems they can provide, categorizing the systems from high end to low-end products. Moreover, the systems can be segmented based on given criteria. This makes it easier for a designer and customer to choose which product families and modules that are relevant for a customer specification.

9.4.2 Modular architecture and interfaces

The product architecture can be regarded as an abstract skeleton of a product platform. It provides a list of all modules in a product family and describes how they can be configured into systems by providing a set of rules. The modules provided can either be listed as the function they provide to the design or the physical components that they contain. In some cases, a mix between the two are presented, as the requirements to a design can be both in terms of physical properties, such as size, and functional performance. The architecture must be constructed such that it addresses all the functions and components that are relevant for a product family. The product platform architecture can be derived using inspiration from System Breakdown Structures (SBS), which decomposes the main function of a system into subfunctions. The product platform architecture essentially does the exact opposite and provides the rules to combine subsystems to satisfy a main function (S. O. Erikstad, 2009).

An interface is a pre-defined system that provides the set of rules governing the compatibility and interaction between the modules in a modular architecture. An interface is crucial for the configuration of systems as a module added to the system need to be compatible with the modules it is connected to. There are many different types of interfaces, but the three most common is slot, bus and sectional modularity. Slot modularity categorizes the modules and provides a different interface for each category. The modules not sharing the same interface are not compatible with each other. Bus modularity shares the same interface across all modules. Sectional modularity shares the same, or very few, interfaces over all modules, but does not provide a platform on which the modules are built upon, meaning that the modules can be placed in an arbitrary way. Figure 9.4.2 illustrates the different interfaces.

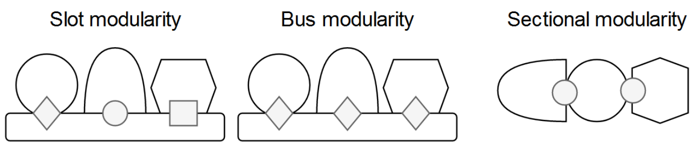


Figure 9.4.2: Examples of modular interfaces.

9.4.3 Mass customization

Mass customization is a methodology that applies a modular approach to modern mass production to provide tailored solutions to customers at low production costs. There are numerous industries that have shifted from designing 'one of a kind' products to using product platform and modularity in their development process. The car industry can offer a wide range of products, where the customer has the opportunity to customize their car from engine power, colors, audio system and seats. This large flexibility enables the producer to maintain a broad product range and deliver products to niche markets, with low cost and development time compared to traditional methods (Mork et al., 2014).

9.5 Configuration based design

Configuration can be defined as an arrangement of parts into a specified combination. Configuration based design configures a system by applying predefined rules and templates to select, scale and synthesise a collection of modules to meet a set of given requirements. This section will research how the modules in a product platform can be configured into complete systems (S. O. Erikstad, 2009).

A configuration system consists of three main elements. The first element is the solutions design representation that conveys information of the generated designs to the user. This information can be divided into primary and secondary object representations. The primary representation is a collection of modules and parameters that represent the customer requirements and describe the design solution. The secondary representation is derived from the primary representation and consist of a 3D model, specifications and performance documentation of the design.

The second element is the configuration process representation and handles the integration of third-party applications. An easy integration of such applications is dependent on understanding the configuration process underlying logic. Providing a configurable and declarative process logic definition accommodates for easy integration of external applications. It is preferred to base the process on a workflow management system. Such a system arranges the infrastructure of set-up, performance and monitoring of a sequence of tasks as a workflow application.

Finally, the third and last element is a configuration knowledge representation which goal is to illustrate the rules and constraints required to define viable solutions from the module platform.

The system that guides a user through a design process is called a configurator. A configurator can have a range of characteristics and features, and should be designed to pay attention to specific aspects of the project. It is crucial to have a suitable configurator for the design process to achieve viable and optimal results. A schematic classification structure that can be used to define the configurator is illustrated in figure 9.5.1. A few of these classifications will be explained (S. O. Erikstad, 2009).

9.5.1 Knowledge base

The knowledge base refers to the information stored in the system and how the configurator applies this information to make decisions. The information may include customer requirements, regulations and other constraints in the project (S. O. Erikstad, 2009).

Rule-based knowledge presents information through a set of rules that is used to run the configuration process. The rules describe a consequence from a condition being true and are structured with a ”condition-consequence-action” framework. The rules are ordered in a hierarchical structure and are dependent on each other. For example, if a functional requirement states the need for a conversion module with a specific energy output type, a rule will be triggered and a fitting module will be added. With such a module added,

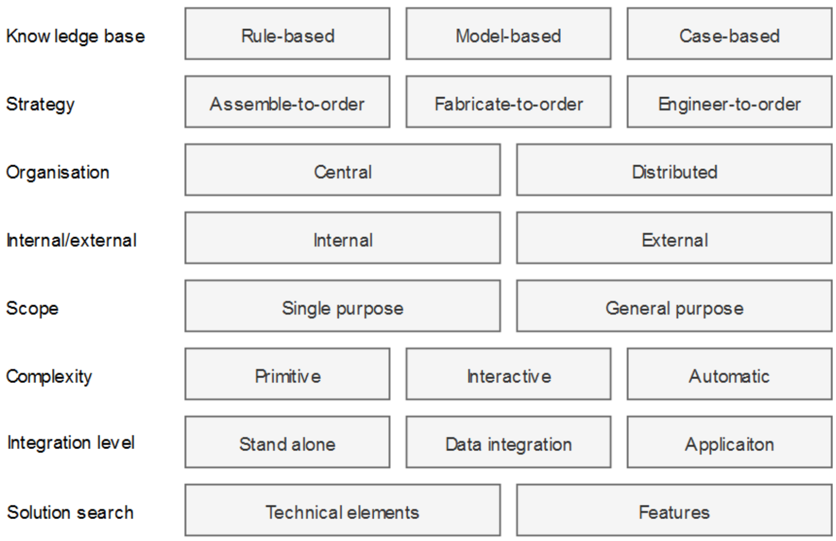


Figure 9.5.1: Classifications of a configurator.

other rules are triggered defining which modules can be added adjacent to it and the necessary scaling of these modules. Configurators that applies rule-based knowledge derives a solution through a step by step process, where the rules are updated and examined at each step.

Case-based knowledge uses a database of previous designs to derive a new solution. The database is searched to find similar designs that can be altered to fit the new requirements or to gather statistical data that can be used to generate a new design. This is similar to the library-based approaches discussed earlier. The negative aspects from the copy and edit method is minimised since the process is applied to a modular level, meaning adding, removing or scaling modules are sufficient to reach the new customer requirements. However, the end phase of such a configurator must be performed manually by an engineer.

9.5.2 Configuration strategy

The configuration strategy refers to the Customer Order Decoupling Point (CODP) which is the point in the value chain of a development where the product is linked to a customer order. There exist four basic CODP strategies, where three are relevant for the design of large and complex systems (Arnold et al., 2008).

Engineer-to-Order (ETO) is the most upstream strategy and highly involves the customer in the product design. The design process involves a significant amount of customization and tailored engineering to satisfy the customer specifications. The complicated design process usually results in a long lead time for the project.

Fabricate-to-Order (FTO) is a strategy where the manufacturer wait to start production until a customer order is received. This strategy is used for systems that can be mostly made by standard, off-the-shelf, components and only a few custom ones. The lead time is reduced compared to the engineer-to-order strategy, as the design process is more efficient and the standard components can be stockpiled.

Assemble-to-Order (ATO) is the most downstream strategy of the three and involves a design process where the product exclusively consist of standard, off-the-shelf, components that the manufacturer can stockpile. This strategy has the lowest project lead time of the three strategies. The customer involvement in the product design is limited to the choice between the standard components offered by the manufacturer, which results in a very short development time.

9.5.3 Configurator complexity

The configurator complexity is divided into three categories. A primitive configurator provides a pre-defined structure or template, which the designer completes. Such configurators are useful for providing a structured approach to a design process, but provides little design freedom and decision support for the designer (S. O. Erikstad, 2009).

An interactive configurator provides more opportunities for the designer to guide the configuration process. Such configurators enable the designer to analyse decisions and check their validity throughout the configuration process.

Finally, an automatic configurator guides the configuration process by adding modules and determining parameter values. Such a configurator is fully driven by an automatic process, leaving the designer with little control over the configuration process.

9.6 Product platform for offshore energy storage

Modularisation has been difficult to implement to ship design due to a very high complexity, making it challenging to identify independent modules in the system. However, the complexity of an energy storage system compared to a ship is lower, which simplifies the implementation of module-based engineering design approaches. Even though identifying independent modules may still be difficult, there are fewer elements to address in an offshore energy storage design than for a ship. Moreover, the overall function of an energy storage system remains the same from one project to the next, to store energy from an intermittent energy production site, which further enables the use of a product platform.

An offshore construction usually involves high maintenance cost as the distance from shore increases. Unscheduled maintenance would therefore be a significant expense that lower the cost-efficiency of the system. The risk and uncertainties of the storage system can be minimised as the knowledge of the modules it consists of increases. Knowing the likelihood of a component in a module failing, the regular maintenance schedule and its costs can be predicted, and the designer can implement measures to keep the storage system running if a crucial component fails. Moreover, modularity makes changing defect components easier, shortening the maintenance time and costs. Modularisation also provides a lower construction cost, as the standardised modules can be constructed separately from the system, allowing for outsourcing.

The configuration of the modules simplifies the design process for the engineer. This decreases the amount of rework and iterations in the design process and enables more time to be spent on searching for an optimal solution. Finding this optimal solution will benefit the cost-efficiency by ensuring the systems ability to meet the requirements of the customer.

There are many positive aspects of a product platform that would benefit the development of an offshore energy storage system. However, as of today, only onshore energy storage systems exist, meaning that an offshore storage system would be classified as an innovative design. Therefore, the design approach needs to enable the benefits of modularity while accommodating for new and innovative solutions. To exploit the positive aspects of a modular approach there is a need for a product platform structure that accommodates for innovative designs and a systems engineering design method that provides a structure to the design process.

Part IV

THE PRODUCT PLATFORM

Chapter 10

Product platform structure

This chapter derives a product platform structure that addresses the issues of using modular design theory for an innovative design. A product platform is usually applied to industries that produce technologies that are well established in the market. This allows for routine design processes, where old designs and modules are used to generate design solutions that require little to no unique design inputs from an engineer. However, as previously mentioned, an offshore energy storage system is an innovative design. As such, the product platform need to enable the designer to explore solutions outside the conventional boundaries of routine design products, without affecting the efficiency of the configuration process.

10.1 Product platform development

These conflicting interests are addressed by dividing the platform into two design processes, one for platform development and one for platform exploitation, see figure 10.1.1. The platform development consists of the design and maintenance of modules in the module catalogue, while the platform exploitation addresses the use of a configurator to combine the modules into systems that satisfy the customer requirements. With this separation, matters of innovation can be limited to the development of the modules, enabling the conceptual design of offshore energy storage systems to be derived using a configurator. These design processes need to enable parallel work, meaning that new modules can be innovated simultaneously as the configurator generates systems for customer orders. Moreover, feedback of information from the generated systems to the development of the platform is implemented to maintain the quality of the product platform.

10.1.1 Development of modules

With this separation, two different design approaches are derived. The development of the product platform requires an engineering design method that enables innovative and tailored designs of modules. As such, the design method must be based on traditional design approaches, where the elements in each module are designed as an integral structure. To minimise the inefficiencies of such design methods a design approach that provides a

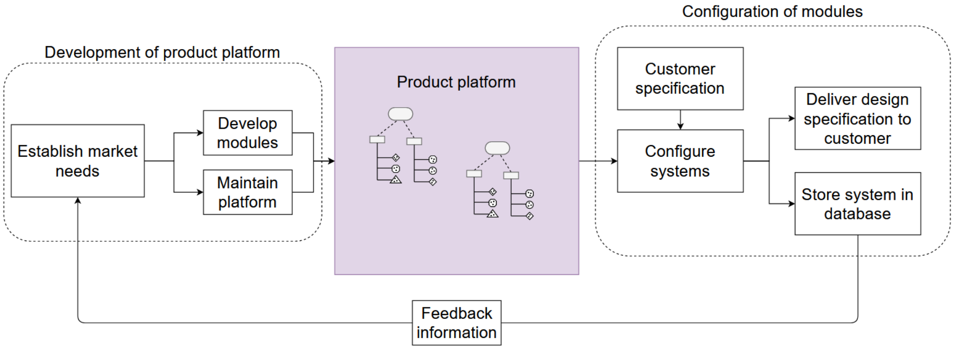


Figure 10.1.1: Development and exploitation of the product platform strategy.

systematic structure to the design process is necessary. The method must minimise the complexity of the design using complexity theory and accommodate for easy integration with the rest of the product platform.

The Systematic Approach by Pahl and Beitz is chosen for the development of the modules in the product platform. This design method provides the design freedom necessary to accommodate for a high degree of innovation while providing a structured approach to derive modules. With a repetitive process of developing the modules, the knowledge at the early stages in the design process increase. Moreover, the method aims to create a design catalogue of working principles of components, meaning that the method can easily be integrated into the design platform by taking the process one step further and combining these working principles into modules.

10.1.2 Configuration of modules

The design method for the configuration of the modules draws inspiration from configuration-based design. The method provides a digitized configurator that combines the modules in the selected product family by following a set of rules. The configurator uses inspiration from Decision-Based design and generates a large amount of energy storage systems. These systems performance will be evaluated and compared to each other using utility theory. This enables the designer to choose between a set of different solutions, increasing the chances of developing an optimal solution. The design approach and its benefits are further discussed in chapter 12. The platform architecture and interfaces are explained as the product platform is established.

The following chapters focus on creating the product platform using the structure that is explained in this chapter. The method for both the development and configuration of the modules are derived.

Chapter 11

Development of modules

The method for developing the modules draws inspiration from the Systematic Approach introduced by Pahl and Beitz (Pahl & Beitz, 1988). This approach is performed by dividing the design process into three different domains and explaining the mapping between these domains, as explained in chapter 9. The first phase of the approach is to establish the needs domain by clarifying the task and determining the needs and criteria that the system is expected to satisfy.

However, task clarification is considered outside the scope of the thesis. As such, the mapping from the needs domain to the functional domain is be explained in detail. However, general requirements are established to get an idea of what stakeholders may expect from an energy storage system. This is important to derive efficient modules that are of interest to the customers. The requirements can be further developed as the product platform evolves by using the customer specifications from the configuration of the storage systems. More requirements can be attained, resulting in more functions and the design of more modules. For the purpose of this thesis, a general requirements list is derived using stakeholder analysis.

11.1 Stakeholder analysis

A stakeholder in a project is an individual or group who are affected by the project in some way. Stakeholders can generally be divided into users, governance, influencers and providers. Users are stakeholder that will use the product of the project. Governance is organizations that have an interest in the management of the project. Influencers are stakeholder that have the power to influence decisions and change the project in any way. Finally, providers are suppliers and vendors in the project.

This analysis is not based on a specific project and therefore variations may occur for different areas and cases. The identified stakeholders are divided into six segments. This is to illustrate the stakeholders' main interests and which field they may have expectations towards. The results are displayed in table 11.1.1.

Table 11.1.1: Identified stakeholders in the renewable energy industry

Stakeholder	Political	Economic	Safety	Technology	Environment	Legal
Board of directors		✓	✓	✓		✓
Employees			✓	✓		
Shareholders		✓				
Government and regulators	✓		✓			✓
Unions			✓			✓
Non-governmental organizations					✓	
Local wildlife					✓	
Public	✓				✓	
Maritime sector			✓			
Energy production sector		✓	✓	✓		
Energy suppliers		✓		✓	✓	
Energy consumers		✓			✓	

11.1.1 System requirements

The general stakeholders in the project have been identified with their corresponding segment of interest. The system requirements must be reduced to criteria that can be directly compared to a system function, to provide the mapping from the needs to the function domain. With more specific customer requirements this mapping would have been performed using a House of Quality (HOQ). Such methods illustrate the dependency of the different requirements and functions. For the purpose of this thesis, a simplified table illustrating the mapping is created. The results are presented in table 11.1.2.

Political

The political segment is considering the general politics that can be connected to the energy production industry. For example, environmental politics such as reaching local and global emission reduction goals, economical politics like taxes or social politics like creating jobs and positions.

Economic

The economical perspective is considering the costs and profits of the system. This segment focuses on the capital expenditures of the project, and the profit that can emerge from such an investment.

Safety

Safety considers the work environment in both construction and operation of the solution. This segment will account for potential hazards that could inflict physical damage to any stakeholder. This segment is usually very important and the value of a life is therefore considered costly, 30 MUSD, in risk analysis. The work environment covers the physical security measures and mental factors such as work hours, job training and operations at the site. Hazards is referring to the mitigation of general hazards at the site.

Technology

The technology segment accounts for all criteria aimed towards the technology itself. The offshore energy solution will be situated far away from the coast, and any scheduled or unscheduled maintenance that is required will be costly. Some stakeholder will therefore have an expectation towards the reliability of the system.

A system that is capable of both providing key grid services to increase grid quality and provide long term storage for energy shifting is optimal for the cost-efficiency of the system. This requires a system flexibility.

There is also a requirement towards the technologies feasibility. A high feasibility is cheaper to design and construct, as it does not require extensive research and innovation. This can be measured by the TRL value explained in chapter 7.

Environment

The motivation behind the storage system is to improve the cost-efficiency of offshore energy production that uses environmentally friendly sources. Therefore it would be unwise to implement a storage system that induces pollution and emissions to the system, both with respect to air and water. Another factor that is important to consider is the system's effect on the local ecosystem and the potential hazards that could arise from the solution.

Legal

The legal segment is considering the stakeholders' interest in the legalities of the project. General rules such as regulations and local or international laws may affect the project and are therefore important to consider.

Table 11.1.2: Mapping from stakeholder requirements to system criteria.

Stakeholder segment	Requirements and needs	System criteria
Political	Meeting emission reduction goals Creating positions and jobs Taxes	None
Economic	CAPEX OPEX Return of investment(ROI)	CAPEX RT-efficiency Energy density
Safety	Work environment Hazards	Operating temp. Operating pres. Work material
Technology	Reliability Flexibility Feasibility	Cycles Capacity Self-discharge rate Storage time Response time TRL value
Environment	Pollution Effect on local ecosystem	Environment
Legal	Regulations Local laws International laws	None

11.2 Functional interrelationship

A function can describe a task in a system using the relationship between its input and output. A functional requirement is a measure of how well a system should be able to perform its function to satisfy the criteria in the needs domain. How well a system performs its function is determined by comparing the system requirement to the system capability of meeting that requirement. This is called system performance. In order to evaluate a system's performance, the functions must be able to represent the requirements from the needs domain. These functions and their functional interrelationship is derived in this chapter (Pahl & Beitz, 1988).

11.2.1 Function structure

The complexity of the system is reduced using SBS. The systematic approach uses an SBS called function structure. This SBS is based on the hierarchical approach and regards the system as a hierarchy of main and subfunctions, where the flow of material, energy and signal between the functions is illustrated. Figure 11.2.1 illustrates how an overall system function is decomposed into main subfunctions and auxiliary subfunctions. Auxiliary subfunctions are functions that have an indirect impact on the overall function. Ideally, the system is decomposed into subfunctions that require little information to describe and are independent of each other, as described by axiom theory. However, for complex systems this is close to impossible to achieve as some dependency between the subfunctions are unavoidable. This dependency needs to be considered when deriving the modules and the module interfaces.

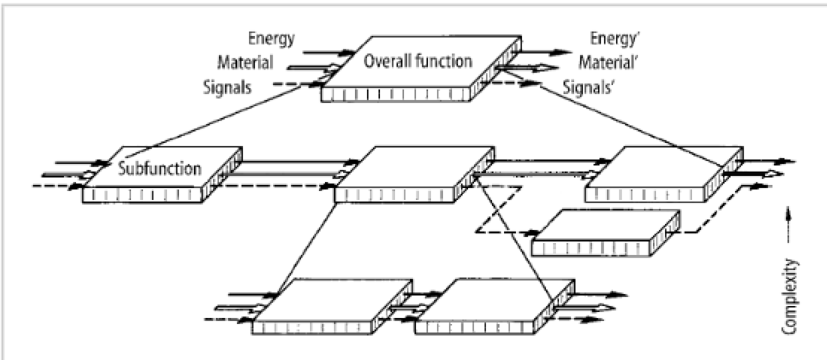


Figure 11.2.1: Example of the decomposition of a system function to subfunctions (Pahl & Beitz, 1988).

The function structure describes the functions in the system from two perspectives. One describes what the function does, such as transform, transport or store, and the other describes the object the process acts on, and to which magnitude. This enables the functions to be described as a flow of matter, energy and information.

Figure 11.2.2 illustrates a function with an input and output of energy, material and signals. Energy can come in many forms, such as mechanical, thermal, electrical or chemical. The energy flow describes the movement of energy through the system and its conversion between these forms. The aim of the material flow is the same, as materials can come in many forms ranging from solids to gases. Finally, signals are used to convey the flow of information in the system. Signals can be received, transmitted and compared and are often used to describe information, data, magnitudes and control impulses in the system.

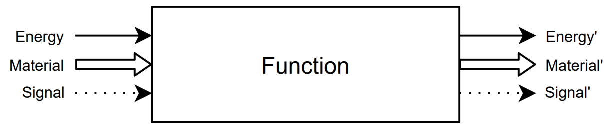


Figure 11.2.2: The conversion of energy, materials and signals displayed by a function with inputs and outputs.

The function decomposition of the offshore energy storage system is slightly simplified to make it more clear. The system is based on the movement of energy, either in its abstract form or as a material acting as an energy carrier. Usually, the energy flow would follow the material flow as the energy is stored within the chemical bonds of the material. However, for this specific case this is redundant information. Therefore, the material flow will describe the energy flow in its physical form. By doing so the conversions between energy carriers and other energy types within the system are easier to identify. This will make the conversion from one energy form to the other more obvious and the model more understandable. A legend explaining the subfunction and flow types for the function structure is presented in 11.2.3.

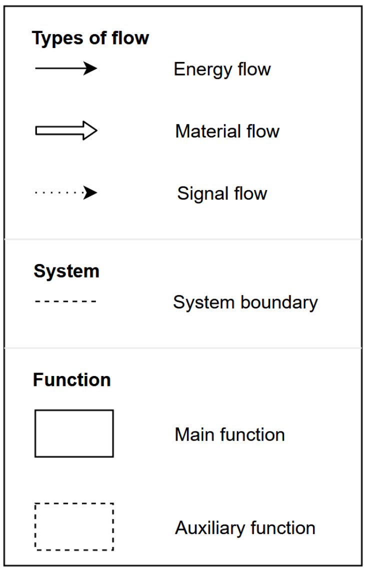


Figure 11.2.3: Symbols used to represent function and flow types in a function structure

The function structure for offshore energy storage systems can be found in table 11.2.4. The overall system function is decomposed into subfunctions. This function structure has the aim of providing a general overview of the functions in an energy storage solution. It is possible to further decompose the function structure. However, the tasks of the system depend on which technology it is built upon. As such, the auxiliary functions for the two conversion subfunctions is derived using examples from mechanical, thermal, chemical and electrical storage systems. The results can be found in Appendix B.1, figure B.1.1. These examples are provided to help identify the energy conversion and energy storage physical effects that will be used to derive working principles later in the thesis. Hydromechanical energy is distinguished from mechanical energy, to differentiate between flow-based and solid-based mechanical energy storage.

By looking at figure 11.2.4, there are two signals that convey information to two switching functions. The first switch function determines if the energy should be sent directly to the grid or if it should be stored for later use. This decision is based on the current grid demand. The second decision block determines if the energy should be sold as an energy carrier or be converted and sold as electricity. This is determined by the market demand and prices.

The energy storage system boundary is regarded from after the energy is produced until it is converted back to electricity. The system boundary excludes the transportation of the energy, as this is considered outside of the thesis scope. The type of transportation will vary with respect to what energy storage solution that is implemented. Although one energy storage solution is deemed most efficient, its transportation solution could impact the efficiency to a substantial degree, causing it to underperform with respect to other solutions. This dependency makes it a viable function to include in the system boundary. However, due to time restrictions and this being a feasibility study it was not considered within the scope of this thesis.

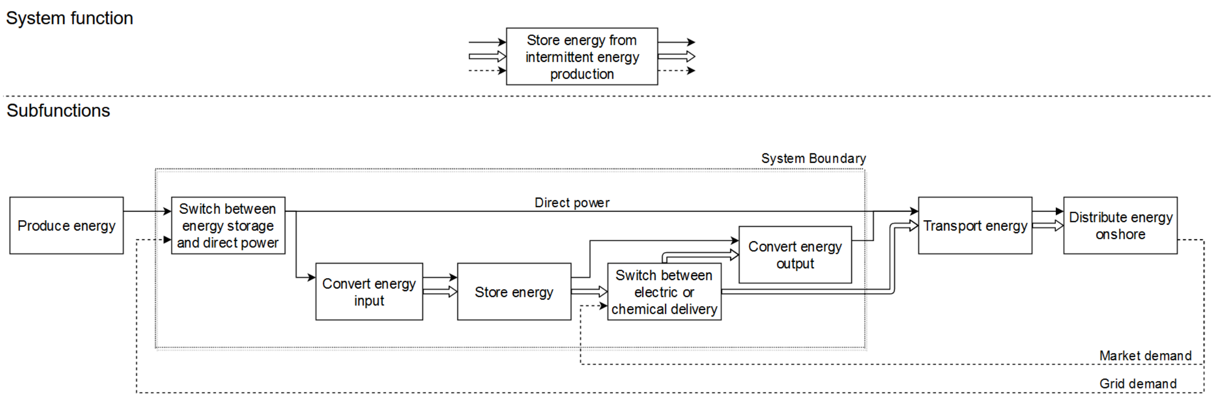


Figure 11.2.4: Function structure of offshore energy storage systems

11.2.2 Determining modules

There are a number of methods that can be used to determine the modules in a system. The decomposition of the main function provides a number of sub- and auxiliary functions to a structure. These functions need to be grouped together based on their dependencies. This can be performed by creating a Design Structure Matrix (DSM).

Figure 11.2.5a illustrates a DSM with seven functions. It is structured as a table where the dependency is assigned with a cross, illustrating that the function in the vertical axis is dependent on the function from the horizontal axis. For example, function 2 is dependent on function 1, but function 1 is not dependent on function 2. Figure 11.2.5b illustrates how such a matrix can be clustered to determine the possible modules in the system. The clustering rearranges the order of the functions to illustrate which functions that should be included in the same modules to minimise the dependency between the modules.

(a) Example of a DSM

(b) Clustering of the DSM

Figure 11.2.5: Clustering of a Design Structure Matrix (DSM, 2021).

As previously mentioned, the detail required for the modules increases from one design process to the next. Since this product platform provides a conceptual design, the detail requirement of each module is low. As such, the function structure has not decomposed the system to a high degree and there are not that many functions acquired. The only possible modules are two energy conversion modules and an energy storage module. As such, there is no need to use a DSM.

However, as the product platform is further developed, the function structure may be further decomposed. As more functions are derived a DSM should be used to explore the possibilities of creating more than three modules, increasing the detail level of the conceptual design.

The only dependency between the three modules is the energy type that flows through them. The output energy type from one module must be similar to the input energy type of its adjacent module. This dependency is addressed by the module interface.

11.3 Working interrelationship

With the modules defined the physical structure that can perform the function of the module is derived. As the module is built up of auxiliary functions the working principle of these functions is established first, and then combined to form the final module.

The functions must be described with more concrete statements. A function is usually fulfilled by a physical, biological or chemical process. For instance, mechanical engineering functions are usually fulfilled by physical processes, while process engineering functions are mainly based on biological or chemical processes. A working interrelationship describes the relationship between the physical effect that realises the process in a function and the determined material and geometric characteristics of the solution. Establishing such a relationship ensures the function is fulfilled in accordance with the task (Pahl & Beitz, 1988).

11.3.1 Physical effects

The physical effect of a process can be described by the physical laws that govern the physical quantities in the process. Figure 11.3.1 provides a table that illustrates the physical effects that can be utilized by the energy storage and conversion auxiliary functions derived in the function structure.

Physical effects may have to be combined to fulfil the task of a function. Likewise, the task of a function can be fulfilled by a number of different physical effects. When doing so, it is important to consider the compatibility between the physical effect in one function and the physical effects of its neighbouring functions. For instance, a hydraulic amplifier can not be powered directly by an electric battery. Moreover, which physical effect that is optimal for a function may vary with external conditions. Therefore, optimal fulfilment and compatibility assessments can only be realistically evaluated after the geometric and material characteristics have been established. This is important to consider when developing a product platform, as defining the modules and their dependency too early may lead to unexpected dependencies between the modules. However, for this thesis, the modules have already been defined as the simplifications of the function structure provides few module configuration alternatives.

Function	Input	Output	Physical effects						
$E_{Mech} \rightarrow E_{Mech}$	Force, pressure, torque	Length, angle	Hooke's Law	Shear, torsion	Upthrust poisson's effect	Boyle-Mariotte	Coulumb's law I and II		
		Speed	Energy law	Conservation of momentum	Conservation of angular momentum				
		Acceleratior	Newton's Law						
	Length, angle	Force, pressure, torque	Hooke's Law	Shear, torsion	Upthrust poisson's effect	Boyle-Mariotte	Coulumb's law I and II	Gravity	Capillary
	Speed		Coriolis force	Conservation of momentum	Magnus effect	Energy Law	Centrifugal force	Eddy current	
	Acceleratio		Newton's Law						
	Force, pressure, length, speed	Force, pressure, length, speed	Lever	Wedge	Poisson's effect	Friction	Crank	Hydraulic effect	
$E_{Hyd} \rightarrow E_{Hyd}$	Pressure, speed	Pressure, speed	Continuity	Bernoulli					
$E_{Therm} \rightarrow E_{Therm}$	Temperature, heat	Temperature, heat	Conduction	Convection	Radiation	Condensation	Evaporation	Solidification	Fusion
$E_{El} \rightarrow E_{El}$	Voltage, current	Voltage, current	Transformer	Magnetic field	Transistor	Transducer	Thermo galvanometer	Ohm's Law	
$E_{Chem} \rightarrow E_{Chem}$	Bond energy	Bond energy	Gibbs free energy	Endothermic reaction	Exothermic reaction	Thermodynamic Laws			
$E_{El} \rightarrow E_{Chem}$	Voltage, current	Bond energy	Gibbs free energy	Endothermic reaction	Coulomb's Law	Arrhenius equation	Thermodynamic Laws		
$E_{Chem} \rightarrow E_{El}$	Bond energy	Voltage, current	Gibbs free energy	Exothermic reaction	Coulomb's Law	Arrhenius equation	Thermodynamic Laws		
$E_{Chem} \rightarrow E_{Therm}$	Bond energy	Temperature, heat	Gibbs free energy	Exothermic reaction	Gas law	Thermodynamic expansion	Arrhenius equation	Thermodynamic Laws	
$E_{El} \rightarrow E_{Therm}$	Voltage, current	Temperature, heat	Joule heating	Peltiereffect	Electric arc	Eddy current			
$E_{Therm} \rightarrow E_{El}$	Temperature, heat	Voltage, current	Electric conductor	Thermoelectric effect	Thermionic emission	Pyroelectricity	Noise effect	Semi-/ Superconductor	
$E_{El} \rightarrow E_{Mech}$	Voltage, current, Magnetic field	Force, speed, pressure	Biot-Savart effect	Electrokinetic effect	Coulomb's Law I	Capacitance effect	Johnsen-Rhabeck effect	Piezo effect	
$E_{Mech} \rightarrow E_{El}$	Force, length, speed,	Voltage, current	Induction	Electrokinetic effect	Electrodymanic effect	Piezo effect	Frictional electricity	Capacitance effect	
$E_{Mech} \rightarrow E_{Therm}$	Force, speed	Temperature, heat	Friction (Coulomb)	Thermodymics 1st law	Thomson-Joule	Hysteresis (damping)	Plastic deformation		
$E_{Therm} \rightarrow E_{Mech}$	Temperature, heat	Force, pressure, length	Thermal expansion	Steam pressure	Ideal Gas Law	Osmotic pressure			
$E_{Hyd} \rightarrow E_{Mech}$	Speed	Force, length	Profile lift	Turbulence	Magnus effect	Flow resistance	Back pressure	Reaction principle	
$E_{Mech} \rightarrow E_{Hyd}$	Force, length, speed, pressure	Speed, pressure	Bernoulli	Viscosity (Newton)	Torricelli	Gravitational pressure	Boyle-Mariotte	Conservation of momentum	

Figure 11.3.1: Physical effects that govern conversion and storage of energy

11.3.2 Energy conversion working principle

The physical effect is realised by the working geometry at the place where the effect is occurring. The working geometry can be described by the arrangement of working surfaces such as shape, position or size and working motions such as direction, type of motion or magnitude. The working surfaces and motions must be established before the working interrelationship can be formulated. The combination of the physical effect with the geometric and material characteristics can formulate the working principle of the solution (Pahl & Beitz, 1988).

With the physical effects that govern the auxiliary functions established the working geometry and motions can be derived. It is important to highlight the energy input and output type, to ensure compatibility between the energy conversion and storage components. The energy conversions were first tabulated to showcase the working geometry and motions that can convert one energy type to another, see figure 11.3.2. This table includes conversions between all the energy principles that are included in this thesis, and provides the working geometry for many of the physical effects derived in table 11.3.1.

11.3.3 Energy conversion modules

The conversion modules must always convert from, or to, electricity and another given energy principle. By using table 11.3.2 such energy conversion modules can be derived. For example, electrical energy can be converted to mechanical rotational energy by using an electric motor.

However, energy conversions are often not direct. Several working geometries and motions can be combined to derive more conversion modules. Examples of such combinations are found in figure 11.3.3. The first module converts hydromechanical energy to electricity by using a Pelton wheel and a generator. Looking at table 11.3.2, the designer would start with hydromechanical energy as input and rotational mechanical energy as output, and from this choose a Pelton wheel. Now the energy input for the next component would be rotational mechanical energy, with an output of electricity. From this, the designer would choose a generator.

The second row derives the working principles of a steam engine. Electricity is used to apply heat to a working medium, for example water. A thermal expansion in a piston chamber increases the pressure, applying a pressure force on the piston. This translation is converted to rotational mechanical energy using a rod and wheel.

The third row derives a combustion generator. The energy is converted from chemical energy to thermal energy in the combustion chamber through a reaction causing a rapid thermal expansion. Which is further converted to mechanical energy by applying a pressure force on the piston. The engineer would need to convert this translational mechanical energy to rotational mechanical energy by using a rod and wheel, which can then be connected to a generator to produce electricity.

It is important to consider the amount of detail when deriving these working principles.

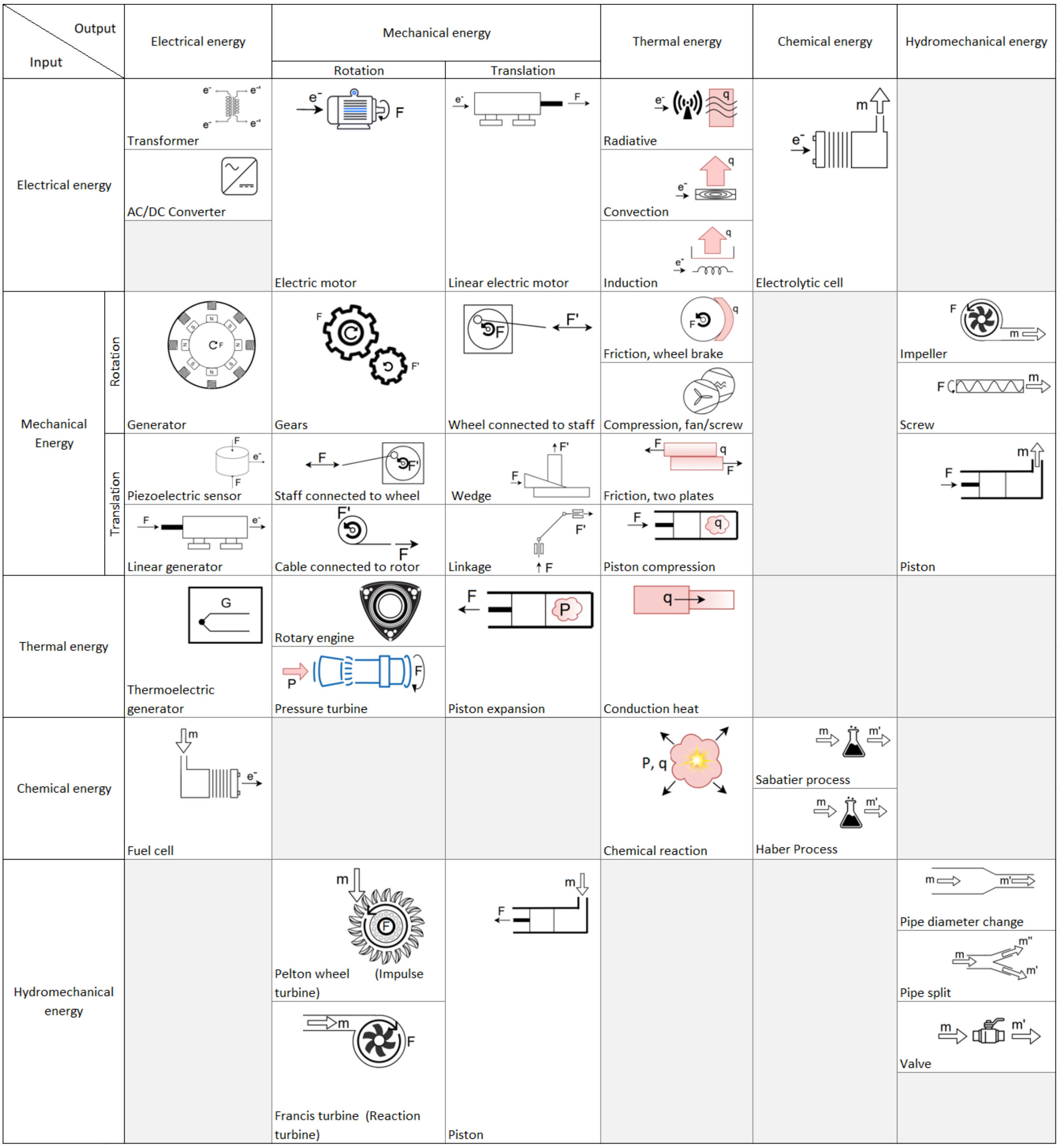


Figure 11.3.2: Working geometry and motions that utilize physical effects for energy conversion between two energy types.

More details increase the number of components that can be derived, but also increases the complexity of the process. For example, a compressor can be regarded as a way to convert electrical energy to thermal energy through compression. However, this process can be described as an electric motor combined with a fan or a linear electric motor combined with a piston to create pressure. By doing so, a lot more variations of a compressor can be derived. Although this is a conceptual design, variations of a component may provide different characteristics that are more suitable for certain situations, thus improving the performance of the concept solution.

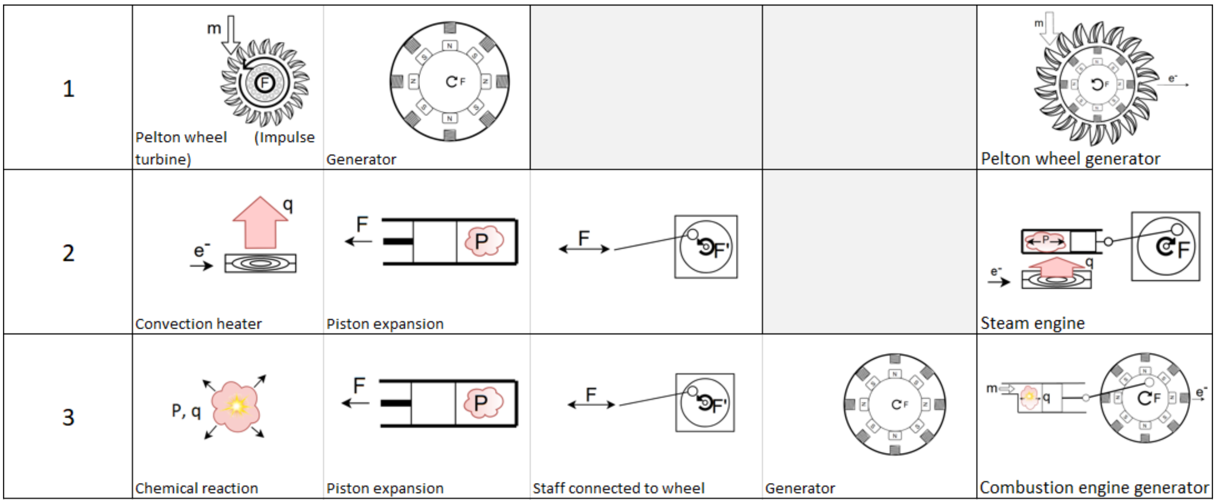


Figure 11.3.3: Examples of deriving conversion modules by combining working principles.

11.3.4 Energy storage working principle

Deriving storage methods is a matter of determining the geometry and motions that enable the storage of energy. Figure 11.3.4 provides the identified working principles that enable kinetic, potential, pressurized and thermal energy storage for the energy storage principles. Describing such working principles using only two dimension is difficult, and therefore several tables were made.

11.3.5 Energy storage modules

With the general working principles established the table can be further expanded on to define the energy storage modules. There are several methods to derive such solutions, but an example is provided in figure 11.3.5. An energy storage working principle is selected from figure 11.3.4 and solutions are further derived by the differentiation between solutions that are above and below the waterline. Differentiating solutions simplify the process of deriving new and innovative designs and enable a structural approach in doing so. It is not considered within the scope of the thesis to derive all possible solutions, and therefore a small example is made to provide a possible approach to further develop the design catalogue.

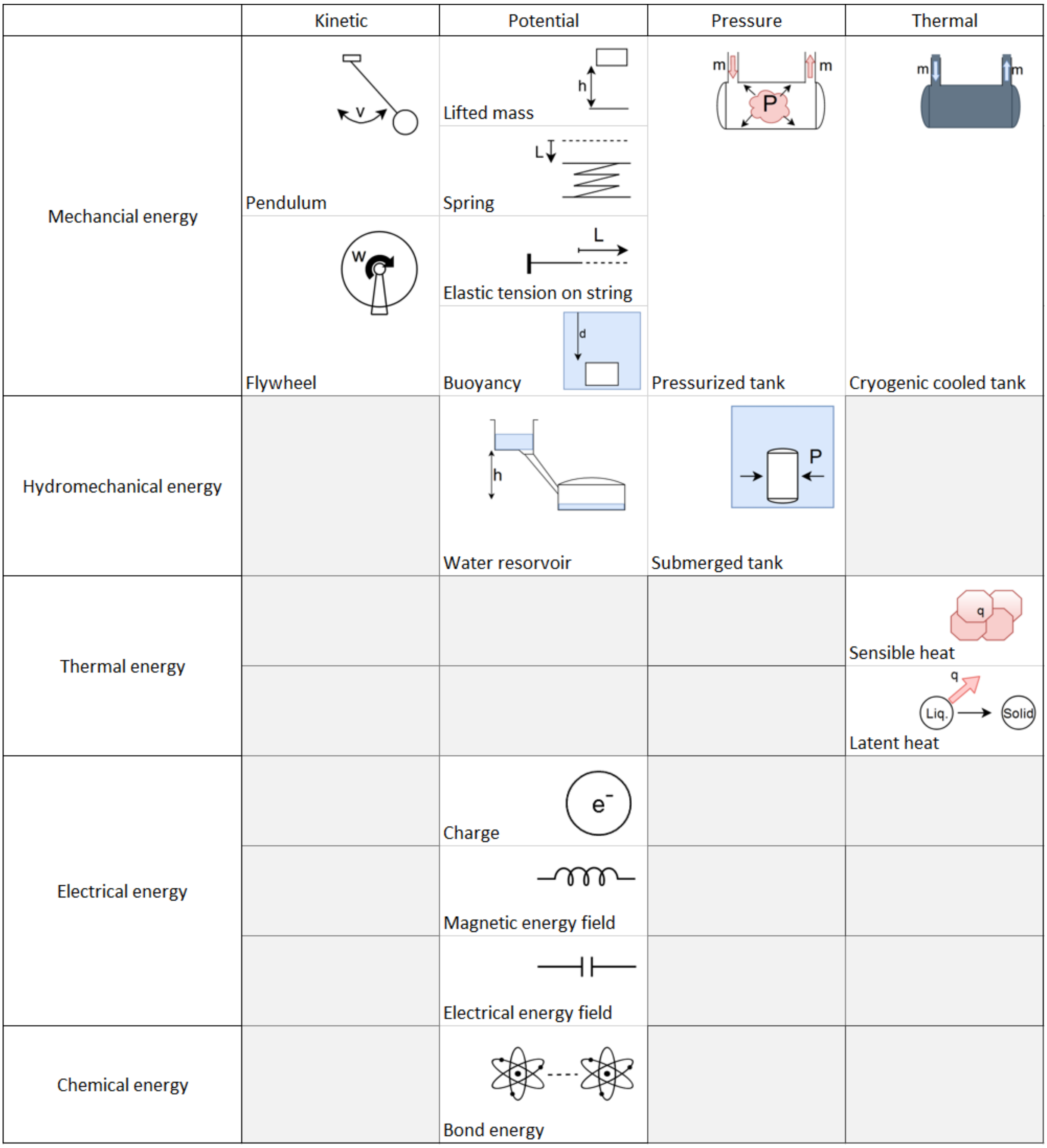


Figure 11.3.4: Working principles that utilize physical effects for energy storage for different energy types.

11.4 Design catalogue

The design catalogue is a catalogue of all the modules that have been derived for the product platform and is provided in figure ??. The catalogue is divided into module 1, 2 and 3, where 1 and 3 are the conversion modules while 2 is the storage module. By combining a working principle from each module going from left to right, a complete energy storage solution can be created. The modules will be compatible if the energy output type is equal to the next components energy input type, which is the modular interface of the product platform. Using such a system enables a designer to generate a large number of system designs in a short period of time. All the necessary information

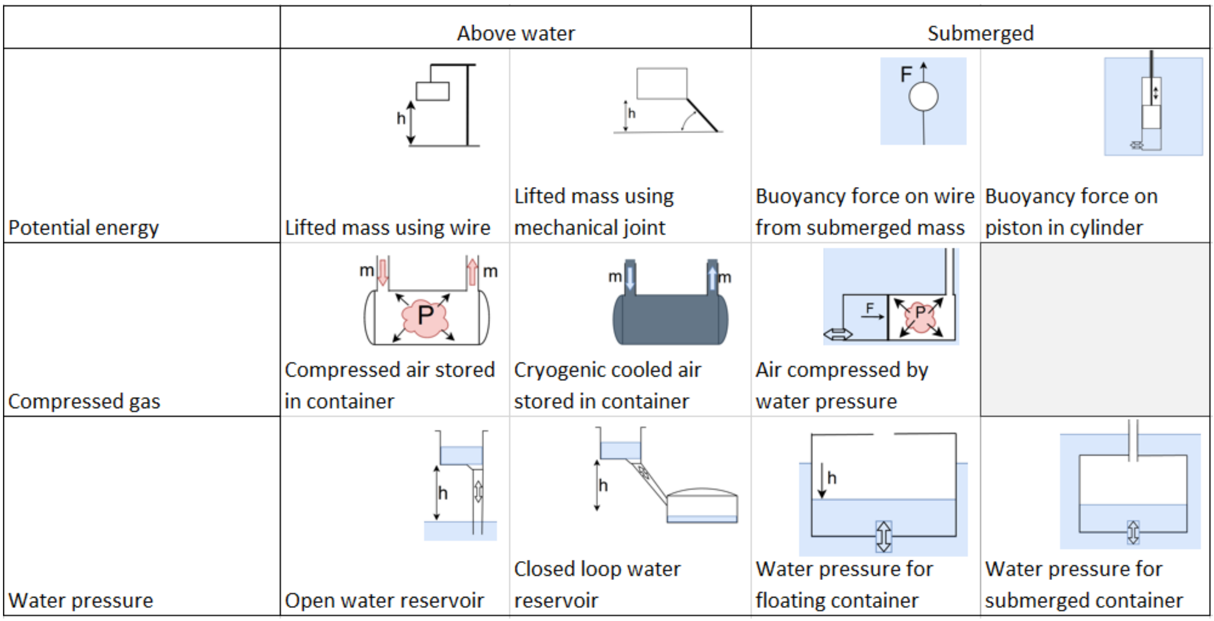


Figure 11.3.5: Deriving storage modules from working principles.

and characteristics of each module that is included in the system can be combined to calculate the performance of the complete system. In this thesis, the configuration process is digitized, but the catalogue will still be available for the designer to look up information about potential modules.

The catalogue provides a short description and a graphical illustration of each module to make it more understandable. The illustrations provide information such as what energy type they can operate with. Due to time constraints, a detailed design of all the modules could not be created and a simplified illustration showing what principle they are based on was developed instead. The storage of compressed air was moved to thermal energy storage, although a CAES system is defined as mechanical energy. This was done due to the close relationship between pressure and heat making the compressor a thermal module for conversion.

The module column in the design catalogue is divided into variation a and b. More variations may be applied as the catalogue is further developed and new variations of working principles are identified. Finally, the rows are provided with a solution number. These divisions are made to enable the catalogue to be digitized. When inspecting a system solution the designer would want to know which modules that the system consists of. The program can simply refer to the module, variation and solution number to relay this information to the designer. For example would M1:1b refer to module 1, solution 1 and variant b, being the winch.

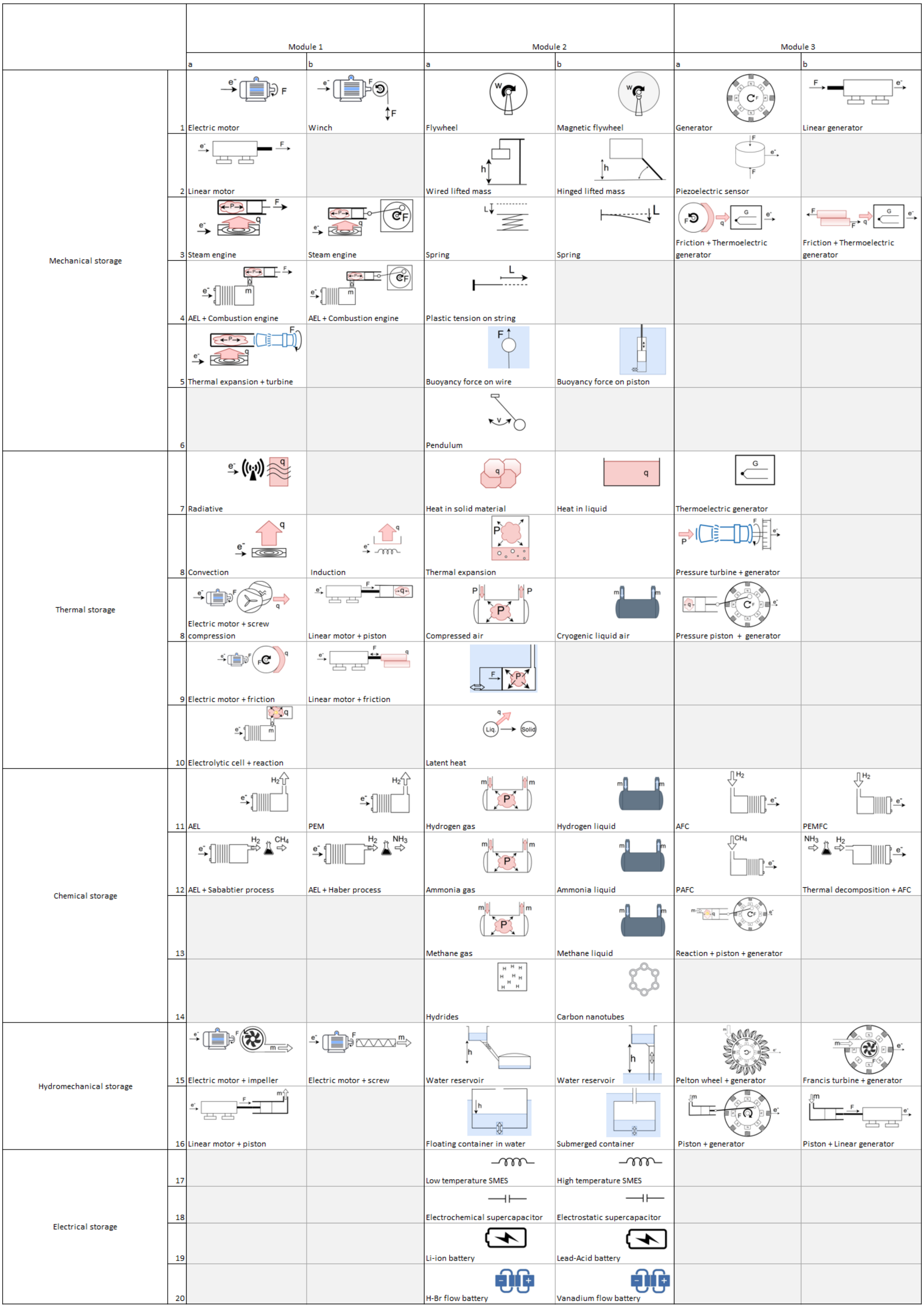


Figure 11.4.1: Design catalogue of the modules derived for the product platform.

Chapter 12

Configuration of modules

This chapter begins the process of developing a method for the configuration of the modules. The chapter defines the characteristics of the configurator and the fundamental theory that supports the configuration process.

12.1 Configurator for offshore energy storage

Figure 12.1.1 illustrates the chosen configurator characteristics for the configuration process of an offshore energy storage system.

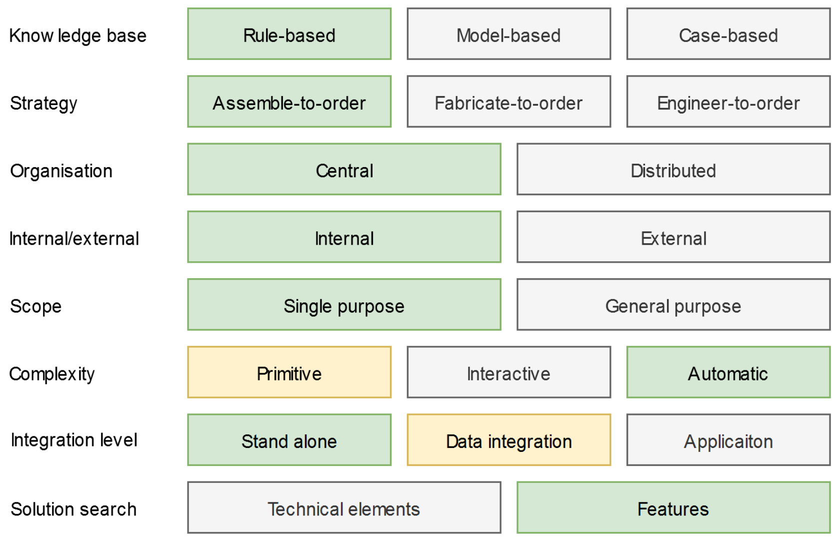


Figure 12.1.1: Characteristics and features of the configurator for offshore energy storage systems.

12.1.1 Knowledge base and configurator complexity

For the knowledge base of the configurator, a rule-based approach is suitable as it separates the configuration knowledge from the design knowledge. In contrast to case-based knowledge, a rule-based configurator will not be dependent on the database of configured systems. This enables parallel work between module development and module configuration, which is crucial for the efficiency of the product platform. The catalogue of modules can be continuously updated independently from the configuration process and a constantly maintained knowledge base that is easily accessible to the configurator throughout a design process can enable better decision making and thus better results.

A rule-based approach is dependent on a clear definition of the structure of the product. For example which parameters and elements it is allowed to operate on, and to what degree. A rule-based approach can therefore not accommodate for innovation. As a routine design process, it is optimal to minimise the complexity of the configuration process. As such, an automatic configurator that requires little input from the designer is required.

However, the configurator should still enable the designer to guide the configuration process to some degree, and evaluate the decisions made throughout the process. To accommodate for this two configurators are made. An automatic configurator that generates a large number of systems based on user inputs and a manual configurator where the level of complexity is primitive, enabling more interaction from the designer.

12.1.2 Configuration strategy

The structure of the product platform enables the use of a downstream CODP strategy for the configuration of the modules. As the systems can be assembled by choosing a set of modules in a select-scale-arrange cycle and the innovation is isolated to the development of the modules it is possible to use the ATO strategy. The configuration consist exclusively of the modules from the module catalogue and the customer involvement is very limited. No requirement of unique engineering combined with a short lead time simplifies the configuration substantially and makes the strategy a viable option to maintain the cost competitiveness of the solution. As this is only the conceptual design phase of the development process, the customer can be more involved in a later stage of the design process.

12.1.3 Additional classifications

Further, the configurator is assumed to be applied to a central design team for internal use. The scope of the configurator is to apply it to a single purpose, which is designing energy storage systems for offshore production. The integration level is assumed to be stand-alone, with the accommodation of implementing input or outputs to third party applications for secondary object design representation. The solution search should be based on the features of the alternative designs, and how these features fulfil the requirements of the customer.

12.2 Minimising configuration time

Minimising the configuration time enables a large number of designs to be generated in a shorter period of time. This allows the designer to make adjustments to the configuration input and rerunning the configuration process without it being too time-consuming. Moreover, less time spent on the configuration process means that the designer can use more time on evaluating the resulting designs and identify the optimal solution. To achieve this it is necessary to establish what information that is required for the configurator to perform its task and which tasks that can be postponed to a later stage of the configuration process.

To evaluate the performance of the generated solution the configurator needs the design representation knowledge of the modules that are included in the system. The primary object representation is necessary to calculate the performance of the complete system, as this is performed by combining the parameters from each module. For example, the total round-trip efficiency of the system will be the combination of the energy efficiency of the conversion modules.

The secondary object representation is what the configurator determines, calculating the system specifications, performance and physical positions in the system. However, some of this information can be postponed to a later stage in the configuration process. The physical positions of the module can be necessary to calculate the power capacity of some of the storage solutions, however, this information can be provided to the configurator as numerical data.

At the evaluation stage, the solutions can be inspected as 2D flow diagrams, illustrating the flow of energy from one component to the next. The data required to generate 2D drawings or 3D Computer Aided Design (CAD) models for all solutions is unnecessarily time-consuming. Using a system-based approach in the evaluation step of the configurator will therefore increase the efficiency of the calculation and diminish unnecessary information. The 2D drawings and 3D CAD models can be generated at a later stage when the number of solutions are fewer.

To create 2D drawings or 3D CAD models certain information is required. The position of the conversion modules with respect to the storage module are often strict. Data describing where the conversion modules can be positioned is therefore necessary. This is referred to as zone-based modelling and is important to properly arrange the modules to illustrate what the system will look like to the user.

12.3 Evaluating results

A solution can be evaluated by comparing the intended performance with the achieved performance of the design, see figure 12.3.1. The intended performance is defined by the customer requirements and set the optimal values for the functional performance of a design. As such, a design can be evaluated by comparing how close its performance is to the optimal values.

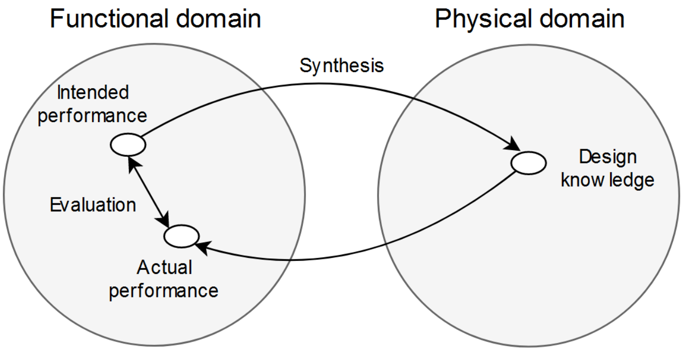


Figure 12.3.1: Evaluation of a designs functional performance

However, the system solutions are still in a conceptual phase, meaning that the actual performance of the design is an estimation based on mathematical models. As such, the evaluation is based on estimated performance values. Hazelrigg addresses this issue in the book *A Framework for Decision-Based Engineering Design* from 1998, arguing that the preferred solution is the one whose expectation has the highest value (Hazelrigg, 1998). This is important to consider when comparing the different solutions to one another, as the extra cost of a solution whose performance is expected to be slightly better than another may be false due to errors from the estimation. In such cases, it may be beneficial to choose the cheaper solution. Such relations can be illustrated using graphical models such as a Pareto front.

There are many requirements that need to be evaluated and the value of the trade-off between the different characteristics of a solution can be difficult to interpret. With a large variety of solutions, it becomes increasingly difficult for the designer to identify the preferred systems. To be able to make a rational choice, there is a need for an automated process that applies a mathematical approach to evaluate both quantifiable and non-quantifiable requirements. Each design point can then be provided with a score of how well its performance meets the requirements, and it becomes easier for the designer to decide which solution to move forward with. This thesis will draw inspiration from Hazelrigg's Decision-Based Design, and apply the use of utility theory(Hazelrigg, 1998).

12.3.1 Utility theory

Utility theory is a method of rank-ordering a set of solutions from least desirable to most desirable. This ranking is achieved by introducing a scalar that describes how well a design satisfies a set of requirements. This scalar is called utility, and effectively describes the value of a design (Hazelrigg, 1998).

Utility functions are used to calculate the performance of a design function by the use of mathematical formulas. The utility functions are provided with an optimal value and a minimal value for a performance requirement and illustrate where on this scale the designs actual performance is. Utility theory therefore enables the designer to evaluate the trade-off between two functional performances by providing the functional requirement as a scale from least desirable to most desirable, instead of a single scalar.

The utility functions normalise the score such that 1 is optimal and 0 is minimal. After calculating the utility for each function, they can be combined to provide a total score for the design. However, the functional requirements of a design are often conflicting, meaning that there is a trade-off between the functional performances of the design. For example, increasing the width of a ship may increase its storage capacity, but may also lower its cruising speed. As a result, the customer needs to evaluate which functional performances that are more important than others. This information is conveyed to the configurator using mathematical weights, which can be derived and calculated using the Analytic Hierarchy Process (AHP). These weights are multiplied by the utility score for their respective design functions.

Chapter 13

Configuration process

The configuration process is illustrated by figure 13.2.1. The configuration process starts by receiving a customer specification with a set of requirements, which are used to derive the functional requirements for the energy storage system. A configurator is used to select, scale and arrange modules based on the set of rules provided by the product platform architecture. After calculating the performance of each solution using utility theory, they are evaluated by an engineer to verify that the solutions are viable and satisfactory. Finally, an optimal solution can be chosen from the set of possible designs. This chapter will further expand on these configuration steps.

13.1 Project requirements

The configuration process begins when a customer order is received. The level detail in the customer specification can vary as some may provide a detailed requirements list for specific components in the system, while others may simply specify a few requirements towards the overall function of the system. Before starting the design process, it is important to properly establish what the customer wants to accomplish with the energy storage system, and what applications the system should be able to deliver. This involves establishing the requirements and restrictions that are expected from the stakeholders.

13.1.1 System requirements

As explained in Chapter 9, modularity handles the complexity of a system by limiting the detail of the modules in early design phases, and increase the detail level as the design phases progress. As such, some requirements may be too detailed to be directly addressed by the module in the conceptual design phase. For example, a customer may have requirements towards what brand to use for a certain component. Although this is too specific to addressed in the conceptual design phase, the modules chosen must enable these requirements to be met at a later stage in the design process.

The requirements from the customer can be related to the physical structure of the energy storage system, such as the size of certain components. However, most of the requirements

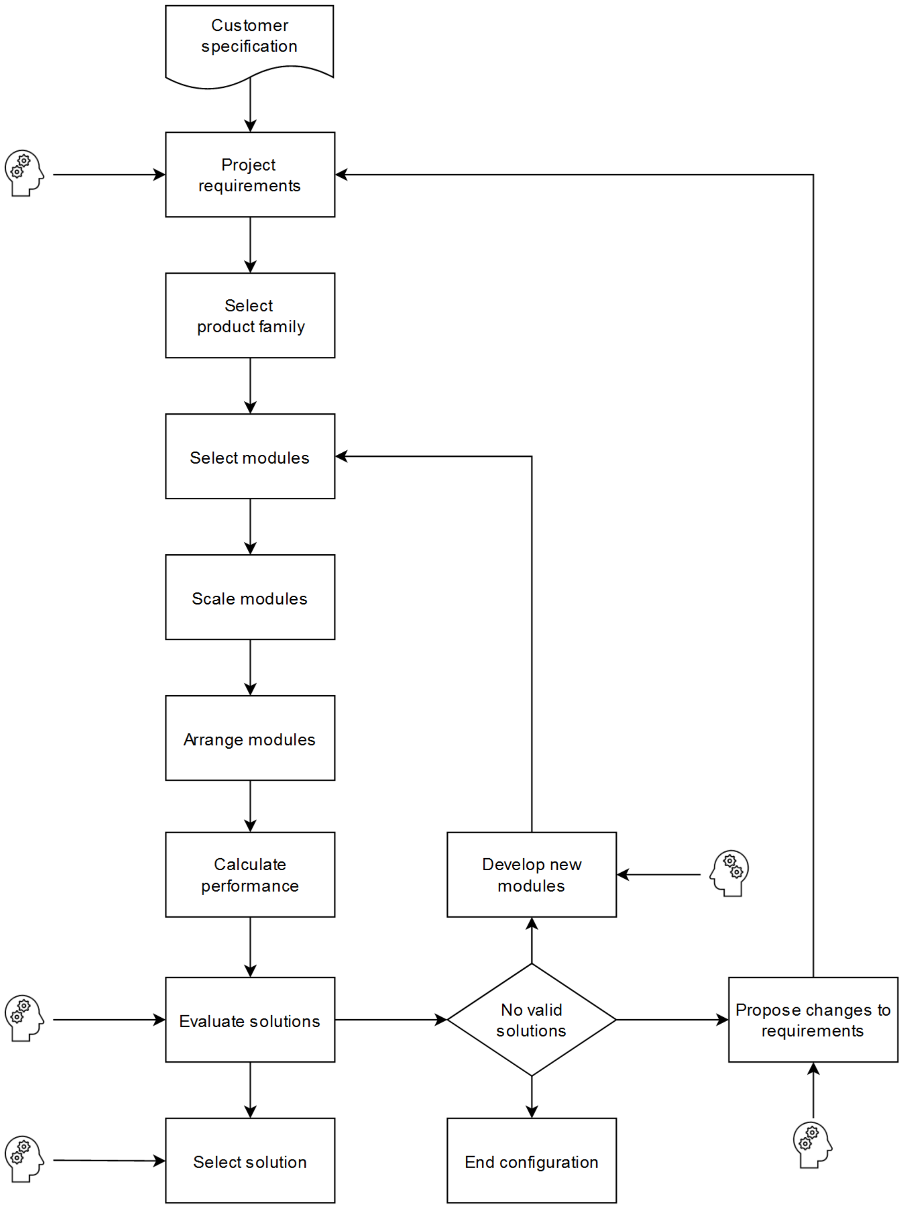


Figure 13.0.1: Flowchart of the configuration process.

will be related to a system function. For example, a customer may want a storage system for long term energy storage. This would give certain criteria towards the energy storage capacity and self-discharge rate. Moreover, there are general criteria that apply to most projects, such as maximising the round-trip efficiency. Such criteria are often restricted with a minimum requirement from the customer.

Additional to the customer needs, external and internal stakeholders will apply a few requirements to the project. Local or international rules and regulations, environmental organizations and societies are external factors that may apply boundaries to the project. Internal factors can be requirements from manufacturers or the owner of the energy production site. The design requirements often conflict with each other such that a design can not fully satisfy all requirements to the highest degree. For example, the customer operates within a certain budget that can not be breached, forcing a trade-off between the design characteristics. Mathematical weights and utility theory are used to establish the value of a trade-off between two characteristics.

13.1.2 Functional requirements

The designs are evaluated by comparing how well the performance of the system meets the system requirements. As a wide range of design solutions are generated it is necessary to automate the evaluation process to decrease the configuration time. However, to automate such a process the project requirements needs to be expressed by a quantifiable value. This is solved by mapping the system requirements to functional requirements and using utility theory for the performance calculation.

There are several methods of mapping customer requirements to functional requirements. The process is often complex, as the correlation between the different requirements is high for large and complex systems. Simultaneously, a proper mapping technique is crucial for the automated evaluation process to find viable solutions. Therefore, a method that properly illustrates the dependencies between the customer and functional requirements is necessary. Such a process can for example be based on a HOQ.

13.2 Product family

The product platform consists of a large number of modules and modules variants. Combining all of them generates a lot of possible design alternatives, of which many are useless to the customer. By choosing a product family the configuration process is faster, as the amount of possible modules to combine is reduced and the number of design solutions is lower, making the performance calculations and ranking of the designs easier. Moreover, the necessary user inputs for the requirements are reduced, reducing the complexity for the designer. However, choosing a product family is also very restricting, as modules are completely left out of the configuration process. It is therefore important to carefully consider which product family that is suitable.

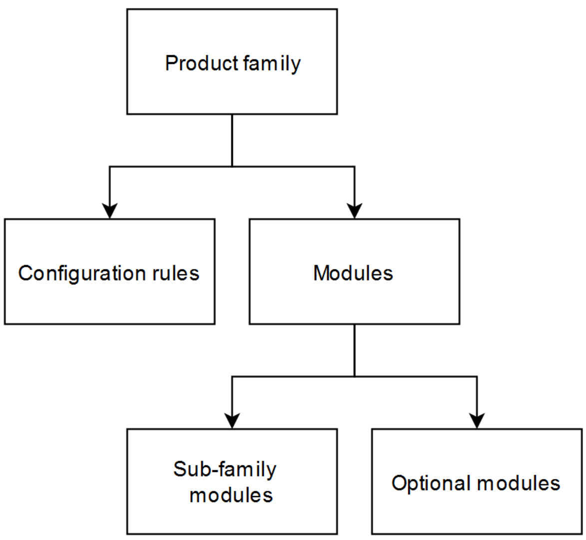


Figure 13.2.1: Product family structure

For this thesis, the product families are onshore and offshore energy storage systems. This is chosen as the configuration rules that apply to the configuration process may differ whether the energy storage system is onshore or offshore. The set of rules for the configurator is therefore included with the choice of a product family. Further, for energy storage systems it is deemed suitable to divide the modules into sub-families of which energy principle they are based on. Energy storage solutions based on the same energy principle often share a lot of characteristics, and it may therefore be beneficial to remove or include some principles based on the customer specification. There are therefore five different subfamilies within the product families. Respectively, mechanical, hydromechanical, thermal, electrical and chemical energy storage. However, the user has the option to manually select modules from family branches that are not chosen if this is deemed necessary.

13.3 Select, scale, arrange

The select, scale and arrange process is automated based on a set of rules and a catalogue of modules to select from.

13.3.1 Select modules

The configurator searches for modules within the product family and combines these to complete systems. The configurator does not make a decision as to what module is best suited, but strictly follow the rules to make sure the systems that are generated are viable. Moreover, given that this is a conceptual design process, the amount of detail is low. This results in a module hierarchy consisting of few levels and nodes, making the number of possible modules manageable.

13.3.2 Scale modules

The configurator scales the necessary modules to fit the functional requirements. For example, the tank capacity of chemical energy storage may be scaled to meet the power capacity requirements. This involves the physical scaling of the tank. Likewise, a flywheel may be scaled for the same purpose. This sets other requirements for neighbouring components, such as being able to handle an increase of power, or an increased charging/discharging rate.

However, an increase in a modules ability to perform its task is not always proportional to an increase in its size. Empirical formulas can be used to describe this ratio and can be established using regression analysis on a database of existing components. Results from such analysis can provide the correlation between a components size and its power rating. The regression analysis only provides an estimate of the module sizes. However, the scaling of modules is mainly to ensure that the functional requirements can be satisfied and that the power required is manageable for each component in the modules. Compared to a system such as a vessel, there are few restrictions to the final geometrical form of the system or the physical size of the modules.

13.3.3 Arrange modules

With all the possible systems generated and scaled, the configurator can determine the modules physical position in the system. The arrangement limitations of the conversion modules are defined by the energy storage module. The offshore energy storage system may be situated on a floating platform, adding geometrical restrictions to the design. The goal of the arrangement process is to create a system that takes advantage of its environment to maximise its efficiency and make the system as compact as possible while accommodating for easy maintenance. However, the need for a space allocation algorithm is low, as there are often few alternatives as to where the conversion modules can be placed with respect to the storage module and the restrictions regarding the shape of the system are few.

There may be many system solutions at this point in the configuration process, and the arrangement of the modules are therefore stored as numerical values. Before illustrating the design solutions using CAD or 2D drawings, the number of possible designs needs to be reduced. Therefore, the visual representation of the systems is generated after the performance calculation, when the number of designs are fewer.

13.4 Calculate performance

At this point in the configuration process, the solution space consists of all the possible systems that can be generated from the set of modules in the product family. This may be a large number of systems which needs to be evaluated against the customer requirements. Performing this process manually would be time consuming and inefficient. The solution space can be reduced by calculating the performance of the acquired systems and comparing them to the project requirements. This calculation is performed using utility theory. The designs that does not meet the minimum requirements will be discarded, leaving a set of viable solutions that can be ranked and evaluated.

13.5 Evaluation and verification

The configuration process is complete and the evaluation of the viable designs require human input. The remaining design solutions are provided in tabular and graphical form and can be ranked with respect to different criteria. At this point, the designer has the option to generate 2D drawings and CAD models, to display the visual geometry of the solutions.

The data provided in the table is verified by the designer. If the inputs to the configurator and the empirical formulas used in the scaling process are unrealistic, the data for the final design solutions can provide a skewed image of how the system actually performs. Although this is a conceptual design and the data provided are only estimates, they need to be consistently accurate enough for the ranking of the design solutions to provide a viable result.

If no solutions are considered viable there is a number of different options for the design process. This stage should be discussed by the different stakeholders in the project, as the motivations behind such a choice may vary dependent on the stakeholders involved. One option is to move forward with the design process by innovating new modules that can satisfy the functional requirements to a higher degree. Another option is to change the customer requirements to be more realistic in terms of what modules and systems the configuration process can develop. The final option is to end the configuration process, as the changes necessary are too extensive and requires a more manual design approach. In such a scenario the requirements for the case should be sent to the module development, to ensure that the product platform has the modules necessary to satisfy such requirements in the future.

13.6 Select solution

The designer is left with a small number of design options that perform well in their own way. The decision of which of these conceptual designs to move further with is up to the customer and the other stakeholder involved in the project. Both primary and secondary object representation will be available to enable the designer to make a rational choice.

Chapter 14

Case study

The intention of the case study is to illustrate how the configuration software can be used to design conceptual offshore energy storage solutions. As the product platform and configuration process are not fully developed, the case study will only illustrate how such a program may look using a mock-up of the software.

14.1 Case

A wind farm is located approximately 200 km off the east coast of Yorkshire. The wind farm consists of 174 floating wind turbines over an area of 560 km^2. With a capacity of 7 MW each, the wind farm has a total generation capacity of 1.2 GW. The depth at the site is approximately 60 m.

The customer has conducted a correlation analysis between the grid power demand and the power generation at the site. Historical data suggest that the site experiences higher wind speeds during the winter season, and lower wind speeds during the summer season. These overall season fluctuations are in balance with the season fluctuations of the grid demand, however, day to day fluctuations are not.

By running a simulation based on statistical wind and grid demand data the customer finds that storing 10% of the energy that is generated during the night will provide a substantial efficiency increase. The energy is sold cheap during this period due to lower energy demand, and selling it during the daytime can increase the cost-efficiency. Moreover, the energy production experiences issues with voltage spikes, and the customer would like an energy storage system that can counteract these spikes. The customer would like to investigate conceptual designs of offshore energy storage systems that can perform these tasks.

14.2 Configuration software

Opening the configuration software displays a start page with three options and a search function, see figure 14.2.1. The user can choose to look at the design catalogue or the database of previously designed systems. This may be beneficial when conversing with the customer to get a general idea of what kind of system they are looking for. Choosing system configuration will prompt the user to choose between automatic and manual configuration. For now, the configuration will continue as an automatic configuration. The manual configuration will be presented later.

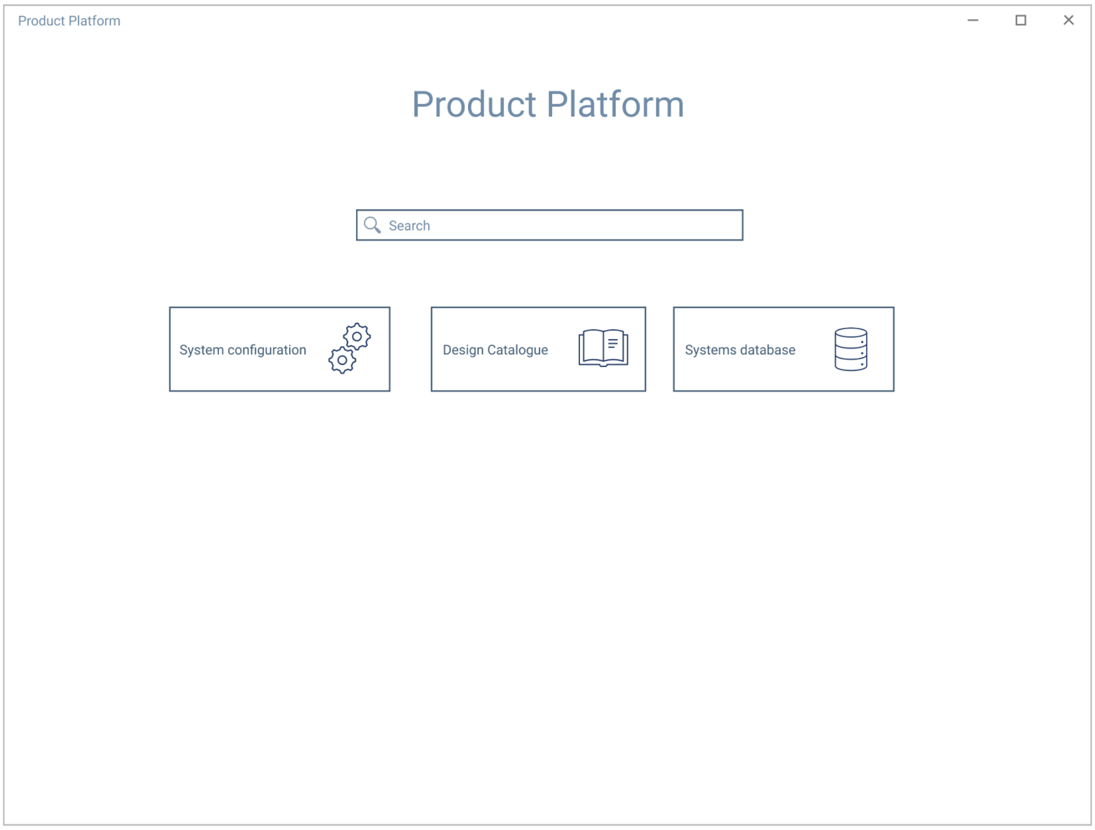


Figure 14.2.1: Configuration software: Startup Page.

14.3 Project information

Before choosing a product family the configurator needs some basic information about the production site. This information is used to estimate how the energy storage modules can exploit the local environment of the site and to what degree. For example, a subsea gravitational storage system will benefit from a deep ocean with respect to storage capacities. Specifying what energy transportation method that is available may reduce the number of relevant modules. Coupled with information such as the intended use-case of the energy storage system and potential energy markets, the configurator can recommend what product family and subfamilies that are most suitable. Figure 14.3.1 illustrates what such a page may look like in the automatic system configurator.

The data is calculated from the information provided by the case, and by using some assumptions. With a total capacity of 1.2 GW it is expected that approximately 30% of this capacity is being produced on average. Storing 10% over a time period of 12 hours results in a storage capacity of 432 MW with a charge/discharge rate of 36 MWh.

For a real case, this calculation would be based on simulations and statistical data to provide a more detailed and accurate result. Statistical wind data is readily available on the web, and by using software such as MATLAB Simulink the user can set up a simulation scenario to calculate the necessary storage capacity.

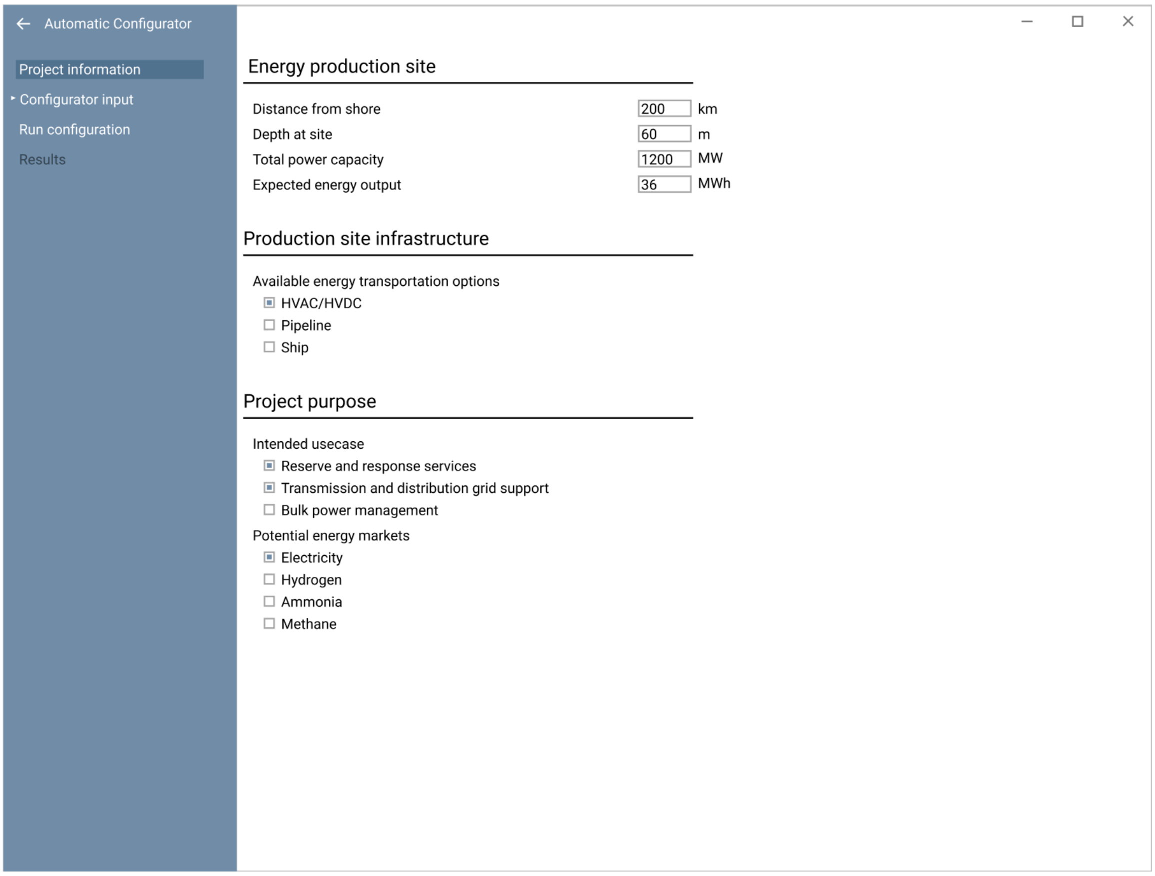


Figure 14.3.1: Configuration software: Project Information.

14.4 Select product family

With the basic project information established the product family can be selected. This step limits the number of possible modules that can be combined to generate complete systems. This reduces the run time for the configuration, but also limits the number of solutions. It is therefore important to closely consider what system characteristics the customer requires, and which product family and subfamily that may satisfy these requirements. Therefore, a recommendation from the configurator is added to the software to help guide the designer through the input process.

Figure 14.4.1 illustrates the product family page in the configurator. From the information provided on the previous page, the configurator recommends disregarding chemical energy storage solutions. Chemical energy storage is best suited for bulk power management. Moreover, the available energy transportation is sub-sea cable and the potential energy market is only electricity. The low round-trip efficiency of chemical storage and high response time makes it unsuitable for this case. It is also possible to further specify which modules that are included for each energy principle in the configurator by viewing the design catalogue.

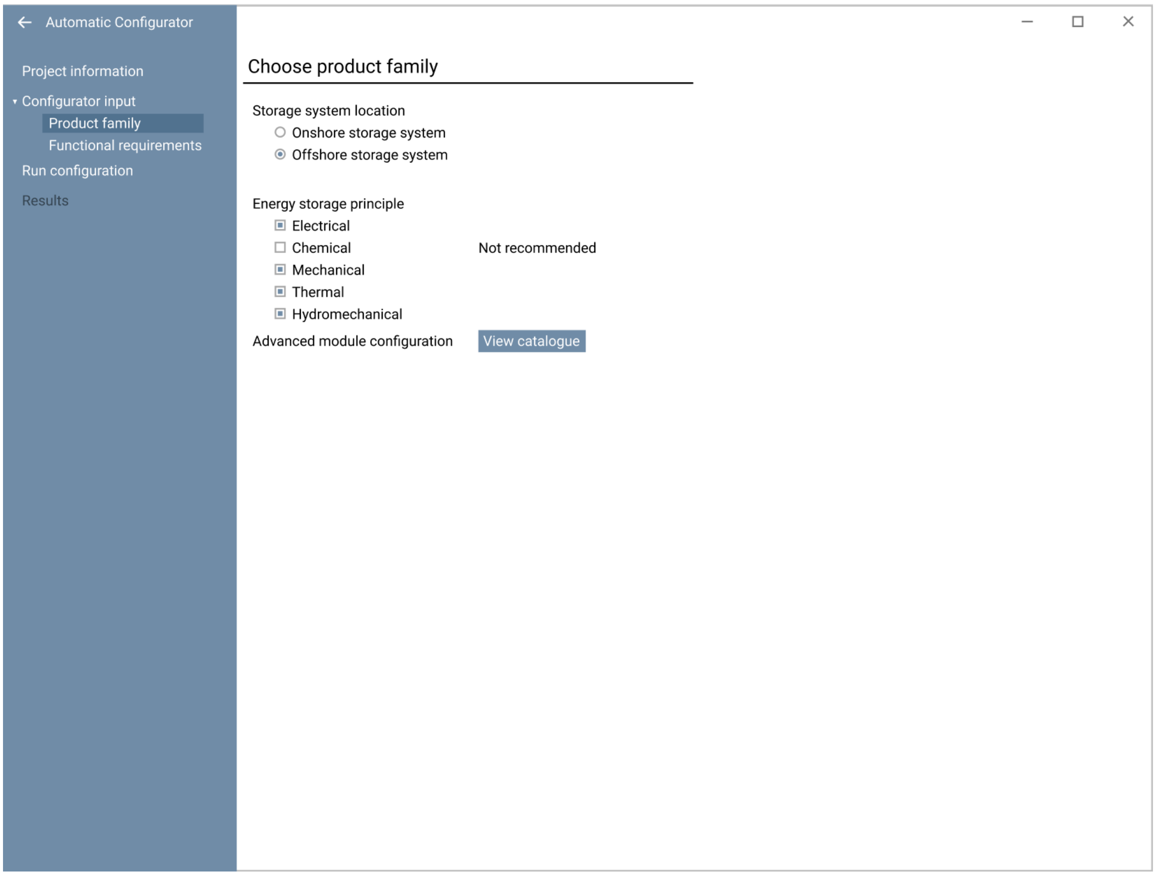


Figure 14.4.1: Configuration software: Product family.

14.5 Input functional requirements

A few customer requirements can be derived from the information provided in the case. However, the detail in the case is not sufficient to establish all the necessary requirements to start the configuration process. Moreover, the customer requirements need to be mapped over to functional requirements to be used as an input to the configurator. As mentioned previously this step must be performed through discussion and analysis with the customer, to derive what the customer wants to accomplish with the system and what boundaries exist. The necessary requirements and boundaries of this case study are assumed.

Figure 14.5.1 provides the input of the functional requirements to the configurator. The functional requirements are first selected by the user, as not all requirements may be relevant for all cases. The user can choose to minimise or maximise the requirements or specify the scale where the performance of the system should be. This scale is used to calculate the utility score for the system. Finally, a weight is added to each requirement. This is to enable the user to prioritize certain functional requirements above others. A utility of 1 is considered optimal, while a utility of 0 is the lower boundary. Any solutions with a performance below this boundary are discarded.

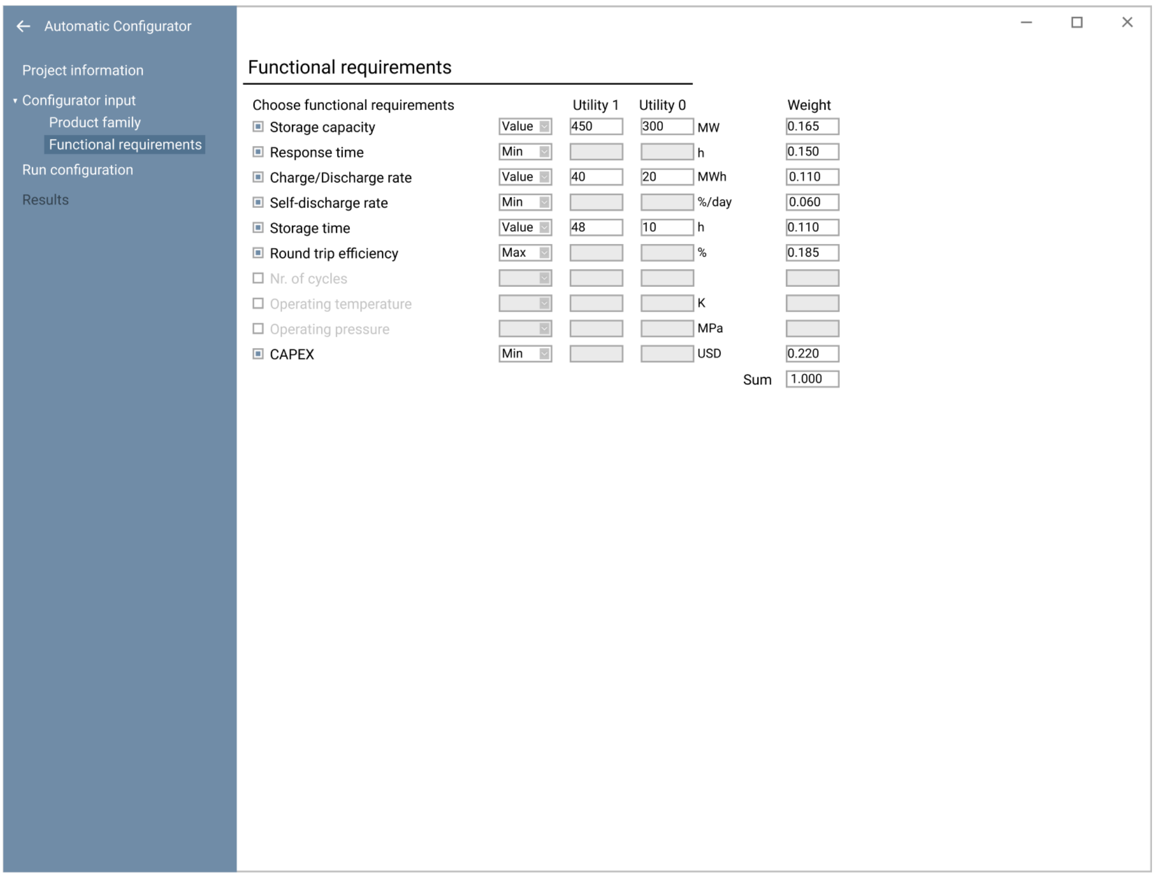


Figure 14.5.1: Configuration software: Functional requirements.

14.6 Run configuration

The necessary information to run the configurator has been gathered. A few configuration options can be added to improve the configuration process, see figure 14.6.1. Generating hybrid systems may be beneficial in some cases to support both bulk management and fast response services. If all the modules are included in the configurator it may be a very time-consuming process. The user is therefore provided with the option to not generate all possible module combination, but rather use a sampling method to shorten the configuration time.

A configuration summary is provided with the number of modules and an estimated configuration time. It is important to remember that these values would be larger in a fully developed system, as there would be more modules in the design catalogue.

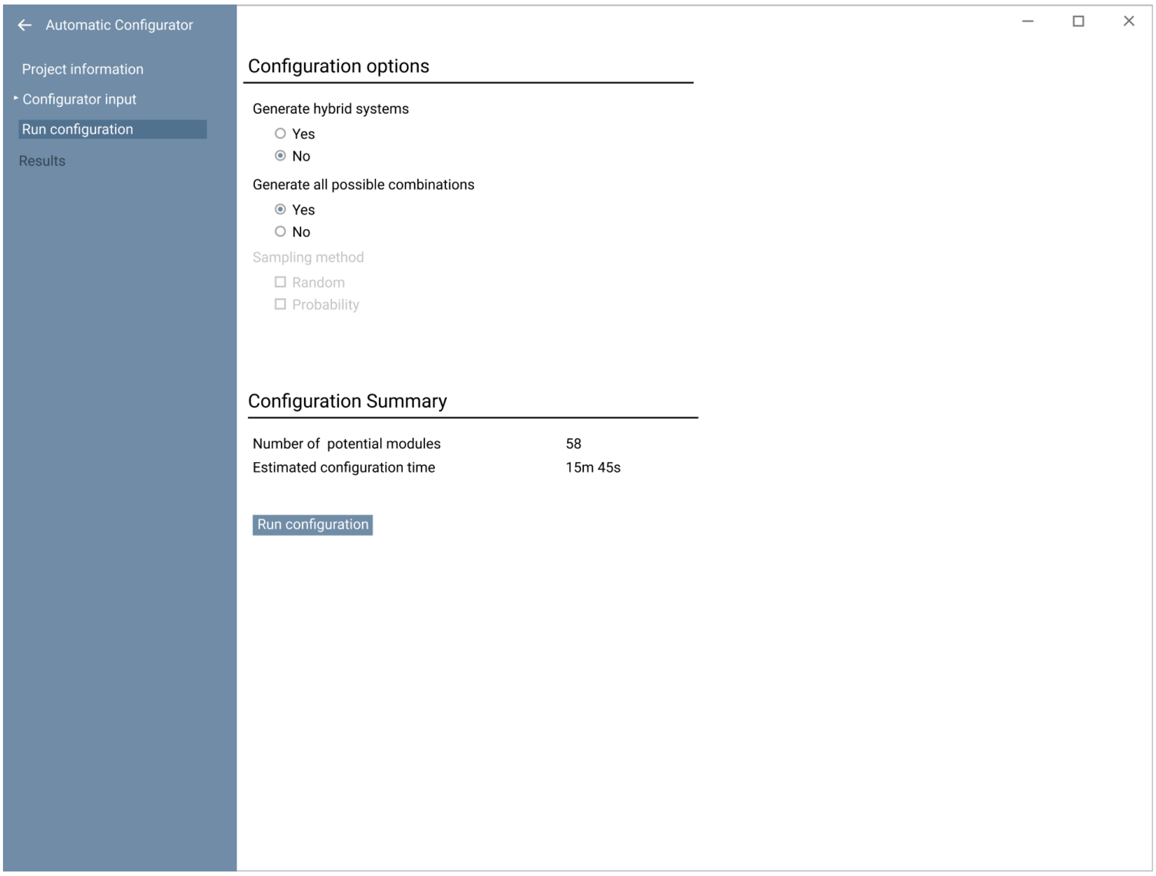


Figure 14.6.1: Configuration software: Configuration options.

The configuration starts with the select and scale process, where module combinations are selected to generate complete systems and scaled to fit the functional requirements as close as possible. The user is provided with the number of solutions found and an estimate of the remaining time for the select and scale process, see figure 14.6.2.

After the select and scale process is complete the configurator calculates the performance of the generated systems and evaluate the results. This process compares the performance to the functional requirements and calculates the utility score for each solution. The solutions with a functional performance below the requirements are discarded. The number of viable solutions and the number of discarded solutions are conveyed to the

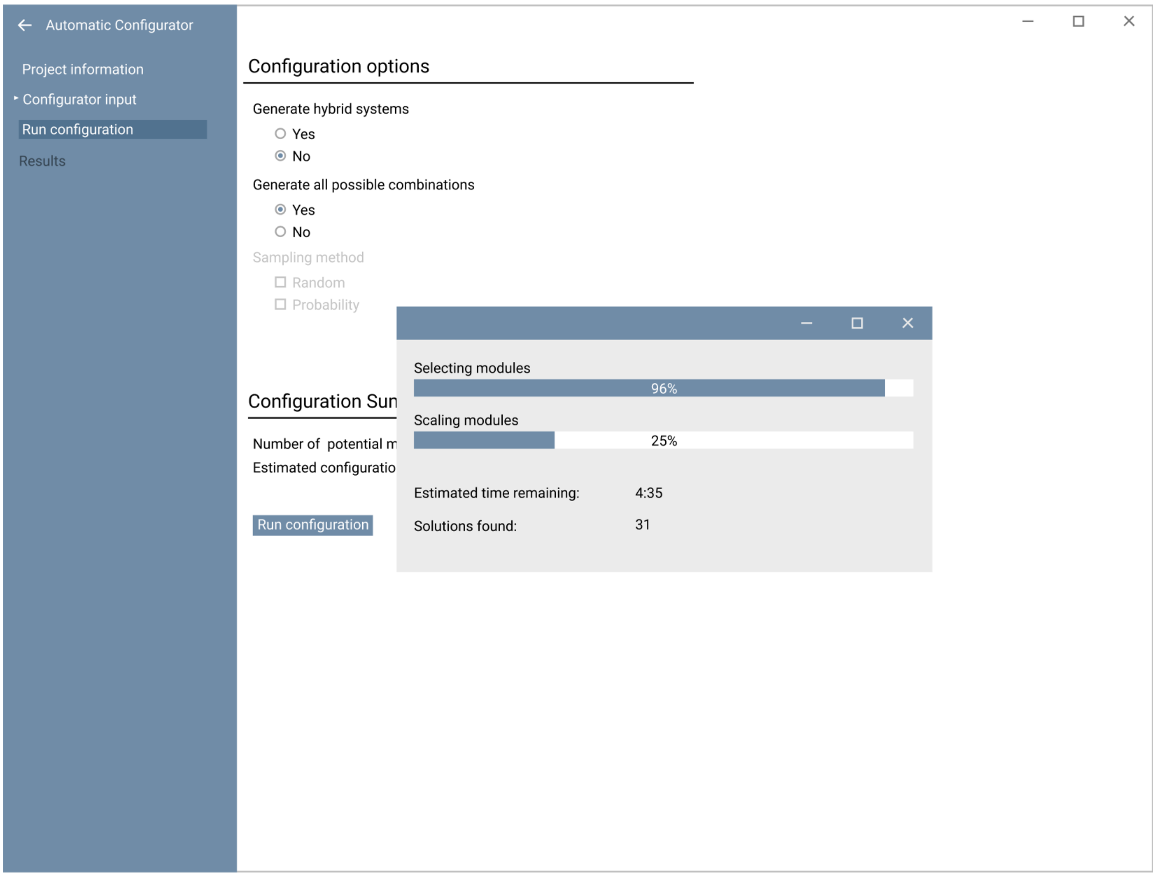


Figure 14.6.2: Configuration software: Select and scale.

user, see figure 14.6.3. If the number of viable and discarded solutions are unsatisfactory, the user can cancel the configuration and make the necessary changes to generate more viable solutions.

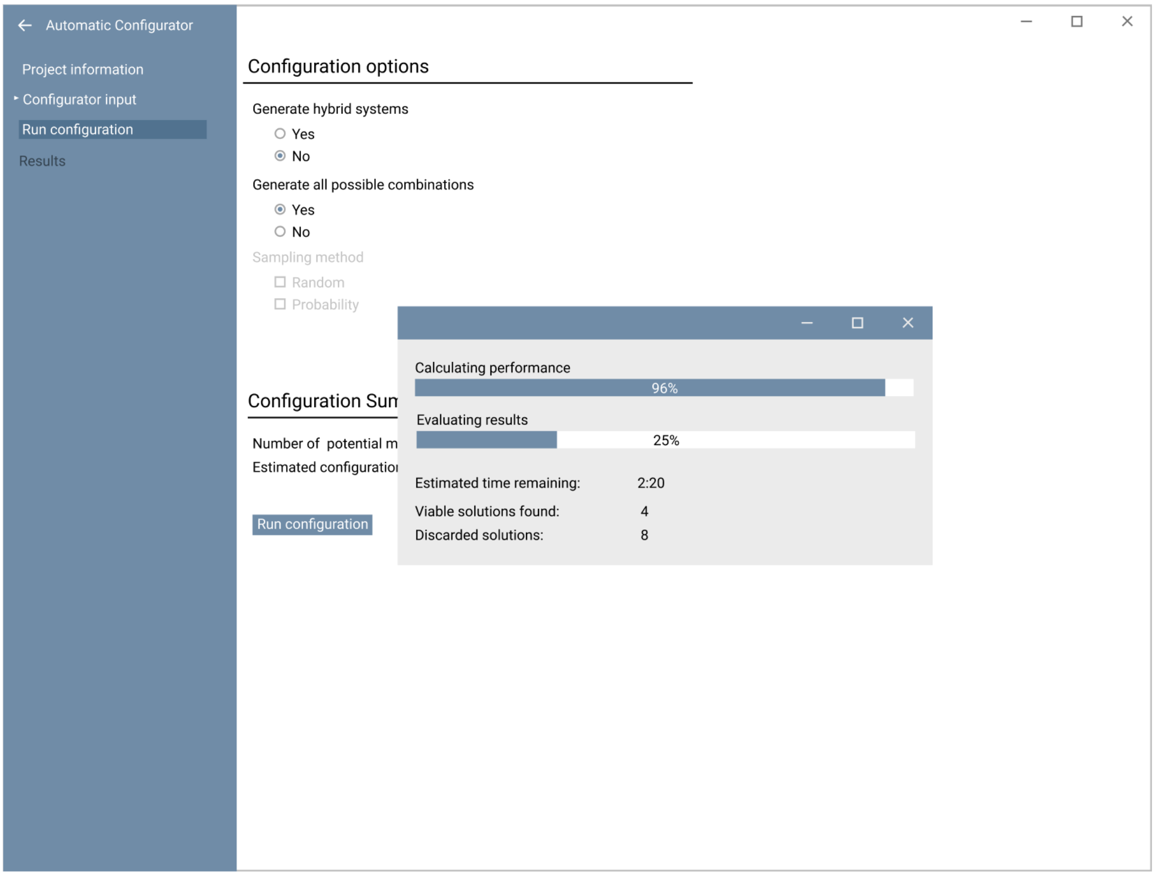


Figure 14.6.3: Configuration software: Calculate performance.

14.7 Results

There are many different methods to display the results. This helps the user to make a rational choice when deciding which design to move forward with. The user is offered to configure both tabular and graphical results in a result options page, see figure 14.7.1. The tabular results can either consist of real values or the utility score of each functional requirement. To minimise the complexity of the table, the amount of information it includes can also be reduced by choosing which requirements that are to be included in the table. Finally, the user is provided with the option to include the total utility score for the solutions and may also include the discarded results in the table.

The options for the graphical results include choosing the data set for the x- and y-axis, and whether this data should be displayed as utility score or real values. The user is prompted to choose a diagram type, which in this case is selected to be a Pareto front.

Figure 14.7.2 illustrates the graphical results of the configuration process. The results are based on rough approximations, and does not represent values for actual systems. This is just to showcase what a graphical result may look like by using the configurator and setting up the graphical option to create a Pareto front.

Figure 14.7.3 provides the tabular result from the configuration. Like the graphical results, these results are also based on rough approximation. The values are calculated from the data collected in the research phase found in Appendix A.1. Moreover, information from

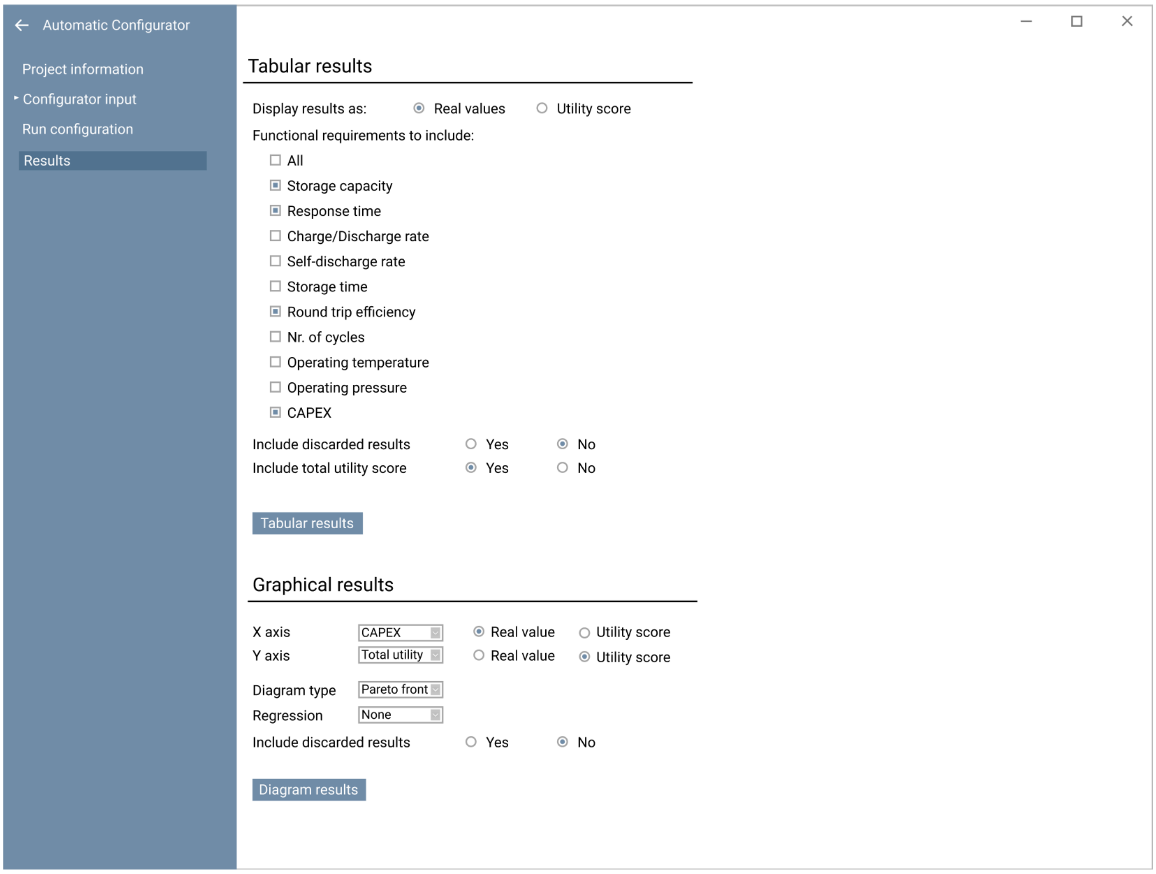


Figure 14.7.1: Configuration software: Result options.

the market analysis suggests that the end result should be a large scale system according to table 3.2.1. The customer wants services such as peak shaving and voltage regulation, which can be defined as capacity firming. This places the storage time at a few hours to days.

These two methods provide a good overview of the available solutions and how they compare to one another. The results illustrate the trade-off between utility score and cost between the solutions. For example, the user may choose the most expensive solutions to get the highest utility score. This will deliver a result that, theoretically, will satisfy the functional requirements to the highest degree. The user may also look for the solution in the Pareto front that provides the highest increase in utility score with respect to cost to develop a cost-efficient system.

The user may require more information about each design to make a good decision of what to move forward with. By selecting the details button, the system will be opened in the manual configurator, providing much more information about the system, and the modules within it.

14.8 Manual configuration

Figure 14.8.1 illustrates what the manual configurator may look like in the configuration software. Using this program the user can drag modules into the grid and connect them

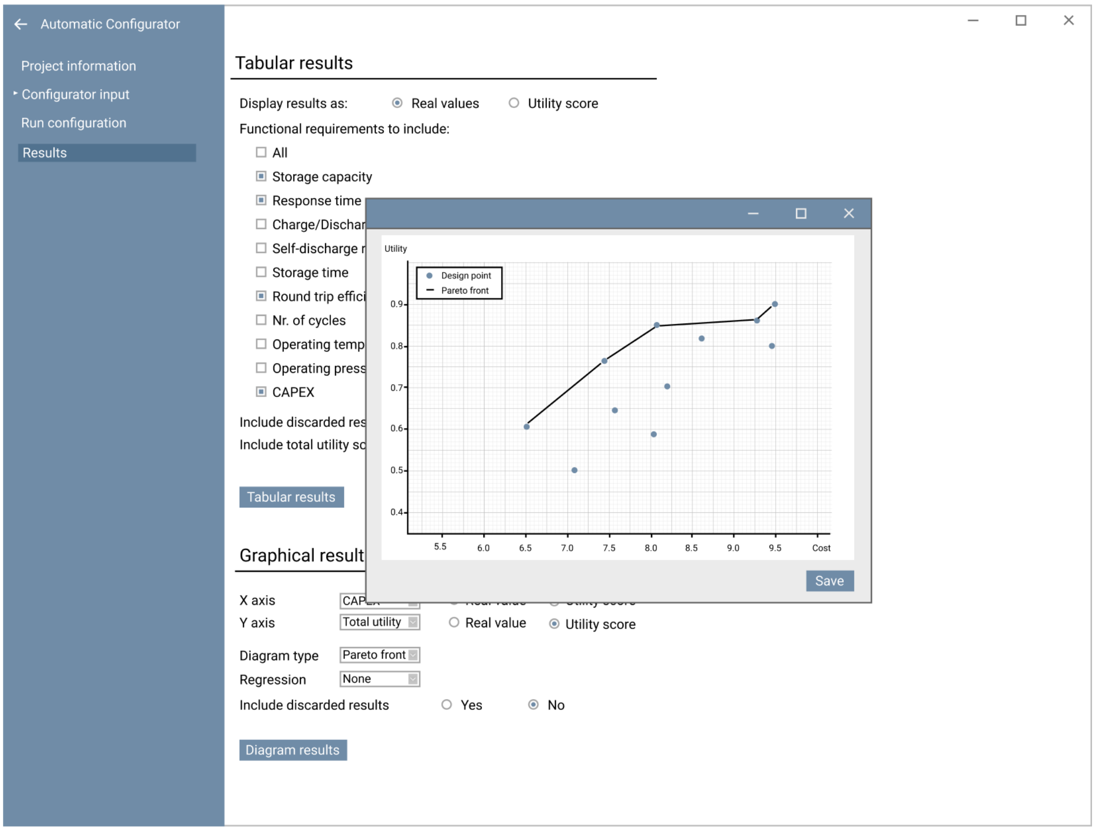


Figure 14.7.2: Configuration software: Graphical results.

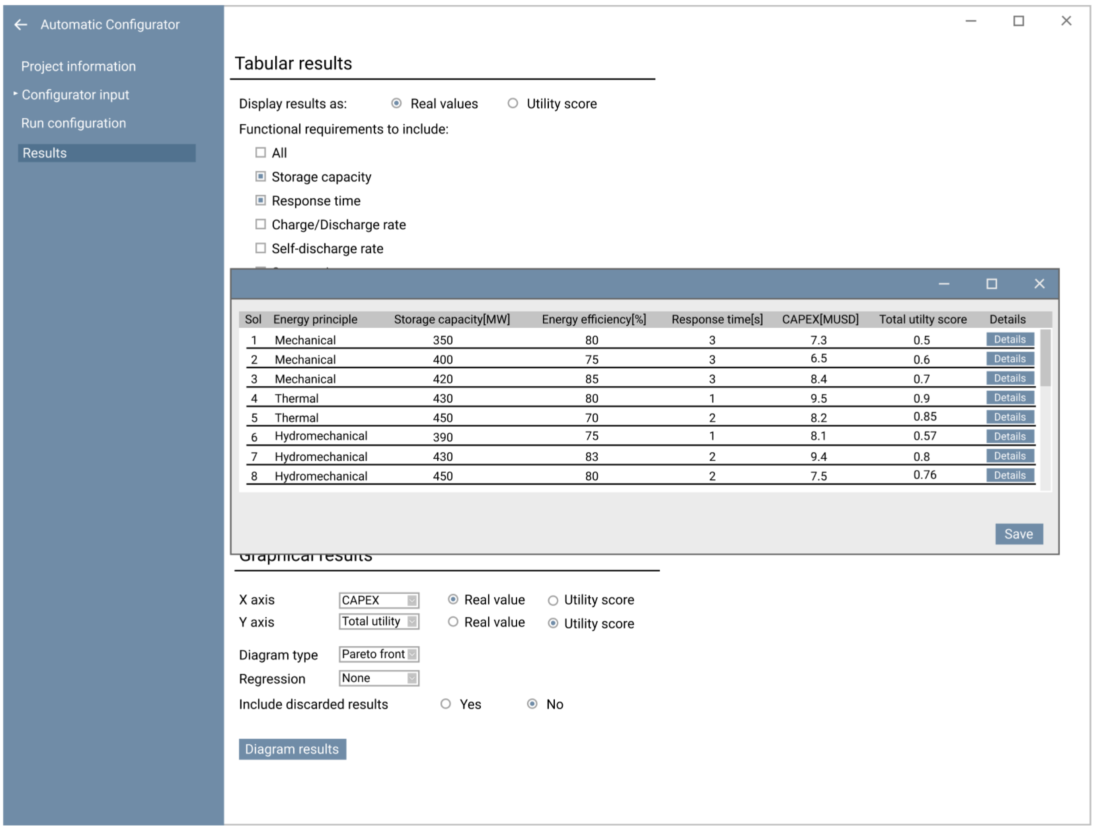


Figure 14.7.3: Configuration software: Tabular results.

together to create complete systems. The source and sink modules simulate the energy input and output to the storage system. The source module defines the basis for the scaling of the modules. By pressing configure, the user can scale each module to fit the customer requirements. This updates the general information about the modules, such as expected lifetime, cost etc.

The connection between two modules verifies that the energy output from one module is the same as the energy input for its adjacent module. If this is not the case, the program will not run. As the calculations are performed the progress is displayed in the lower right corner, along with any errors or warnings.

Using the buttons on the top of the screen, the user can display the results as a graph or table. This process is similar to the automatic configurator. However, a few additional options are available, such as generating a 2D drawing or 3D CAD model of the system. The rightmost button provides the user with the opportunity to compare the generated system with other systems in the database.

Using the tools provided the user is able to identify the design point that seems most promising with respect to the customer demand, and move forward to the next design phase.

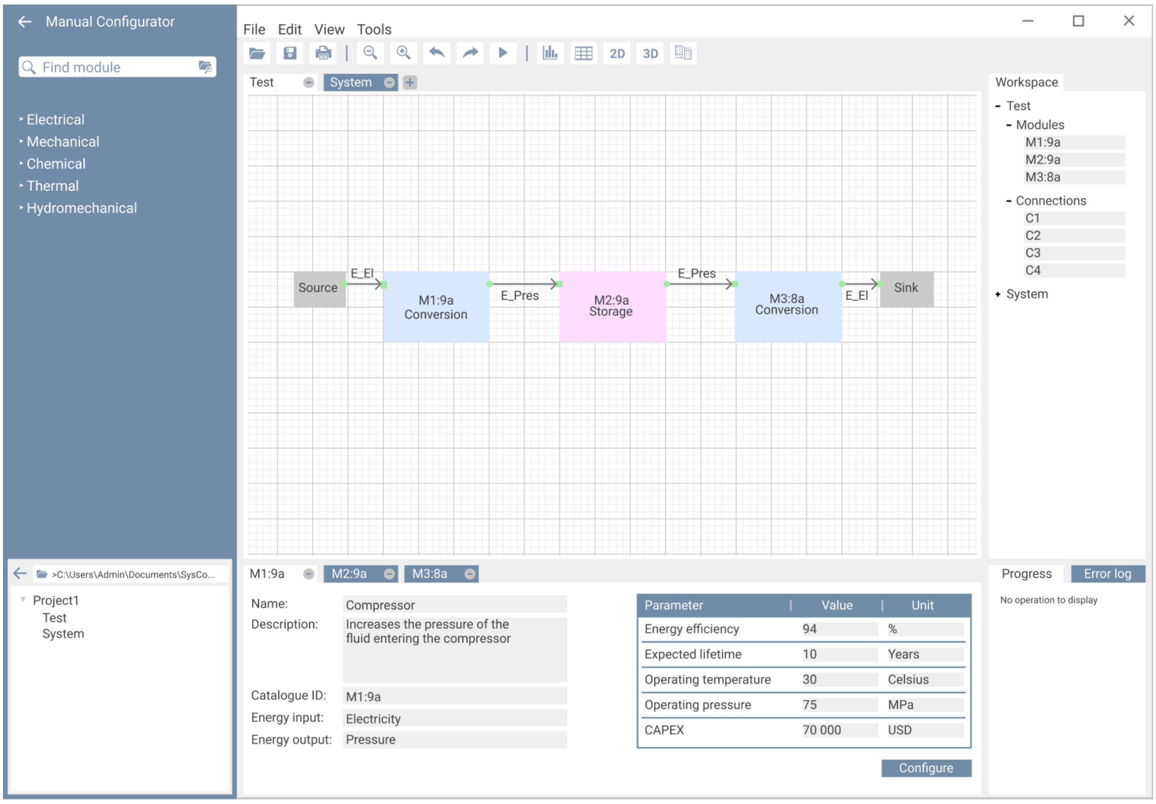


Figure 14.8.1: Configuration software: Manual configuration.

Part V

DISCUSSION AND CONCLUSION

Chapter 15

Limitations and simplifications of thesis methodology

This chapter includes discussions related to the thesis methodology. The goal is to provide a reasoning for the decisions made throughout the thesis and highlight potential simplifications and limitations. By clarifying such information, the work process and its results can be replicated, and the potential for further work is conveyed.

15.1 Market analysis

The market analysis aimed to provide a logical reasoning for the increased investments in offshore renewable energy production and how this enables a market increase for energy storage systems. The potential cut in cost or increase in profits from using an energy storage system was not investigated. Finding the necessary data to estimate would have been too time consuming, and was also not directly relevant to the scope of the thesis.

However, if the system is to be further developed in greater detail, it would be necessary to investigate the potential economical benefit from using an energy storage system. Furthermore, the economical benefits from developing a product platform should be established. This is to verify that the necessary capital investments into the development of the platform provide a positive Return of Investment (ROI).

15.2 Literature study

The first objective of the thesis was to gather the necessary information to enable good decision making when developing the product platform. This objective was considered very important as it provides the foundation of knowledge the rest of the thesis is built upon. The literature study was divided into two segments, energy storage technologies and engineering design theory. The combination of the information attained was crucial to effectively create a product platform.

15.2.1 Energy storage technology research

Energy storage principles were investigated to attain an understanding of the fundamental processes that govern energy conversions and storage. This information was used when investigating current and upcoming energy storage technologies to understand their working principles.

Data was gathered to establish important characteristics such as energy efficiency and response time. Gathering this data was difficult as there was minor, and sometimes major, differences in values from one source to the next. Therefore, only recent sources were used when possible and their values were compared to other sources to ensure as low deviation as possible.

The results from this research were necessary to understand what components and working principles different energy storage technologies are based on. This was used as an inspiration when deriving the modules in the product platform. The research also provided insight into what services the different energy storage systems could provide to a production site. The specification data was also used in the case study to simulate the functional performance of the design points.

15.2.2 Engineering design theory

The goal for the research of engineering design theories was to provide an understanding of the challenges of designing complex systems, and how different engineering design approaches aim to solve these issues. Positive and negative aspects of different design approaches were introduced to enable good decision making when developing the system architecture and the design process for both the development and use of the product platform.

The research was performed as objective as possible, even though the decision to use a product platform for the design process was a part of the thesis objective. To exclusively look for theory that supports the use of product platform is considered bad practise, and therefore both positive and negative aspect of the design approah was researched.

15.3 Product platform

Due to the wide scope of the thesis, the time constraint became a significant limitation to how in-depth the analysis of some of the topics could be. Creating the product platform is a time-consuming process, and deriving a complete system was not possible with the given time constraint. As a consequence, a few simplifications had to be made.

15.3.1 Development of design catalogue

The time constraints limit the number of modules that could be derived for the design catalogue. However, a systematic approach that enables the future development of the catalogue has been established. There are multiple ways to derive more modules. First, the function structure can be further decomposed. By doing so, new subfunctions can be derived. The physical effects that govern the subfunctions can be further developed, allowing more working principles to be derived. Finally, one can find new ways to combine the working principles to create new modules or variants of modules.

15.3.2 Mapping from needs to function domain

The mapping from needs to functions domain was not considered within the scope of the thesis. Although the use of HOQ and other methods have been mentioned throughout the thesis, such methods were not explained in detail. The mapping from customer needs to functional requirements is something that occurs through discussion with the customer, and the method used may vary depending on the case. It was therefore unnecessary to provide a systematic approach for this mapping since the development of the product platform is from a general standpoint, and not altered towards a specific case. However, establishing the basic needs from the market was necessary to understand what kind of functional requirements that may be expected from the system. A stakeholder analysis was performed to provide this fundamental understanding of the market needs.

15.3.3 Identification of modules

The level of module breakdown is only three, two conversion modules and one storage module. These three was chosen after analysing the function structure and identifying that the only dependencies between these modules are the energy type output and input. If the function structure was further decomposed and more subfunctions were identified the catalogue may consist of more modules, increasing the detail level of the conceptual design. A DSM or HOQ should be created to properly identify the dependencies between the functions, and use this information to derive independent modules. However, with the low decomposition of the function structure, this was not necessary for this thesis.

The functions can be further decomposed into auxiliary functions that may help reduce the complexity. For this study, the function structure tries to include all possible energy storage solutions. Although this was necessary to get a general overview of the development process, creating a functional structure and identifying market needs based on a specific energy principle, or even using a specific case, might lead to more functions being discovered, and thus more modules. This is why the feedback loop from the configured cases to the development of modules is important, to understand the ever-changing needs of a growing market and how modules should be developed to satisfy these needs.

15.3.4 Level of module detail

The level of detail in the modules in this thesis is low. There is little to no information about the modules in the design catalogue, and the design points generated in the case study is based on the data collected in the energy storage technology research. By identifying the components in each module the general characteristics such as energy efficiency and response time can be estimated. However, gathering this information was considered too time-consuming and not necessary to reach the objectives of the thesis.

15.3.5 Module configuration

A case study was performed to provide an example of how the configuration software may look. Provided a simple case, the aim of the chapter was to illustrate what such software could look like, providing the necessary input from the designer and a showcase of the results. As such, the feasibility along with the benefits of using a configurator was illustrated. Creating the software was considered outside of the thesis scope, as it would require large amounts of programming and software development. The illustrations provided was therefore only mock-ups of what the software may look like.

Chapter 16

Discussion of results

This chapter presents and discusses the results of the thesis. Positive and negative aspects of the design process are presented, along with an objective review of the product platform usability and if it solves many of the issues related to the design of an innovative and complex system.

16.1 Product platform background

From the engineering design research, it was discovered that the complexity of designing large systems can be explained by a high number of dependent elements. The inefficient design of such systems is based on the general lack of design knowledge at the beginning of a design process and the decreasing amount of design freedom as the design evolves. Traditional design approaches design such systems using an iterative process that is inefficient and time-consuming. These methods are dependent on a large amount of input from the designer, but also enables a tailored design for the customer and accommodates for a high degree of innovation.

According to complexity theory, the complexity of the design process can be reduced by decomposing the function structure of the system into subfunctions that are independent of each other. A modular design approach is based on this theory, where the idea is to create independent modules to simplify the design process. Moreover, the design knowledge at the beginning of a design process increase since information of the identified modules are known, and the design freedom throughout the design process is high as the designer can easily replace modules without affecting any other element in the system. However, such methods often restrict innovation, as the customer is restricted to choose from the set of available modules. Since an offshore energy storage system is an innovative design, the product platform needs to be based on several engineering design methods.

16.2 The product platform

The goal of the product platform was to enable an efficient conceptual design method for the development of offshore energy storage systems. This requires a time-efficient development method that is able to design cost-efficient solutions for a customer. As such, a product platform that enables the benefits of a modular structure, while accommodating for innovation was necessary.

The product platform address this issue by dividing the platform structure into two development processes, one for the development of the modules and another for the configuration of the modules. As such, matters of innovation could be addressed when designing the modules, enabling the benefits of a modular structure for the configuration of the energy storage systems. The feedback from the configured cases is considered to be very important to maintain the relevancy of the product platform. A market that is constantly growing may experience significant changes in needs over time, and it is important that the product platform contains the modules required to meet these needs effectively.

The Systematic Approach by Pahl and Beitz was used to provide a structure to the development of the modules. The method derived a design catalogue of modules and module variants by using a structured approach. The configuration of these modules is based on product platform theory and configuration based design. A configuration software uses inputs from the designer to configure a large number of systems by selecting, scaling and arranging the modules in the design catalogue. The performance of the systems are calculated using utility theory and evaluated against the customer requirements.

The product platform architecture is described in terms of the product families and modular interfaces. There are two product families in the platform, namely onshore and offshore energy storage systems. Onshore systems were added to the platform to expand the possible use-cases for the platform and share the cost of developing the platform over more projects. The product families were further divided into subfamilies based on the energy type the modules support. The module interfaces are based on a slot interface structure. They are divided into categories based on what energy type they are compatible with and each category is given its own interface. This ensures that the energy output from one module is equal to the energy input type of its adjacent module.

16.3 Discussion of product platform

This section will evaluate the product platform obtained and discuss the positive and negative aspect of the design approach.

16.3.1 Development of modules

Pahl and Beitz's Systematic Approach provides a structure to the development of the modules. This is important when designing innovative systems as a lot of time is often wasted on iterative processes and rework. With a structured approach, the designer can get comfortable with the design process and develop new modules with a higher efficiency. Developing more modules is a matter of further deriving functions, their physical effects, their working principles and combining these to complete modules.

However, developing a structured approach to derive the storage modules proved to be difficult. The axis of the two-dimensional tables used to derive the working principle of the modules have a big impact on what types of modules it is possible to derive. In this thesis, the axes were established by investigating what energy output the conversion modules deliver, thus deriving what energy type the storage modules needed to support. However, describing all the possible storage modules and their variations within these two-dimensional tables are not possible. As a result, several tables need to be made and the axis on these tables must be chosen by the designer. This is a difficult process that has a huge impact on what type of energy storage modules and module variants the designer can develop. However, such issues are difficult to avoid in the development of innovative structures.

The Systematic Approach originally developes a design catalogue of working principles, where these can be combined to a final design. This design catalogue had a very similar function to what was wanted from the module database in the product platform. As such, the systematic approach provided a natural transition from creating working principles to a catalogue of modules. It was only a matter of combing these working principles to develop modules instead. Although not implemented completely, the mock-up of the integration of the module catalogue provides a fundamental understanding of how well the design approach is suited for the development of modules as it was very easy to integrate into the product platform.

16.3.2 Configuration of modules

The product platform enables the benefits from a modular structure to be applied to the design of an offshore energy storage system. The modular structure enables a ATO downstream CODP strategy using a configurator, increasing the efficiency of the design process by decreasing the lead time.

Having standardised components reduces the construction cost of the system and accommodates for outsourcing and globalisation of the supply chain. The modules can be replaced without affecting the rest of the system due to their self-sufficiency, which reduces the maintenance cost of the system. Moreover, the reliability of each module and its can be evaluated, and the risk of a failure can be mitigated by adding backup measures in case of failure. These benefits are important as the offshore storage system will be situated far away from the coast, and any unscheduled maintenance will be very expensive.

The configuration process enables a comparison between a large amount of different energy storage systems. Instead of spending a large amount of time on creating one system, the designer can focus on finding an optimal system by evaluating the generated solutions against each other. Finding this optimal solution will benefit the cost-efficiency as the energy storage system can deliver its applications efficiently.

There are also some negative aspects of the use of a modular design approach. A traditional design approach is able to create more tailored solutions by addressing every element in the design, where a modular approach will use standardised modules that are not optimized for the specific case. This may lead to a less optimized physical architecture or performance for the design. However, the detail level of the configuration and its modules are too low to evaluate this issue. The design process is only conceptual, and keeping the detail level low may enable the design to be tailored and optimised later in its design process. If so it is important to provide feedback to the design catalogue if new module or module variants are created.

16.3.3 Product platform structure

The product platform structure provides an efficient method of developing conceptual offshore energy storage systems. Although the platform was not fully developed, the fundamental theory supporting it was established. Creating the design catalogue of modules and a method to configure these to complete systems provides an overview of the feasibility of the product platform. The case study further developed this understanding, showcasing how the configurator can be used to configure optimal designs for a customer specification.

The cost-efficiency of using a product platform for the development of conceptual offshore energy storage systems is difficult to evaluate due to the low level of detail. More in-depth studies must be performed to further develop the product platform and its design methods to be able to perform such an evaluation. However, the feasibility of creating the product platform has been established and the benefits and downsides of such an appraoch have been evaluated.

Chapter 17

Conclusion

The main objective of the thesis was to develop an efficient design approach using product platform technology for the conceptual design of offshore energy storage systems and evaluate the method. This objective was reached by fulfilling the secondary objectives of the thesis.

The main issue of the objective was discovered to be the innovation required to develop an offshore energy storage system. A modular structure is often used on routine designs that require low amounts of user input, where independent modules are combined to create complete systems. This enables a high degree of knowledge at an early stage in the design process and a low degree of complexity, making the design process more efficient. However, the configuration of modules does not accommodate well for innovation. The product platform and its structure must therefore enable the benefits from a modular approach while accommodating for innovation.

The product platform solves this issue by dividing the development process of the offshore energy storage system into two segments. One being the development of the platform, and the other being the exploitation of it to configure systems. By doing so, matters of innovation can be isolated to the development of the modules, enabling the configurator to combine modules using a downstream CODP strategy. These development methods were derived using inspiration from Pahl and Beitz Systematic Approach, Configuration-Based Design and Hazelrigg's Decision-Based Design.

The product platform provides a number of benefits to the design process. Standardisation of the modules results in a lower cost in development and maintenance. Moreover, it decreases the lead time for the project by enabling a downstream ATO strategy. A key benefit of the product platform is that its configuration process generates and compares a large number of different systems. This enables the designer to focus on finding an optimal solution within the set of provided systems instead of spending time on the development of the systems. Finding this optimal solution will benefit the cost-efficiency by ensuring the energy storage ability to meet the requirements of the customer.

There are also some negative aspects of the use of a modular design approach. A traditional design approach is able to create more tailored solutions by addressing every element in the design, where a modular approach will use standardised modules that are not optimized for the specific case. This may lead to a less optimized physical architecture or performance for the design. Moreover, the downstream CODP strategy provides little design freedom for the customer, as the systems are composed of a given set of modules. However, this is only the conceptual design phase and any changes applied to the design can be performed at a later stage in the development.

In conclusion, the product platform provides many benefits to the conceptual design of offshore energy storage systems, and the issue of applying a modular approach to an innovative design seems to have been solved with the product platform structure. Although the platform was not fully developed, the fundamental theory supporting it was established. Creating the design catalogue of modules and a method to configure these to complete systems provides an overview of the feasibility of the product platform. The case study further showcased how the configurator can be used to configure optimal designs for a customer specification.

The cost-efficiency of using a product platform for the development of conceptual offshore energy storage systems is difficult to evaluate due to the low level of detail. More in-depth studies must be performed to further develop the product platform and its design methods to be able to perform such an evaluation. However, the feasibility of creating the product platform has been established and the potential benefits and downsides of such a method have been evaluated.

17.1 Recommendations for future work

The recommendations for future work are based on the simplifications and limitations in the thesis. As the scope of this thesis was wide, the recommendations will be to continue the work with an in-depth analysis of some of the segments. This is because the study concludes that the product platform is feasible and should be further investigated. The following list provides the main challenges that should be solved in future work.

Perform an in-depth analysis of the market to better understand the potential profits or cut in costs that can be provided.

An in-depth analysis of customer needs to derive more functional requirements and thus more modules. A systematic method of mapping between customer needs and functional requirements should be derived.

Further develop the product platform to enable evaluation and verification of the efficiency of the design method.

Create the configuration software.

References

Amiryar, M. E., & Pullen, K. R. (2016). A review of flywheel energy storage system technologies and their applications. *Applied sciences*. doi: https://doi.org/10.3390/app7030286

Arnold, J. T., et al. (2008). *Introduction to materials management* (6th ed.). Pearson.

Behabtu, H., et al. (2020). Review of energy storage technologies' application potentials in renewable energy sources grid integration. *Sustainability*. doi: 10.3390/su122410511

Blanco, P., & Pérez-Arribas, F. (2017). Offshore facilities to produce hydrogen. *Energies*, *10*. doi: https://doi.org/10.3390/en10060783

Brown, T. (2017). *Ammonia for energy storage: economic and technical analysis.* https://ammoniaindustry.com/ammonia-for-energy-storage-economic-and-technical-analysis/.

BVGA. (2019). Global offshore wind market report. *BVG Associates*.

CNESA. (2020). *CNESA Global Energy Storage Market Analysis.* http://en.cnesa.org/latest-news/2020/5/28/cnesa-global-energy-storage-market-analysis-2020q1-summary. ((Retrieved 01.06.2021))

DNV. (2020a). Energy transition outlook 2020 executive summary.

DNV. (2020b). Energy transition outlook 2020 power supply and use.

DSM. (2021). *Clustering a DSM.* https://dsmweb.org/clustering-a-dsm/. ((last checked 06.06.2021))

EASE. (2020). *Mechanical Energy Storage.* https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_PHES.pdf. ((last checked 27.10.2020))

EC. (2020). *EU strategy on offshore renewable energy.* https://ec.europa.eu/energy/topics/renewable-energy/eu-strategy-offshore-renewable-energy_en. ((Retrieved 09.10.2020))

EERA. (2019). *Superconducting magnetic energy storage.* https://eera-es.eu/wp-content/uploads/2019/04/EERA_JPES_SP5_Factsheet_final.pdf. ((last checked 20.10.2020))

Elmegaard, B., & Brix, W. (2011). Efficiency of compressed air energy storage. *The 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*.

Erikstad, S., & Levander, K. (2012, 01). System based design of offshore support vessels.

Erikstad, S. O. (2007, 10). Efficient exploitation of existing corporate knowledge in conceptual ship design. *Ship Technology Research*, *54*, 184-193. doi: https://doi.org/10.1179/str.2007.54.4.005

Erikstad, S. O. (2009). Product platforms and modularization in shipbuilding. *NTNU*.

ESRU. (2020). *Ammonia storage.* `http://www.esru.strath.ac.uk/EandE/Web_sites/17-18/windies/ammonia-storage.html`. ((last checked 06.10.2020))

Evans, J. H. (1959). Basic design concepts. *Journal of the American Society for Naval Engineers*(3), 671-678.

FLASC. (2021). *FLASC - Hydro-Pneumatic Energy Storage.* `https://www.offshoreenergystorage.com/`. ((Retrieved 01.06.2021))

Gaspar, H. M., et al. (2012). Addressing complexity aspects in conceptual ship design: A systems engineering approach. *Ship Production and Design*, *12*(3), 145-159. doi: https://doi.org/10.5957/JSPD.28.4.120015

Goel, A. (1997). Design, analogy, and creativity. *IEEE Expert*, *12*(3), 62-70. doi: https://doi.org/10.1109/64.590078

Gustavsson, J. (2016). Energy storage technology comparison. *KTH School of Industrial Engineering and Management*.

Gür, T. M. (2018). Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. *Energy Environmental Science*(10).

Haile, E. G. (2015). H2/br2 flow battery system architecture and control system analysis. *TECNICO LISBOA*.

Hazelrigg, G. A. (1998). *A Framework for Decision-Based Engineering Design* (Vol. 120) (No. 4).

Holzinger, C., et al. (2019). *Global Energy Storage Market Forecast 2019.* `https://www.luxresearchinc.com/hubfs/Lux%20Research%20-%20Global%20Energy%20Storage%20Market%20Forecast%202019%20-%20press.pdf`. ((Retrieved 01.06.2021))

HydrogenEurope. (2020a). *Hydrogen Production.* `https://www.hydrogeneurope.eu/hydrogen-production-0`. ((last checked 03.10.2020))

HydrogenEurope. (2020b). *Hydrogen Storage.* `https://www.hydrogeneurope.eu/hydrogen-storage`. ((last checked 03.10.2020))

IEA. (2020). *ETP Clean Energy Technology Guide.* https://www.iea.org/articles/etp-clean-energy-technology-guide. ((last checked 20.10.2020))

IFE. (2021). *Floating Photovoltaics.* https://ife.no/en/research/floating-photovoltaics/. ((Retrieved 25.05.2021))

IRENA. (2018). Renewable energy benefits: Leveraging local capacity for offshore wind. *International Renewable Energy Agency*.

IRENA. (2019). Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects (a global energy transformation paper). *International Renewable Energy Agency*.

Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by pem water electrolysis – a review. *Materials Science for Energy Technologies*, *2*(3), 442-454. doi: https://doi.org/10.1016/j.mset.2019.03.00

Lenntech. (2020). *Environmental effects of bromine.* https://www.lenntech.com/periodic/elements/br.htm. ((last checked 18.10.2020))

Letcher, T. M. (2016). *Storing energy: With special reference to renewable energy sources* (1st ed.). Elsevier.

Makai. (2020). *Ocean Thermal Energy Conversion.* https://www.makai.com/ocean-thermal-energy-conversion/. ((Retrieved 23.09.2020))

McDonald, T. P., et al. (2012). A demonstration of an advanced library based approach to the initial design exploration of different hullform configurations. *Computer-Aided Design*, *44*(3), 209-223. doi: https://doi.org/10.1016/j.cad.2010.12.004

Molina, M. G. (2010). *Dynamic modelling.* IntechOpen. doi: https://doi.org/10.5772/7092

Mongird, K., et al. (2019). Energy storage technology and cost characterization report. *U.S. Department of Energy*.

Mork, O., et al. (2014). *The maritime innovation factory.* doi: https://doi.org/10.13140/2.1.3605.3280

Mueller, D. (2019). *Getting offshore wind power on the grid.* https://www.tdworld.com/renewables/article/20972636/getting-offshore-wind-power-on-the-grid.

Mutarraf, M. U., et al. (2018). Energy storage systems for shipboard microgrids—a review. *Energies*, *11*(12). doi: https://doi.org/10.3390/en11123492

Pahl, G., & Beitz, W. (1988). *Engineering design - a systematic approach* (3rd ed.). Springer.

Pan, F., & Wang, Q. (2015). Redox species of redox flow batteries: A review. *Molecules*, *20*(11). doi: https://doi.org/10.3390/molecules201119711

Rathi, A. (2018). *Stacking concrete blocks is a surprisingly efficient way to store energy.* https://qz.com/1355672/stacking-concrete-blocks-is-a-surprisingly-efficient-way-to-store-energy/.

Ritchie, H. (2020). *Energy production and consumption.* https://ourworldindata.org/energy-production-consumption. ((Retrieved 08.10.2020))

Shea, G. (2019). *Fundamentals of Systems Engineering.* https://www.nasa.gov/seh/2-fundamentals. ((last checked 06.2.2021))

Siemens. (2020). *Efficiency.* https://www.siemensgamesa.com/en-int/products-and-services/hybrid-and-storage/thermal-energy-storage-with-etes. ((last checked 06.10.2020))

SimScale. (2021). *What Is Heat Transfer?* https://www.simscale.com/docs/simwiki/heat-transfer-thermal-analysis/what-is-heat-transfer/. ((last checked 18.10.2020))

Sprake, D., et al. (2017). *Housing Estate Energy Storage Feasibility for a 2050 Scenario.* https://www.researchgate.net/figure/Applicable-power-ranges-and-discharge-power-duration-of-different-energy-storage_fig7_320273548. ((Retrieved 25.05.2021))

SUT. (2020). *Offshore Renewable Energy.* https://www.sut.org/educational-support-fund/information-for-careers-in-underwater-technology-and-science/for-school-leavers-and-beyond/offshore-renewable-energy/. ((Retrieved 23.09.2020))

Thurber, M. (2020). *Power-to-gas for long-term energy storage.* https://www.energyforgrowth.org/memo/power-to-gas-for-long-term-energy-storage/.

UIUC. (2020). *Scientific Principles.* http://matse1.matse.illinois.edu/energy/prin.html. ((last checked 18.10.2020))

UNFCCC. (2020). *What is the paris agreement?* https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement. ((Retrieved 08.10.2020))

Victanis. (2020). *Market Review Of Energy Storage Systems.* https://www.victanis.com/market-review-of-energy-storage-systems. ((last checked 20.10.2020))

Vogt, C., et al. (2019a). Methane promising route for storage of renewable energy from sun and wind. *Nature Catalysis*. doi: https://doi.org/10.1038/s41929-019-0244-4

Vogt, C., et al. (2019b). The renaissance of the sabatier reaction and its applications on earth and in space. *Nature Catalysis*. doi: https://doi.org/10.1038/s41929-019-0244-4

Wang, Y., et al. (2017, 06). Room-temperature sodium-sulfur batteries: A comprehensive review on research progress and cell chemistry. *Advanced Energy Materials*, *7*. doi: https://doi.org/10.1002/aenm.201602829

Appendix A

A.1 Energy storage technologies summary

Table A.1.1: Energy storage summary. Data from various sources referenced in Chapter 5.

Energy form	Technology	Response time	Storage time	Op. temp.[C]([K])	Op. pressure
	SMES	ms	Days	(4-40)	-
	EC	ms	Days	-	-
Electrical	Lead-Acid	ms	Days	-	atm
	H-B Flow battery	ms	Days	25	atm
	Li-ion	ms	Days	-	atm
	NaS	ms	Days	300	atm
	Hydrogen gas	min	Months	30-80	35/75 MPa
	Liquid hydrogen	min	Months	-253	-
	Carbon nanotube	min	Months	-192	-
Chemical	Hydrides	min	Months	300	Moderate
	Methane	min	Months	300-400	-
	Ammonia	min	Months	400-650	20-40 MPa
	PSH	s	Months	-	-
Mechanical	CAES	s	Months	-	-
	LAES	s	Months	-190	9-14 MPa
	Solid gravitational	s	Months	-	-
	FES	s	Minutes	-60	<10 Pa
	ETES	s	Months	600	-
	PHES	s	Months	-160-500	Ambient-1.2 MPa
Thermal	LHTES	s	Months	-	-

Table A.1.2: Energy storage summary continuation. Data from various sources referenced in Chapter 5.

Technology	**Energy density[Wh/kg]([Wh/L])**	**Efficiency[%]**	**Self-discharge[%/day]**	**Cycles(Years)**	**CAPEX[USD/kWh]**
SMES	0.5-5	> 95	0-10	(20-30)	770-7744
EC	6-20	92	-	(20-30)	300-2000
Lead-Acid	30-40	50-92	0.1-0.3	50-100	60-154
H-B Flow battery	-	70	-	(10-20)	-
Li-ion	200-300	80-90	0.02	700–3000	100-200
NaS	150–240	75	20	700–2000	9–22
Hydrogen gas	33 570 (833-1250)	34-44	-	-	-
Hydrogen liquid	33 570 (2200)	30-40	-	-	-
Carbon nanotube	(4440)	-	-	-	-
Hydride	(>2200)	-	0	-	-
Methane	15 444	30-38	-	-	-
Ammonia	6250 (3194)	23-41	-	-	-
PSH	0.5-1.5	>80	0	20000-50000	65-165
CAES	30-60	75-85	0	5000-20000	11-130
LAES	-	70	0	-	-
Solid gravitational	-	75-85	0	(60)	120-380
FES	100-130	85-95	20-100	10^5-10^7	1105-3870
ETES	-	40	5	-	-
PHES	15-30	70-75	-	(20-30)	24
LHTES	-	-	-	-	-

A.2 Technology readiness level

Table A.2.1: TRL value definitions (IEA, 2020).

Technology	TRL value
Energy Production	
Seabed fixed offshore wind turbine	9
Floating offshore wind turbine	8
Tidal current	5
Tidal range	8-9
Solar	8
Wave	4
OTEC	4
Energy Storage/Conversion	
SMES	8 [10]
EC	8 [37]
Lead-Acid	8 [37]
Flow battery	8
Li-Ion battery	9
NaS battery	8[37]
AEL	9
	8
Hydrogen physical storage	11
Hydrogen solid storage	8 [43]
Sabatier process	8-9 [42]
Methane storage	11
Ammonia storage	9[41]
AFC	9
PEMFC	8
PAFC	7
PSH	11
CAES	8
LAES	9
FES	9
Gravitational energy storage	5
ETES	8-9
PHES	9
LHTES	5-7
Energy Distribution	
High voltage transmission	8
Hydrogen shipping	3
Methanol shipping	8-11
Ammonia shipping	8-11
Pipeline	11
Chemical Energy Consumption	
Hydrogen engine	4-5
Methanol engine	8-9
Ammonia engine	4-5
Hydrogen EV	5-6
Methanol EV	6
Ammonia EV	4-5

A.3 Electrolysers and fuel cells

Table A.3.1: Characteristics of common electrolysers fuel cells (Haile, 2015)(Kumar & Himabindu, 2019)..

Fuel cell	**Operation temp[C]**	**Fuel**	**Efficiency[%]**	**Power [kW]**
AFC	80-100	H_2	60	5-150 kW
PEMFC	70-80	H_2	40-50	5-250 kW
PAFC	200-220	H_2 from methanol	40-50	20kW - 2MW
MCFC	600-650	H_2 and CO from fossil	45-60	100 kW - 2 MW
SOFC	800-1000	H_2 and CO from fossil	50-65	100-250 kW
Electrolyser				
AEL	30-80		70	
PEM	70-80		80	

Appendix B

B.1 Auxiliary subfunctions

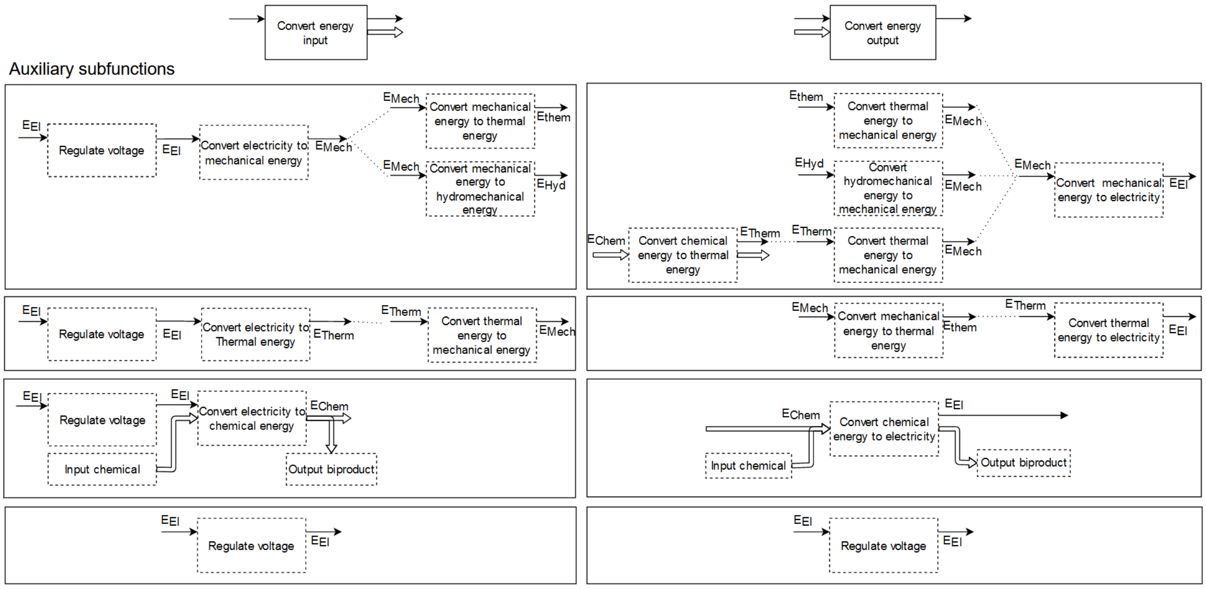


Figure B.1.1: Deriving auxiliary subfunctions from function structure

NTNU

Norwegian University of
Science and Technology