Feasibility of a Pumped Storage Hydro & Wind-Power Hybrid Setup

A study based on a real case in Sweden

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"In the past twenty weeks, I have never had a day where my Excel file did not crash without a specific reason".

- Frank Lotfi

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

ACoE	Average Cost of Electricity
aFRR	Automatic Frequency Restoration Reserve
BA	Balancing
BL	Base Load
BOP	Balance of Plant
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CF	Capacity Factor
DA	Day-ahead
EPC	Engineering, Procurement and Construction
EU	European Union
FCR-D Down	Downward Frequency Containment Reserve - Disturbance
FCR-D Up	Upward Frequency Containment Reserve - Disturbance
FCR-N	Frequency Containment Reserve
FFR	Fast Frequency Reserve
IN	Intraday
KPI	Key Performance Indicators
IRR	Internal Rate of Return
LCoE	Levelized Cost of Electricity
LCoS	Levelized Cost of Storage
mFRR	Manual Frequency restoration reserve
O&M	operation & Maintenance
OPEX	Operational Expenditure

PPA	Price Purchase Agreement	
PSHHS	Pumped Storage Hydropower Hybrid System	
PSH	Pumped Storage Hydropower	
PV	Photovoltaic	
RES	Renewable Energy Source	
WE	Wind Electricity/Energy	
WPS	Wind Power System	

Symbols

$A_{res,upper}$	Area of the upper reservoir	$[m^2]$
C_{cs}	Cost of the penstock material	[€/kg]
$C_{E,loss}$	Cost of the energy loss for the *PSH*	[€]
C_{tot}	Total cost of the energy loss and pipe	[€]
Δh	Delta of the height variation between the reservoirs	$[m]$
ρ_{cs}	Density of the penstock material	$[kg/m^3]$
ρ_{w}	Density of water	$[kg/m^3]$
E_{gen}	Rated generation energy	$[MWh]$
E_{loss}	Energy loss for the *PSH*	$[MWh]$
E_{p}	Potential Energy of the upper reservoir	$[MWh]$
$E_{p,adj}$	Adjusted Potential Energy of the upper reservoir	$[MWh]$
E_{pump}	Rated pumping energy	$[MWh]$
η_{g}	Efficiency of the turbine for generation	[%]
η_{p}	Efficiency of the pump for the *PSH*	[%]
$h_{L,major}$	Major Head loss for the *PSH*	$[m]$
$h_{L,minor}$	Minor Head loss for the *PSH*	$[m]$
$h_{L,tot}$	Total Head loss for the *PSH*	$[m]$
$h_{res,lower}$	Height of the lower reservoir	$[m]$
$h_{res,upper}$	Height of the upper reservoir	$[m]$
$h_{res,level}$	Regulation amplitude of the reservoir	$[m]$
K_{L}	Loss coefficient for minor losses	$[-]$

L_{res}	Distance between the reservoir	$[m]$
μ_W	Dynamic viscosity of water	$[-]$
P_g	Generated Power	$[MW]$
C_{pen}	Cost of the penstock	[€]
m_{pen}	Mass of the penstock	$[kg]$
P_p	Pumping Power	$[MW]$
$P_{r,p}$	Potential Rated Power of the upper reservoir	$[MW]$
$P_{r,adj}$	Adjusted Potential rated power of the upper reservoir	$[MW]$
Q_g	Generated Flow	$[m^3/s]$
Q_p	Pumping Flow	$[m^3/s]$
$SP_{DA,i}$	Hourly spot price for electricity on the day-ahead market	[€/MWh]
$SP_{DA,max}$	Max Hourly spot price for electricity on the day-ahead market	[€/MWh]
$\overline{SP}_{DA,i}$	Average Max Hourly spot price for electricity on the day-ahead market	[€/MWh]
$SP_{DA,min}$	Min hourly spot price for electricity on the day-ahead market	[€/MWh]
$\overline{SP}_{DA,min}$	Average min hourly spot price	[€/MWh]
$SP_{DA,Recent}$	Next hourly spot price for electricity on the day-ahead market	[€/MWh]
$\overline{SP}_{DA,Recent}$	Average next hourly spot price for electricity on the day-ahead market	[€/MWh]
$SP_{DA,Recent+6}$	Six hours in advance hourly spot price for electricity on the day-ahead market	[€/MWh]
$\overline{SP}_{DA,Recent+6}$	Average six hour in advance hourly spot price	[€/MWh]
t_s	Storage duration of the *PSH* system	$[s]$
t_{pen}	Thickness of the penstock	$[m]$
ε	Roughness coefficient	$[-]$
v_{max}	Max velocity in the penstock	$[m/s]$
V_{pen}	Volume of the penstock material	$[m^3]$
v_{pen}	Velocity in the penstock	$[m/s]$
V_{res}	Volume of the reservoir	$[m^3]$
d	Diameter of the penstock	$[m]$
f	friction factor for the *PSH*	$[-]$
g	Gravity	$[m/^2]$

Re	Reynolds Number	[−]

Abstract

The introduction of the Renewable Energy Directive 2009, increased the renewable energy sources *(RES)* in the European Union *(EU)* and especially Sweden. Given the uncontrollable nature of weather patterns, energy generation is likely to become more volatile, thereby elevating the risk of curtailment and negative energy prices. The electricity demand in Sweden is also poised to rise sharply in the upcoming years. Implementing a storage technology, in this case, a small-scale pumped storage hydropower interconnected with a wind power system as a hybrid setup, indicated stability regarding both reliable and constant generation by reducing idle hours from the Wind Power Systems *(WPS)*. The simulated model for the projected Pumped Storage Hydropower *(PSH)* site indicated that spot price optimization is feasible, allowing for storage opportunities when demand is low and generation when demand is high. The primary limitation appeared to be the cost elements related to the capital expenditure *(CAPEX)* and operational expenditure *(OPEX)* estimation where EPC, the powerhouse structure, and grid fees had a significant unfavorable impact on the cost assessment.

1 Introduction

In this chapter, the reader is introduced to a brief introduction regarding the trends of the European energy distribution system and possible solutions for sustained energy. One solution is storage technologies, especially, Pumped Storage Hydropower, and how it can be optimized with renewable energy sources. The scope and objective of this thesis, are presented with set limitations and conditions regarding the feasibility of the pumped storage hydropower hybrid system (PSHHS).

1.1 Trends of the European Energy power system

Through the years, the usage of fossil fuels has been a significant topic in the energy industry where usage of the renewable energy sources has become vital for the generation of energy. The introduction of the Renewable Energy Directive 2009, increased the renewable energy sources *(RES)* in *EU* from 12.5% in 2010 to 23% in 2022. Sweden's share of *RES* consumption reached 66%, the highest in the *EU*. The trend of increasing the *RES* has been clear and a new revised directive was entered into force in November 2023, increasing the 2030 target to 42,5%, but a target of 45% is within the future scope [1]. In cohesion with the *RES* directive, the proposal of reducing greenhouse gas emissions by at least 55% is projected to be achieved by 2030. [2].

A report from Ember, states that the *EU*s reduction in usage of fossil fuels accelerated rapidly during 2023 and dropped down to an all-time low of 19% of the total energy generation. Usage of *RES* rose to an all-time high of 44% with wind and solar power as the driving factors with a combined total of 27% of the energy generation. The energy generated from wind power rose to 18% which was an increase of 13% compared to 2022, surpassing gas at 17% for the first time. The constant rise of wind power has been clear during the last two decades (2000-2023) with an increased energy generation from 0,8% to 18% [3].

According to a report from the European Commission, an estimation of 69% of the total energy consumption by 2030 is set to be accounted for by *RES*. Wind and solar power are set to account for 55% of this and are estimated to cover 67% of the total European energy generation [4].

As one can see, the usage of renewable energy sources in Europe and especially Sweden is increasing. Fossil fuels saw an all-time low of 15% of the energy mix but could decrease if more storage technologies are implemented in the energy power system. Ember states that implementing storage technologies would reduce energy curtailment and instead harness it to maximize energy generation from the *RES*. Incorporating various storage systems enhances flexibility, which helps mitigate negative energy spot prices, curtailment, and price cannibalization. Negative prices and price cannibalization can occur for periods with high supply and low demand, reducing the overall price efficiency of renewable power plants [3].

Electricity demand has declined in recent years, with a 3.4% drop in 2023, resulting in a total decrease of 6.4% compared to 2021 [3]. According to a forecast by the IEA, Europe's electricity demand is projected to rise by an average of 2.3% between 2024 and 2026 [5].

The mentioned trends suggest that reducing reliance on fossil fuels will increase the demand for (*RES*). Given the uncontrollable nature of weather patterns, energy generation is likely to become more volatile, thereby elevating the risk of curtailment and negative energy prices.

A report by Svenska kraftnät asserts that electricity demand in Sweden is poised to rise sharply in the upcoming years. If all applications for connection were approved, the total power demand would surpass current consumption levels [6]. Driven by new industrial developments and the transition from fossil fuel-based industries to (*RES*), the energy demand could potentially surge to 150% of the current level by 2045 [7].

A recommendation was proposed in a report by Riksbank, advocating for *PSH* technology as a suitable option to accommodate the increased demand, in line with the expanding usage of renewable energy sources *(RES)* [8].

The objective set forth by BayWa r.e. Nordic AB involves analyzing the feasibility of a small-scale pumped hydropower storage system coupled with a wind power system to enhance flexibility and improve overall efficiency in energy pricing.

1.2 Scope and Objectives

The objective of the thesis is to assess the concept of a hybrid project with a small-scale pumped hydropower system coupled with a Wind power system. The hybrid project is investigated through a preliminary feasibility study of technical, regulatory, and financial aspects in the Swedish context. A comprehensive evaluation will be conducted to address key challenges including operating strategy and site optimization, alongside a profitability assessment. The following feasibility aspects will be assessed in this thesis.

- Study of existing literature on pumped hydro solution/market
- Assessment of different synergy modalities and revenue streams
- Assessments of the technical design aspect including
  - *PSH* design and layout
  - Potential energy losses
  - Optimization of pipe selection
  - Cost assessment of optimized pipe selection
  - Selection of turbine
- Characterization of the generation profile and operation strategy
- Cost assessment (CAPEX/OPEX) for the solution
- Modelling of the business case and understanding of the economic characteristics

A hybrid set-up of renewable energy sources coupled with an energy storage technology is advantageous in both technical and economic aspects. Since pumped hydro storage can store bulk energy for longer period, combining it with a renewable source is expected to improve the system's generation profile and its profitability. But, in a Swedish scenario with mostly medium and low head sites available a good investigation is required to understand the benefits that can be realized with hybridization of renewable energy projects.

A real location of the provided *PSH* system was provided by BayWa r.e. and will be denoted as "*Site Hydro*". A data sample of generated electricity from an undisclosed Wind Power System *(WPS)* was also provided. The hybrid system will be referred to as "*Project Hybrid*" and denoted as *PSHHS* system.

1.3 Conditions and Limitations of the Scope

As mentioned in Section 1.2 the first objective was to use existing literature studies and use them as a base reference for techno-economic aspects, site design, and operation strategies. The collected data will be a rough evaluation reference for the analysis made in this thesis but are suitable when evaluating the simulated and calculated results.

All the simulated revenue streams from the *PSHHS* system are hypothetical and should be considered as potential future outputs. The Day-ahead market and the generated electricity from a *WPS* are the synergy modalities utilized to simulate the different revenue streams. The Intraday market and ancillary services are not considered in the simulated revenue stream, but rather discussed as potential synergy modality.

The economic valuation is site-specific and costs such as *CAPEX* and *OPEX* will fluctuate between the various litterateurs. The optimal estimations of such costs were calculated utilizing the PERT estimation method, see section 4.1. The *CAPEX* and *OPEX* costs were divided into different categories to evaluate the various cost elements. The used literature costs were adapted and adjusted accordingly to fit the set categories.

The site optimization was also set with some limitations regarding its design parameters including, head height, area of the reservoirs, regulation of the reservoir height, power for both pumping and generation mode, etc. Input parameters like the ones described above were estimated by various calculations which will be presented in chapter 2 in Section 3.1.

Some limitations were also set in the operation strategy, especially regarding the revenue output. The operation strategy utilized old *DA* spot prices, which in reality is not correct since *DA* spot prices are made public after the order from operators has been set. See section 3.7.2 and 2.1.2 for clarification of the *DA* spot market.

1.4 Literature reviews

Besides using the provided information and description details provided from BayWa r.e. various literature was used as a base reference regarding design, operation, and cost models of the *PSH* system. The main literature regarding the technical design of the *PSH* system was a performance and assessments report from [9] where an iterative process solution regarding the design parameters was presented. The theory presented in the report is based on previous technical reports and supported by a literature book on fluid dynamics by Young [10].

The operation strategy was based on previously established working documents provided by BayWa r.e. and from the report on the feasibility of a *PSH* system where operation strategy for arbitrage trading was presented [11]. This laid the foundation of the constructed operation strategy for the hybrid setup.

Regarding the cost assessment, various reports were investigated where different economic parameters such as CAPEX and OPEX were presented. The main literature used for the estimation of the CAPEX and OPEX, where presented from the following cost assessment reports [12], [13], [14], [15] and [16]. The cost categories that were used in this report were devised and implemented per the literature [12] and [15].

2 Theory

In this chapter, diverse technologies and theoretical subjects will be addressed and presented to establish the base understanding of the contents of this thesis. Contents to be addressed and discussed in this chapter include, for example, the function of the Nordic energy market or power and flow equations.

Technologies that also will be addressed are the following:

- *Pumped Storage Hydropower (PSH) & its mechanical components*
- *Wind Power Systems*

2.1 Swedish Energy Market

The PSHHS that will be presented and addressed in this thesis is located in Sweden. Thus, a brief understanding of the Nordic energy market is necessary to understand the beneficial application of the PSHHS.

2.1.1 Distribution of the Energy Market

The Swedish energy market can be divided into two separate divisions where the energy trading is non-competitive with open pricing but a regulated monopoly driving the distribution network. The trading of the energy is done on one singular market but the market itself is divided into different sub-markets which can be seen below [17].

- The Discount Market
- The Day-Ahead *(DA)* Market
- The Intraday *(IN)* Market
- The Balance *(BA)* Market

The Discount Market's main application is to manage the various risks that can occur, which entail price variations over time and between the four electrical zones. The financial trading for the Nordic market is set on the NASDAQ Commodities where long-term agreements and price hedging opportunities can be bought for days, weeks, quarters, and years [18].

On the *The Day-Ahead Market*, a balance between supply and demand is set to determine the optimal spot price. The auction procedure is done anonymously by different representatives. The purchase and sales offers are matched to determine the collective hourly electrical spot price across the various electrical zones which is determined one day in advance. The spot price is used as a reference for financial electricity trading where it is calculated without including potential transmission constraints. The ”final” electricity price is determined by the cost to generate and transmit the final kilowatt-hour required to meet demand [18].

The Intraday Market is a concrete balancing market for continuous trading of hourly contracts. Representatives can adjust the purchase contracts that were made on the *DA* to compensate for potential irregularities in energy usage. This allows the representative to trade balances one hour in advance to compensate for the irregularities. The *IN* is primarily used by representatives responsible for energy balancing, even though it is not required [18].

The Balance Market is where *Svenska Kraftnät* and other European transmission network operators can purchase energy from various ancillary services to compensate/balance to fulfill their system responsibility. *Svenska Kraftnät's* responsibility is to ensure a balance between consumption and production in the Swedish electricity system. In Sweden, the frequency needs to be stable at 50 Hz which can be regulated by ancillary services that use a manual or automatic reserve. The manual reserves are accessed by a joint Nordic regulating power market [18].

As described above the various sub-markets are constructed as safety measures to ensure balance and stability regarding the trading and frequency. Figure 2.1 visualizes the connection and order between the different markets. From this report,

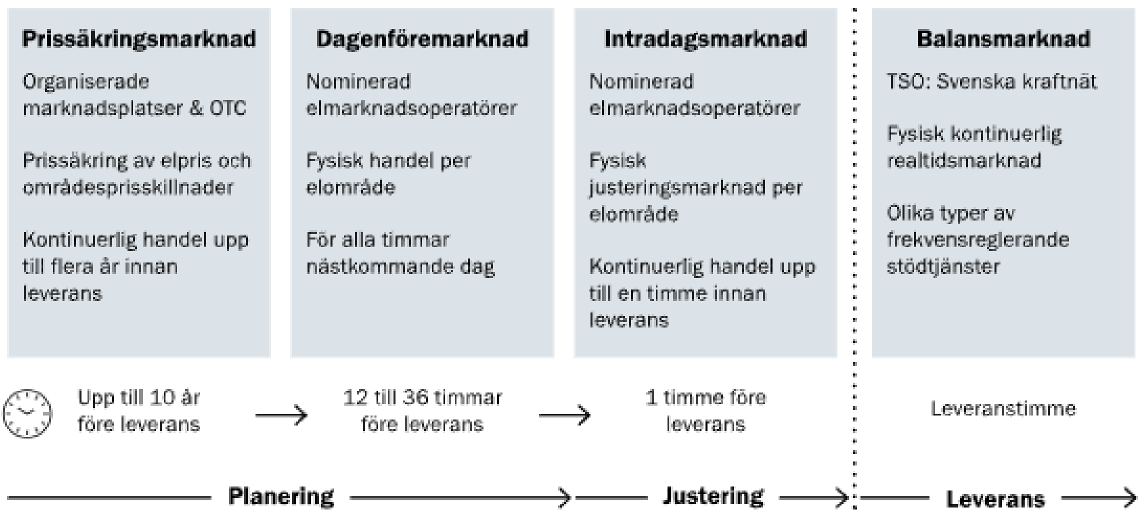

Figure 2.1: Swedish Sub-markets [18]

2.1.2 More about Day-Ahead Market

As will be discussed later in the thesis, the *DA* spot market will be a significant factor regarding the result/evaluation of the business and operation strategy of the *PSHHS*. It is therefore beneficial to have a brief comprehension of the *DA* spot market and how the *PSHHS* can utilize its market.

As mentioned in Section 2.1.1 the hourly electrical spot price is determined one day in advance where the auction is done anonymously. The trading can be done up to 12:00 and the system prices for the oncoming day are then released at 13:00. See the following example for a brief explanation of the trading of the *DA* market.

- Monday 11:00 - Order for Tuesday
- Monday 13:00 - Spot prices released for Tuesday
- Tuesday 11:00 - Order for Wednesday
- Tuesday 13:00 - Spot price released for Wednesday

To clarify, the spot prices are released after the order placements which entail some implications that will be discussed later in the thesis.

2.1.3 Ancillary Services

In Section 2.1.1 regarding the *BA*, it was mentioned that energy could be purchased from different ancillary services for balancing and system responsibility purposes. The following ancillary services can be seen below [19].

- Fast Frequency Reserve *(FFR)*
- Frequency Containment Reserve - Normal *(FCR-N)*
- Upward Frequency Containment Reserve - Disturbance *(FCR-D Up)*
- Downward Frequency Containment Reserve - Disturbance *(FCR-D Down*
- Automatic Frequency Restoration Reserve *(aFRR)*
- Manual Frequency restoration reserve *(mFRR)*
- Disturbance reserve
- Power Reserve

The types of ancillary services that could be suitable to a *PSHHS* would be, the frequency restoration reserves i.e. *aFFR* or *mFFR*. This will be further discussed in later sections of the thesis.

The *aFFRs* main objective as the other services, is to restore the frequency to 50 Hz for both downward and upward regulation. The *aFFR* is activated automatically when the frequency deviates from 50 Hz. The reserve is bought up in advance in a capacity market. The key features of this type of reverse can be seen below [20].

The *mFFRs* main objective as the other services, is to restore the frequency to 50 Hz but compared to the *aFFR*, the *mFFR* is manually activated based on *Svenska Kraftnäts* request and can be used in upwards and downwards regulation. The trading of the *mFFR* can be done on either the capacity market or the energy activation market which have different requirements and can be seen below [21].

The specific requirements for each ancillary service can be seen below in Figure 2.2.

Updated May 2nd 2024

Overview of the requirements for reserves

Remedial action	Frequency containment reserves			Frequency restoration reserves	
FFR	**FCR-D upward**	**FCR-D downward**	**FCR-N**	**aFRR**	**mFRR**
Fast Frequency Reserve (Snabb frekvensreserv)	Upward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning uppreglering)	Downward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning nedreglering)	Frequency Containment Reserve - Normal (Frekvenshållningsreserv -Normaldrift)	Automatic Frequency Restoration Reserve (Automatisk Frekvens-återställningsreserv)	Manual Frequency Restoration Reserve (Manuell Frekvens-återställningsreserv)
Upward regulation	Upward regulation	Downward regulation	Symmetrical upward and downward regulation	Upward and/or downward regulation	Upward and/or downward regulation
Minimum bid size 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 1 MW	**Minimum bid size** Capacity market: 1MW** Energy activation market: 5MW
Activation Automatic activation for changes in frequency when there are low levels of rotational energy in the system	**Activation** Automatic linear activation within the frequency interval 49,90 - 49,50 Hz	**Activation** Automatic linear activation within the frequency interval 50,10 - 50,50 Hz	**Activation** Automatic linear activation within the frequency interval 49,90 - 50,10 Hz	**Activation** Automatic activation for frequency deviations from 50,00 Hz	**Activation** Manual activation when requested by Svenska kraftnät
Activation time Three alternatives for 100%: - 0,7 seconds (at 49,50 Hz) - 1,0 seconds (at 49,60 Hz) - 1,3 seconds (at 49,70 Hz)	**Activation time** Activation time for FCR-D up is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 2 on page 18	**Activation time** Activation time for FCR-D down is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 2 on page 18	**Activation time** Activation time for FCR-N is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 1 on page 14 as well as requirement 9 on page 28	**Activation time** 100 % within 5 minutes	**Activation time** 100% within 15 minutes
Volume requirements for Sweden Up to about 100 MW	**Volume requirements for Sweden** Up to 567 MW	**Volume requirements for Sweden** Up to 547 MW*	**Volume requirements for Sweden** 235 MW	**Volume requirements for Sweden** Up to 111 MW	**Volume requirements for Sweden** Capacity market: Up to 300 MW Energy activation market: No volume requirement
Endurance - Endurance: 30 seconds alternatively 5 seconds - Repeatability: Ready for activation within 15 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour

*** Actual plan for procurement is lower than the volume requirement since FCR-D downward is a new product that was introduced in January 2022. The procurement plan is updated quarterly. More information is available in Swedish on Svenska kraftnät's webpage:** www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/

** A cleared bid on the capacity market implies a commitment to submit a bid on the energy market.
More detailed information on the requirements is available in Swedish in the BSP agreeement and associated regulatory documents. They are available for download on Svenska kraftnät's webpage:
https://www.svk.se/aktorsportalen/leverantor-av-balanstjanster-bsp/bsp-avtalet/

Figure 2.2: Ancillary Services and its specific requirements [22]

2.2 Pumped Storage Hydropower

In this section, the Pumped Storage Hydropower (*PSH*) system will be presented, covering topics such as its application, technical design parameters, and capital structure.

2.2.1 Application of PSH

The main function of the pumped storage hydropower system is to store energy and in this case, the potential of the energy storage is in the form of water. In most configurations, the *PSH* uses two water reservoirs at varying elevations to store the water as a form of energy storage. Water is pumped up to the upper reservoir with a required power input (often when energy is in surplus or when spot prices are low) which in this thesis will be denoted as ”pumping mode”. To generate power, water flows back down the lower reservoir through a turbine which is connected to a generator that produces the desired power output [23]. For future reference, this mode will be denoted as ”generation mode” (occurs when energy is in deficit or when the spot prices are high). See Figure 2.3 for visualization of a typical open loop overhead *PSH* system.

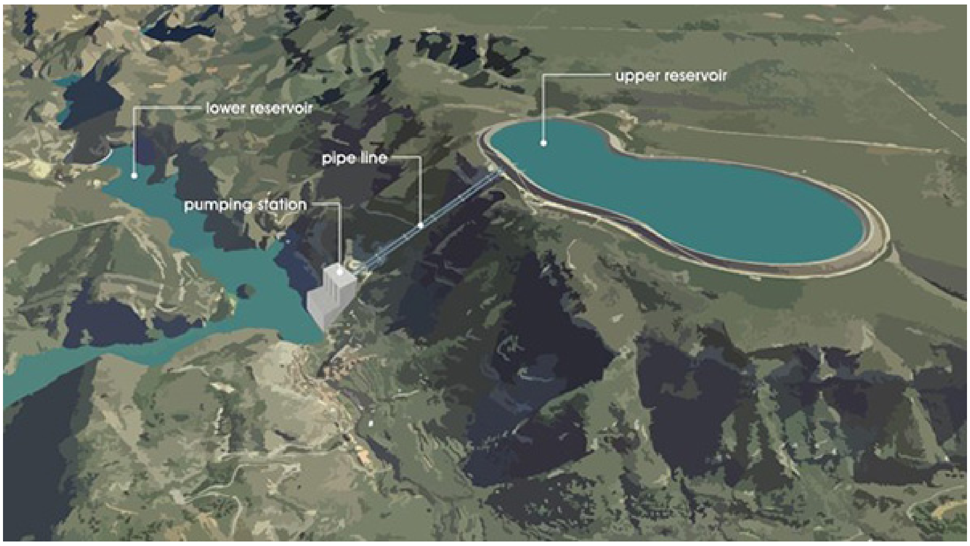

Figure 2.3: Typical Open Loop Overhead *PSH* System [24]

2.2.2 Technical Parameters

PSH systems can be implemented and designed in various ways which can be characterized as *Open* or *Closed-loop*. According to [23], *open loop* is characterized by an ongoing hydrologic connection to a natural body of water, whereas *closed loop* reservoirs do not have a connection to a natural source of water flow.

The operation modes of the *PSH* system can be configured by various technologies including the mode of operation speed. The most common type of deployed *PSH* speed-unit, is the fixed speed unit where a singular turbine can operate in (pumping and generation mode i.e. This is also one of the most cost-effective solutions and with fixed-speed units, frequency regulation ancillary services can be supported by balancing regulation, but only in generation mode. But with adjustable-speed units, the *PSH* system can support balancing regulation to the frequency ancillary services in both pumping and generation mode. The main disadvantage of this technology is its increased cost of about 25-30% compared to the fixed-speed units. Another variant, the ternary unit, offers higher flexibility with faster response times in both pumping and generation modes. However, the trade-off is its ability to match the required ramp rates for balancing regulation in frequency ancillary services. [12] In this thesis a fixed-speed *PSH* unit will be assumed as configuration mode.

A typical *PSH* system can be characterized by the following components .

- Upper & Lower Reservoir for *Open* & *Closed-loop* systems.
- Penstock or an underground tunnel for the transportation of water
- Generator/Motor
- Turbine/Pump
- Transmission line connected to the electrical grid

The design and implementation of the *PSH* system technologies can vary while they achieve the same output. See the following examples of different *PSH* systems with each specific design.

- Small scale Overground *PSH* system
- Small scale Overground *PSH* system + Wind Power system *(PSHHS)*
- Underground mine PSH
- Small PSH with reservoirs of corrugated steel and floating membranes

The *Over/underground PSH* system can be visualized with figure 2.3 where it is characterized as an *open loop* system since natural water sources such as rivers or streams are connected. The reservoirs can be built artificially where natural water sources are preferred as reservoirs, especially regarding capital costs, which will be discussed in Section 4.1. One planned *PSH* system in Australia called Snowy 2.0 is estimated to generate 2 GW with a potential storage capacity of 350 GWh of energy. The plant will use two existing reservoirs with the upper reservoir set at 650 m above ground and requires a 27 km long underground tunnel as a connection [25]. See figure 2.4 for a graphical visualization of the Snowy 2.0 project.

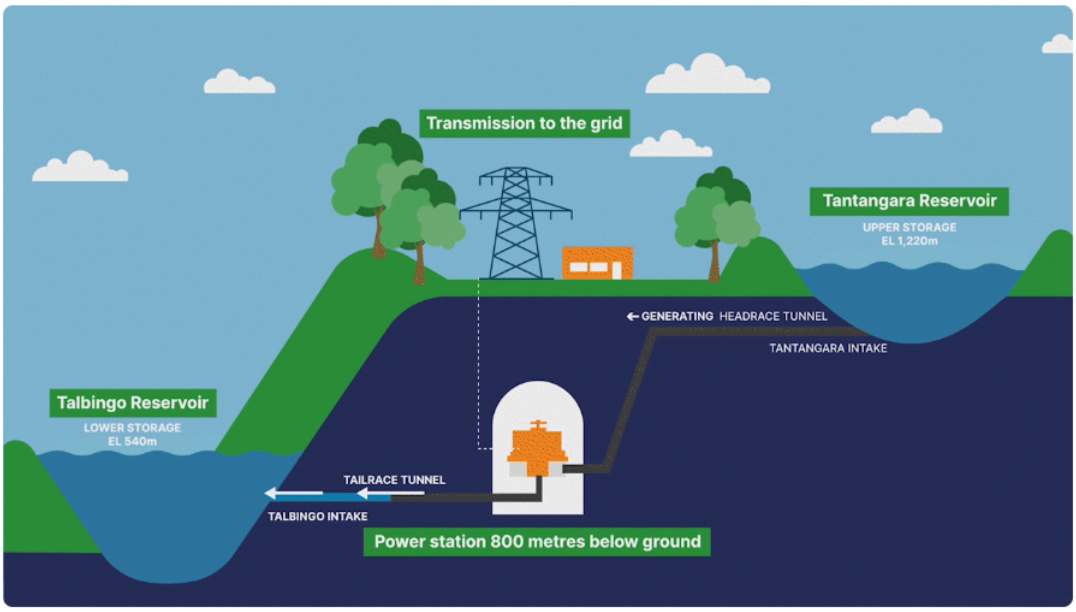

Figure 2.4: Graphical Overview of the *PSH* system Snowy 2.0 [26].

The *Small scale overground PSH coupled with a Wind Power system* in this thesis is characterized by the same design as mentioned above. The main difference is that the *PSH* is connected with a *WPS* by a transmission line between the systems.

Underground mine PSH utilizes an upper existing or a built artificial reservoir and is connected to abandoned mines underground by old tunnels and galleries. Compared to the overground *PSH*, where tunnels or pipes are underground, the lower reservoir is overground. But in this design, the reservoir is located in the mines where the powerhouse also is located underground which contains components such as the turbine/pump and generator.

2.2.3 Project Cost of PSH

The development cost for a *PSH* is generally difficult to pinpoint since the characterization of such cost is site-specific regarding external factors such as physical, environmental properties, etc [27]. The project costs of a *PSH* system can be divided into two separate costs one of which is capital expenditure/cost *CAPEX* and the other being operational expenditure *OPEX*. The various cost elements will be presented by utilizing external literature as a base reference which categorizes the costs differently

Capital Expenditure: Direct & Indirect Costs

According to a report from literature [12] capital costs can be divided into two different categories: indirect and direct costs. Indirect costs usually cover 15-33% of the direct costs and can be divided into various categories. The following table provides examples of the various cost elements for direct and indirect costs. [12]

Table 2.1: Direct vs indirect cost for a *PSH* system with various cost elements.

Direct Costs	**Indirect Costs**
Materials	Taxes, external fees, bonds
Construction including tunnels, dams, roads, waterway, tunnels, etc.	Engineering studies for various categories such as environmental, planning, etc.
Cost of Equipment	Permit and licensing
Labour for construction of structures	Engineering planning and studies
Installation and supply of various equipment	Construction management
Reservoir agreements/contracts	

As seen in Table 2.1 the capital cost can be divided into various elements utilizing the following literature in Table 2.2 the structure of the *(CAPEX)* could be devised and adjusted accordingly to the *PSH* site which was investigated in this thesis.

Table 2.2: Literature used as base reference when categorizing and estimating the *CAPEX* elements

Base reference report	**Year**	**Size**	**CAPEX**
Cost and performance report [12]	2020	100 MW (10h)	$2623
Entura repot [13]	2018	377 MW (12h)	$1535
Lu 2017 Thesis PKV X [14]	2017	55MW	$1475
NREL A report [15]	2022	116 MW	$2708
Black & Veatch [16]	2012	500 MW	$2196

The categorization of the cost elements of the capital cost was devised using the report from (Black & Veatch) [16] and is represented in Table 2.3 below. As mentioned before the cost varies on a multitude of factors and is divided differently from project to project and for that reason, the various CAPEX values from Table 2.2 were revised with the estimated capital cost division from the (Black & Veatch) report.

Table 2.3: Categorization of the direct capital expenditure for the *PSH* site

Direct CAPEX Categories	
Reservoir	€/kW
Waterway	€/kW
Powerhouse Civil	€/kW
Powerhouse structure and BOP electromechanical	€/kW

- **Reservoir Cost:** The report from (Black & Veatch) estimated the upper reservoir cost by including costs such as reservoir clearing, emergency spillways, excavation and grout curtains, and inlet/outlet. The reservoir was assumed to be artificially constructed with a built gravity dam [16]. The report from Entura does not specify the assumed parameters regarding the reservoir costs but states that the cost varies depending on whether the reservoir exists or is artificially built. It also includes the cost of the dams required for the reservoir and in this instance also includes both of the reservoirs for the cost [13]. A similar assumption is made from a report made by NREL [15] in comparison to the report from Entura. The cost structure of the reservoir from (Black & Veatch) was assumed as the optimal estimation of the reservoir cost(including upper and lower reservoir), see Equation 2.1.

$$C_{\text{reservoir}} = C_{\text{dam}} + C_{\text{clearing}} + C_{\text{excavation\&lining}} + C_{\text{spillway}} + C_{\text{inlet\&outlet}} \tag{2.1}$$

  The investigated *PSH* site in this thesis is a Bluefield site that already utilizes existing reservoirs [28] and since both, the reports from Entura and NREL estimate the cost of two reservoirs, the total cost of the reservoir was reduced with 50%. See Equation 2.2.

$$C_{\text{reservoir,adjusted}} = 0,5\ C_{\text{reservoir}} \tag{2.2}$$

- **Waterway:** The cost elements in the waterway category consist according to the Entura report of either tunneling costs for underground penstocks or costs for surface penstocks [13]. The same is assumed from the Black & Veatch report where a fully underground penstock is assumed for the proposed cost of the tunneling/waterway [16]. However, the report from NREL includes surface penstocks for a small PSH system as cost elements for the waterway, aligning well with the PSH site in this study. The total costs for the waterway encompass expenses directly related to the surface penstock (materials, supports, anchors, etc.) as well as costs for civil work, as detailed in Equation 2.3. [29]

$$C_{\text{waterway}} = C_{\text{penstock}} + C_{\text{civil}} \tag{2.3}$$

- **Powerhouse Civil:** From the (Black & Veatch) report, powerhouse excavation costs are mentioned and defined as costs bound to the excavation of the powerhouse and could be interpreted as civil costs in this scenario [16]. However, in the report from Entura, the powerhouse civil costs are assumed to include elements such as cable, exhaust shaft, and tunnel costs. It also mentioned that the cost is site-specific where flow and head are proportional to the total cost of the powerhouse civil. cost. [13]

- **Powerhouse structure and BOP Electromechanical:** This cost is defined as the powerhouse structures, equipment, and balance from the Black and Veatch report [16]. The report from Entura relates the cost to head, discharge, and type of technology of the station where it also brings up the different speed units (see sub-Section 2.2.2) as cost factors [13]. Adapting the (Black & Veatch) estimation the cost could be defined as Equation 2.4.

$$C_{\text{powerhouse,tot}} = C_{\text{BOP}} + C_{\text{E\&M}} + C_{\text{structure}} \tag{2.4}$$

Recalling Table 2.1 the indirect costs include various cost elements and as for the direct cost of the CAPEX, the indirect costs can vary between *PSH* sites. Using the literature from Table 2.2 the following categorization of the indirect cost of the CAPEX was concluded, see Table 2.4.

Table 2.4: Categorization of the indirect capital expenditure for the *PSH* site

Indirect CAPEX Categories	
EPC (Engineering, procurement, and construction)	€/kW
Owners cost	€/kW
Grid Fees	€/kW

- **EPC** In the (Black & Veatch) report the *EPC* (Engineering, procurement, and construction) is not directly mentioned but costs such as construction, project management, and plant location are included as "other cost" parameters and in context to this study, it is assumed as *EPC* costs [16]. Entura includes preliminaries and general, design and approvals, and contingency as indirect costs and are assumed as *EPC* costs [13]. Similar assumptions are made from the report from NREL where *EPC* as a cost of its own is mentioned and other costs such as contingency, developer cost, sales tax, and overhead and profits [15].

- **Owner's Cost** In (Black & Veatch) the Owner's cost is applied on top of the total cost i.e. the sum of the direct and indirect costs [16]. The report from Entura applies the owner's cost as a percentage of the direct costs such as the other indirect costs included in the *EPC* category [13].

- **Grid Fees:** In Sweden, grid fees are applied when a system is connected to the main grid through a specific tariff [30]. A previous thesis from LTH, in collaboration with BayWa r.e., estimated these grid fees to be between €150,000 and €200,000 per kW.

Operational Expenditure: Fixed and Variable Cost

The *OPEX* is described as the yearly costs related to standard maintenance, repair, refurbishment, and labor for the operation [15]. The OPEX can be divided into fixed and variable operation and maintenance *(O&M)* costs and were estimated using the report from ESGC as the benchmark. It is mentioned that the labor costs decrease when the capacity of the *PSH* increases which for a small *PSH* system increases the labor costs. The assumed fixed *O&M* costs can be seen in table 2.5.

Table 2.5: Fixed *O&M* Costs for Different *PSH* System Sizes

Component	**Unit**	**15 MW**	**100 MW**	**1,000 MW**
Duration	(hrs)	12	10	10
Labor-related fixed O&M	(€/kW-year)	17.7	16.5	3.3
Parts-related fixed O&M	(€/kW-year)	5.9	5.9	5.9
Refurbishment-related fixed O&M	(€/kW-year)	9.4	9.4	9.4
Annual Grid Fee	(€/kW-year)	10.0	0.0	0.0
Total fixed O&M	**(€/kW-year)**	**43.05**	**30.30**	**17.70**
Percentage of capital cost	2%	2%	2.00%	1.40%

The variable O&M costs are defined as required usage associated with consumables for the operation of the *PSH* system and were set to the estimated valuation per the ESGC report [12]. See Table 2.6.

Table 2.6: Fixed O&M Costs for Different *PSH* System Sizes

Component	**Unit**	**15 MW**
Duration	(hrs)	12 0
Total Variable O&M	**(€/kWh-year)**	**0,4815**

2.3 Wind Power

As mentioned in Section 1, wind power has seen an increased market share of electricity production during recent years. Wind power turbines harness the kinetic energy from the wind through its large rotating blades, driving a generator that generates electricity to the grid. Wind power systems *WPS* can be located both on-shore and off-shore and for this study, an onshore *WPS* is investigated. Wind is regarded as a sustainable renewable energy source since its small impact on the environment but the main drawback is its volatile pattern regarding electricity generation. [31]

2.3.1 Power Purchase Agreement *(PPA)*

In the existing *WPS* systems, the price of the generated electricity is determined by specific price purchase agreements that vary on various factors such as the generated volume of the electricity per year also known as the base load required to be delivered to the grid. *PPA* are common with renewable production systems like solar PV systems or such as in this case *WPS*. With supervision from BayWa r.e. a fixed set *PPA* was applied for the price of the electricity sold to the grid from the investigated *WPS*.

3 Methodology of the PSH Design & Operation Strategy

The reader will in this chapter, first be presented with the methodology of the PSH Design and then shown the constructed algorithm for the operation strategy of the PSH system. The implemented methodology used to investigate the PSH design and the operational strategy is presented in Figure 3.1 below

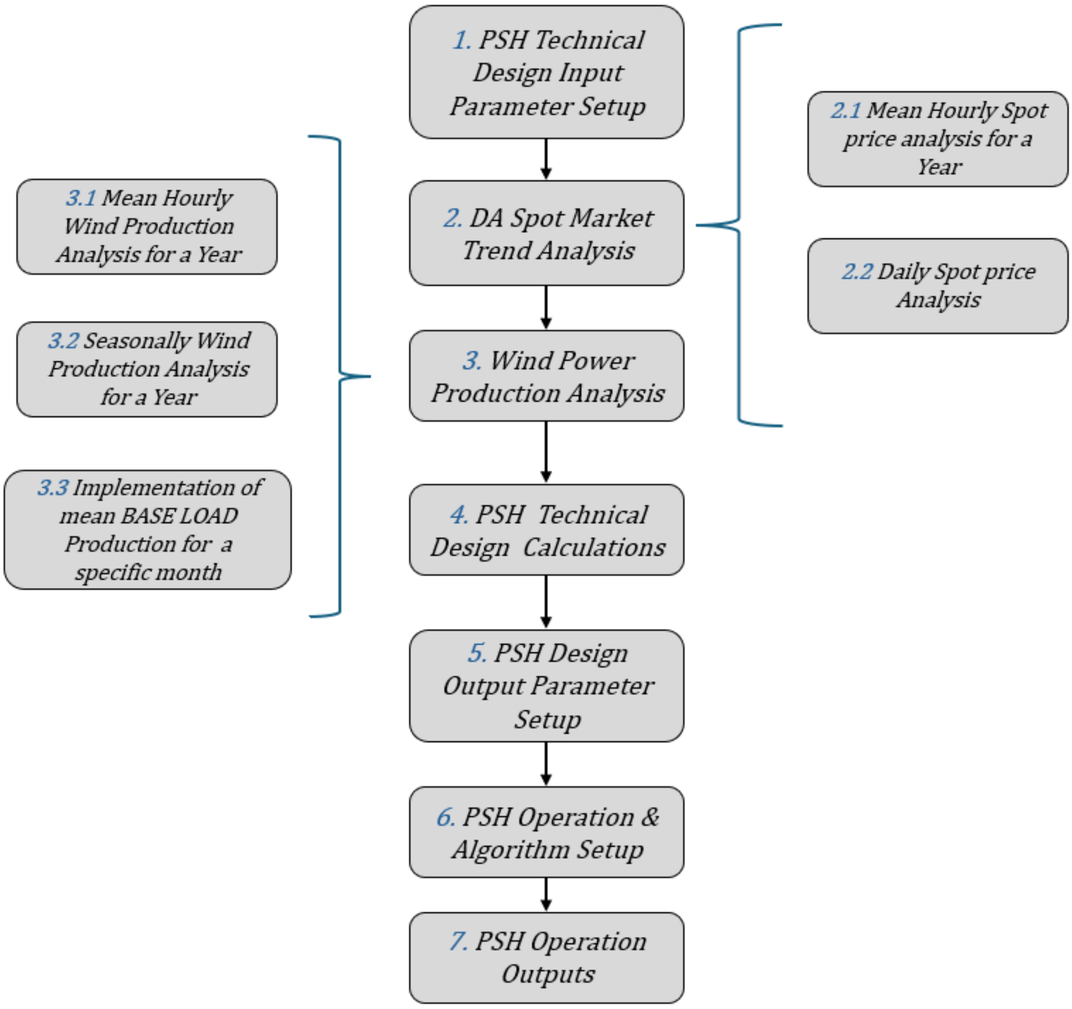

Figure 3.1: PSHHS Design & Operation Method Setup

3.1 PSH Design Input Setup

As mentioned in Section 2.2 the *PSH* system can be designed in various ways and in this study, it will be characterized as an overground *PSH* system. The upper and lower reservoirs are existing reservoirs in an undisclosed location referred to as *Site Hydro*. The upper reservoir will need a constructed dam for water storage. The connection between the reservoirs will be a singular surface penstock constructed out of carbon steel. To transport the water i.e. when the *PSH* system is pumping water to store or generate electricity, a singular Francis turbine will be used which is connected to a generator. The idea is then for the system to be connected to the a *WPS* which will require a newly constructed transmission line.

The design inputs consist of the available parameters and dimensions from the existing reservoirs and must be determined before the design of the *PSH* system can be made. The following input parameters must be determined before constructing the hypothetical *PSH* system.

- Area of the reservoir
- Available water level variation
- Water Volume used for 1 Storage cycle
- Upper reservoir height
- Lower reservoir height
- Direct distance between the reservoirs

As mentioned in Section 1.3, the primary literature used in this study for the technical design of the *PSH* system were [9] and [32]. Both sources establish similar parameters for constructing the technical design. The following input parameters for *PSH* were assumed per the limitations and conditions discussed in Section 1.3. See Table 3.1.

Table 3.1: Upper and Lower Reservoir properties of *Site Hydro* .

Upper & Lower Reservoir properties	
Area of reservoir ($A_{r,upper}$)	0,27 km^2
Available water level variation ($h_{r,level}$)	1,5 m
Water Volume used for 1 Storage cycle (V_r)	405 000 m^3
Upper reservoir height ($h_{r,upper}$)	170 m
Lower reservoir height ($h_{r,lower}$)	37 m
Direct distance between the reservoirs (L_r)	2700 m

3.2 Day-ahead Spot Market Trend Analysis

Since the Day-ahead market was the main factor in the hypothetical *PSH* system setup some basic analyses were made regarding its patterns and trends. The main objective of this analysis was to observe any trends or fluctuations in cohesion to the time of the day. The hourly *DA* spot prices were accessed from the power exchange operator NORDPOOL [33]. Hourly *DA* Spot prices from 2017-2023 in SE XYZ were collected and used when conducting the analysis. An average value of numerous hourly spot prices corresponding to a specific hour for a whole day was created to observe the price fluctuation for a day. The following result in figure 3.2 regarding the pattern of the daily spot price was obtained from the constructed function by using the worksheet tool, Microsoft Excel.

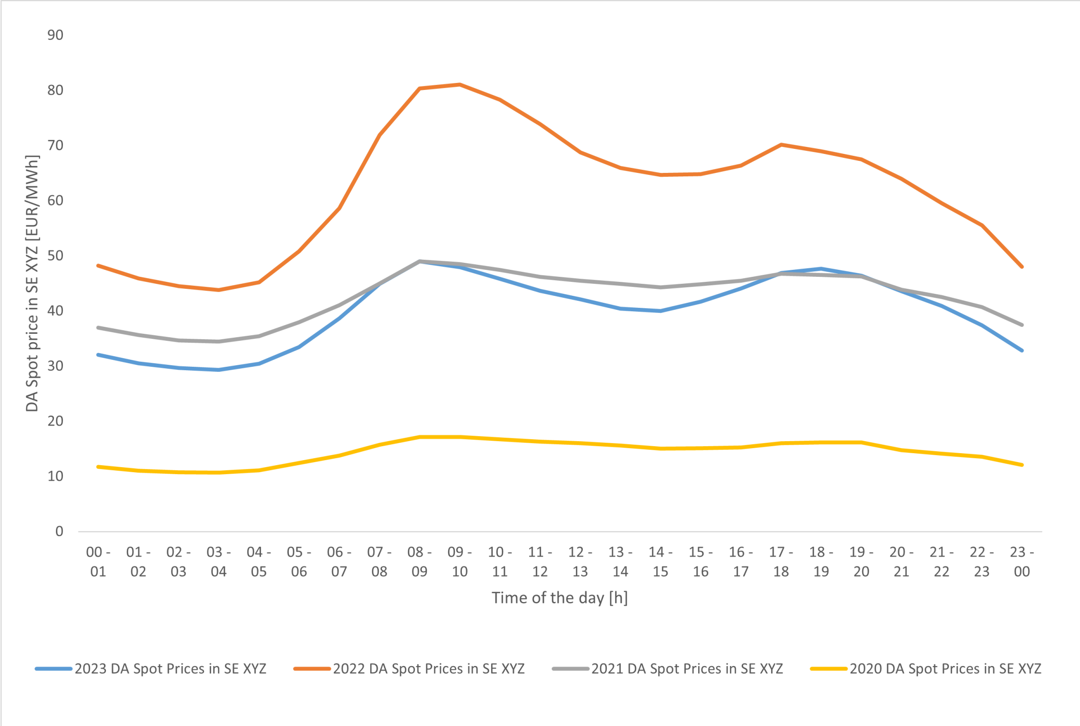

Figure 3.2: Average hourly *DA* Spot Price for a day between 2020-2023

The conclusion of the result in figure 3.2 was the pattern of the daily spot price, fluctuates in a six-hour interval where the spot prices seem to be lower at later points in the day and higher in the middle part of the day. This pattern appears to apply to all of the year samples with varying amplitude for each specific year. This result was also deemed acceptable because according to a publication from GodEL electric prices are generally higher in at later parts of the morning and become lower during the nights [34].

Based on the conclusion derived from the analysis, an optimal storage time between 6-12 hours to achieve full storage capacity for the *PSH* system was chosen.

3.3 Wind Power Production Analysis

The subsequent step in the *PSH* design setup involved analyzing the wind power data provided by BayWa r.e. As seen from figure 3.1, the corresponding step was divided into four sub-steps. The main objective of the step was to establish the set base load *(BL)* per the *PPA*, introduced in Sub-sections 2.3.1 & 3.3.3 which was used as a base value reference in the operation algorithm strategy.

3.3.1 Mean Hourly Wind production Analysis

The first sub-analysis was to calculate the average hourly electricity generated from a *WPS* between 2018-2023 for a specific day. This was the same method used in Section 3.2, where the objective was to identify a potential connection between the established conclusion in the *DA* spot market and a possible pattern from the produced electricity from the *WPS*. The result of the average generation from the *WPS* is presented in figure 3.3.

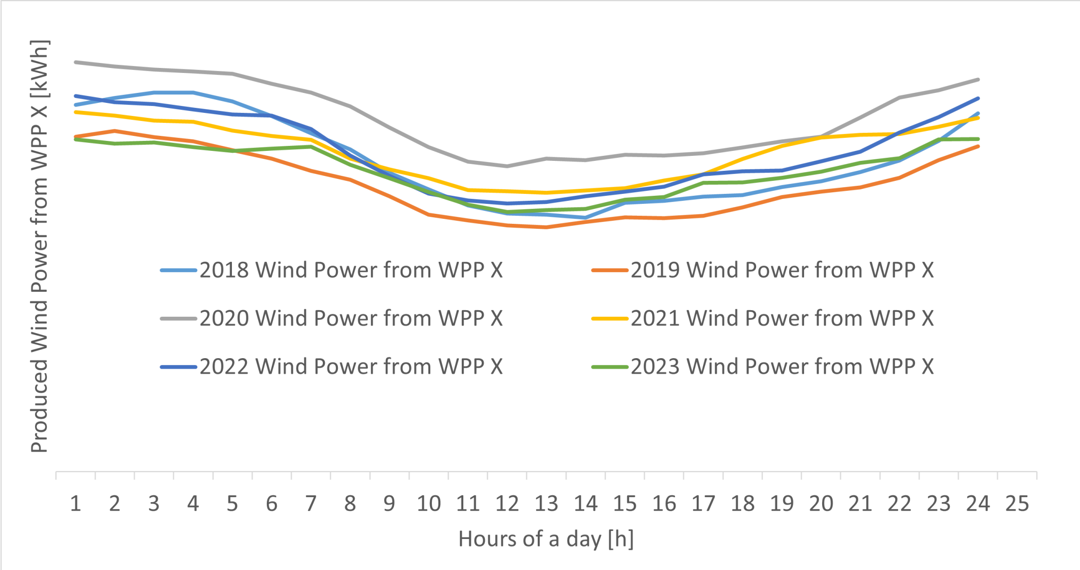

Figure 3.3: Hourly Average electricity produced the *WPS* for a day between 2018-2023

By a simple comparison between figure 3.2 and 3.3, it was concluded that average produced electricity i.e. the graph in figure 3.3 had a inverse pattern of the established graph in figure 3.2. Based on the results of the comparison, it was assumed that when spot prices were high, the *WPP* was low. Further analyses were deemed necessary to validate and ensure the composed hypothesis regarding the relationship between the *WPS* generation and the *DA* spot price.

3.3.2 Seasonally Mean Hourly Wind production Analysis

In this step, it was deduced that a season-based analysis of *WPS* production could further refine the existing assumptions and identify variations in generation across different seasonal weather conditions. This is also supported in an article from eia.gov where it can be seen that the U.S.'s *WPS* capacity factors fluctuate depending on the specific month [35]. Using the same Excel function as in Section 3.3.1, the average electricity produced from the *WPS* was calculated and divided into four seasons, see figures 3.4 and 3.5.

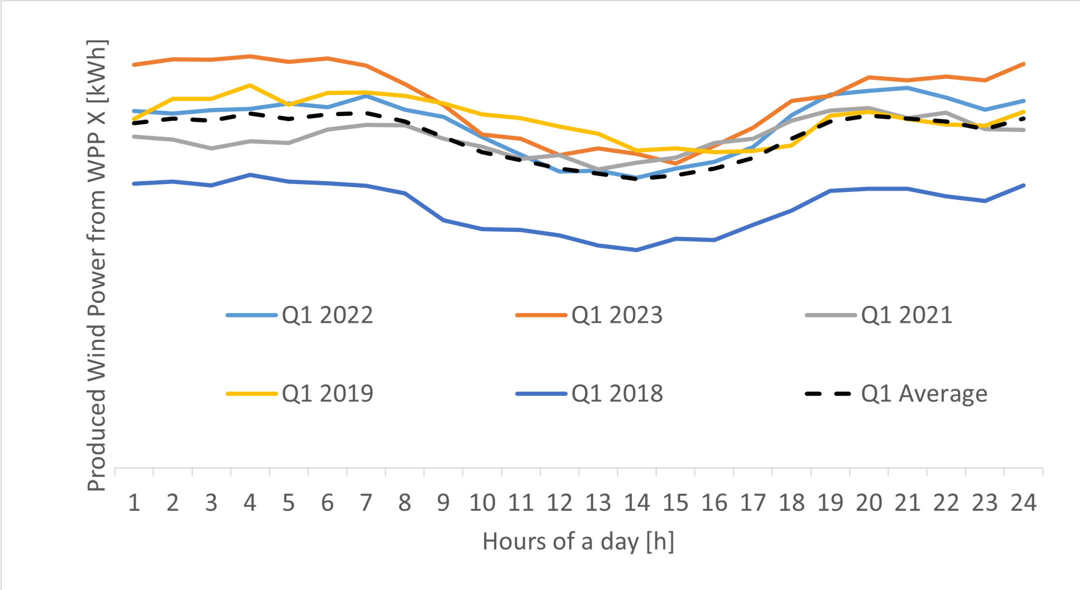

Figure 3.4: Q1 (Dec-Feb) Hourly Average electricity produced from *WPS* for a day between 2018-2023

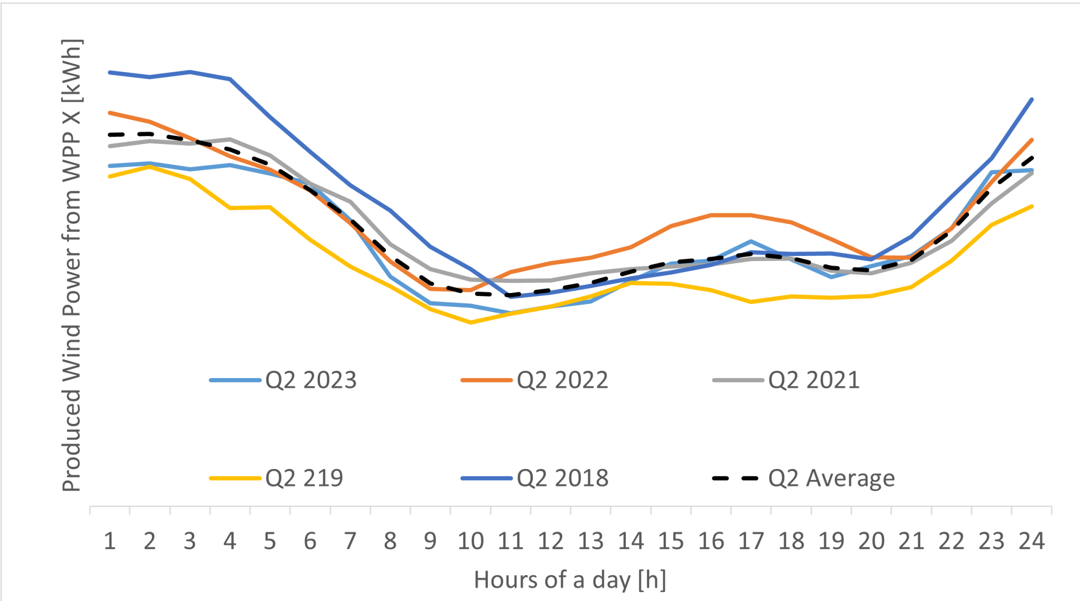

Figure 3.5: Q2 (Mars-May) Hourly Average electricity produced from *WPS* for a day between 2018-2023

From figures 3.4 and 3.5 it was concluded that the generation *WPS* fluctuates depending on the various months/seasons. The hypothesis regarding the connection between the *DA* spot price and the *WPS* generation, was evident, especially in figure 3.5. One last comparison was made where the 2023 *DA* spot price was directly plotted against the electricity produced from *WPS* in 2023. The following result can be seen in figure 3.6.

It was finally validated that there was a connection between the different factors, which helped with the construction of the algorithm regarding the regulation and operation of the produced electricity from *WPS* to the *PSH* system. See Section 3.7.1 for the implementation and setup of the regulation and operation of the produced wind power.

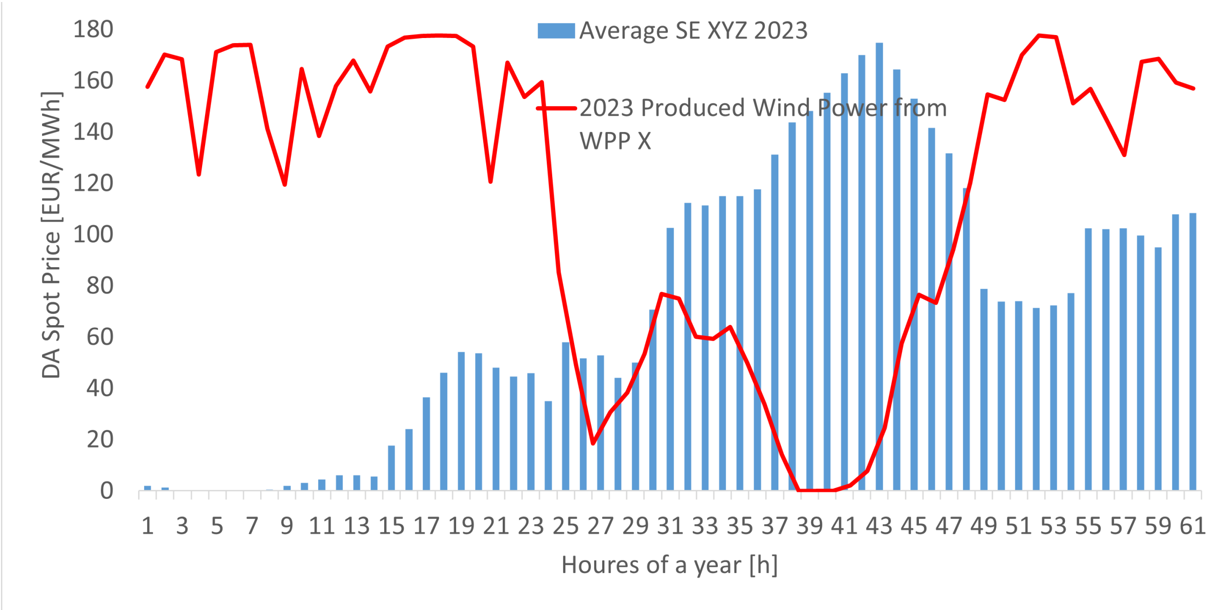

Figure 3.6: *DA* spot price plot against electricity produced from *WPS* (2023) in SE XYZ

3.3.3 Implementation of mean Base Load production for a specific month

The next phase was to calculate the mean base load for each specific month for a year, this was required since this was the reference value used in the *PPA* when establishing the optimal price of the produced electricity from *WPS* . The base load was obtained by the following method.

1. Arrange the data for each specific hour between 00:00 and 23:00 for each month.
2. Calculate the average value of electricity produced during each specific hour across all days of the corresponding month. For instance, calculate the average production for 13:00 across all days of the month.
3. Repeat this calculation for every month, considering data from multiple years.
4. Finally, calculate a new average for each specific hour across the same months but for different years. This will provide an average base load for each hour of the day across various years for the same month.

The following result was obtained regarding the estimated base load from *WPS* between 2018 and 2023, see figure 3.7. Various cases were also implemented to visualize a case if the *BL* would decrease with a certain percentage. By analyzing the figure, the *BL* decreases around spring and summer and then increases around autumn/winter.

Since electricity production statistics from *WPS* is confidential the real *BL* can not be presented but for clarification a data sample is provided in table 3.2 below which are the same values presented in figure 3.7.

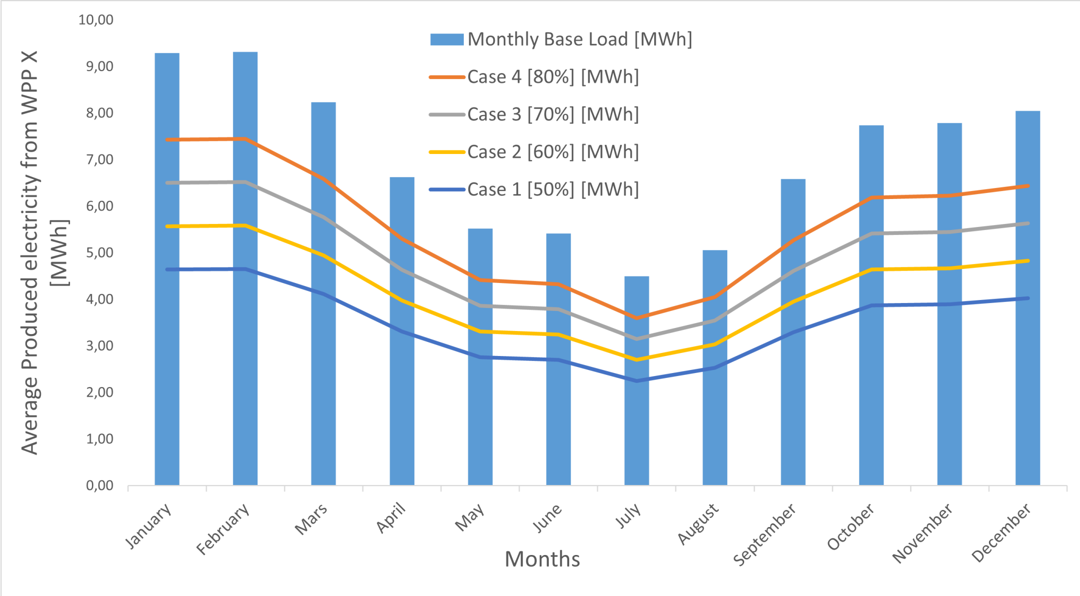

Figure 3.7: DATA SAMPLE Calculated Base Load between (2018 and 2023) of generated electricity from *WPS* used in the *PPA*.

Type	January	February	Mars	April	May	June
Monthly Base Load [MWh]	9,29	9,31	8,24	6,63	5,53	5,41
Case 4 [80%] [MWh]	7,43	7,45	6,59	5,30	4,42	4,33
Case 3 [70%] [MWh]	6,50	6,52	5,77	4,64	3,87	3,79
Case 2 [60%] [MWh]	5,57	5,59	4,94	3,98	3,32	3,25
Case 1 [50%] [MWh]	4,64	4,66	4,12	3,31	2,76	2,71

Type	July	August	September	October	November	December
Monthly Base Load [MWh]	4,50	5,06	6,59	7,74	7,79	8,05
Case 4 [80%] [MWh]	3,60	4,05	5,27	6,19	6,23	6,44
Case 3 [70%] [MWh]	3,15	3,54	4,61	5,42	5,45	5,64
Case 2 [60%] [MWh]	2,70	3,04	3,95	4,64	4,67	4,83
Case 1 [50%] [MWh]	2,25	2,53	3,29	3,87	3,89	4,03

Table 3.2: DATA SAMPLE Calculated Base Load between (2018 and 2023) of generated electricity from *WPS* used in the *PPA*.

3.4 PSH Technical Design Calculations

The next phase of the method described in figure 3.1, was to conduct various calculations for the technical design of the *PSH* system. The methodology of this step can be seen in figure 3.8 below where various sub-steps were conducted for the final technical design. As mentioned in Section 1.4, the literature [9] was used for inspiration, particularly concerning the technical design related to pipe selection. The Literature [10] proposed various equations which were used for the technical design. The method proposed in Figure 3.8 was developed in conjunction with the insights from the literature sources [10] and [9].

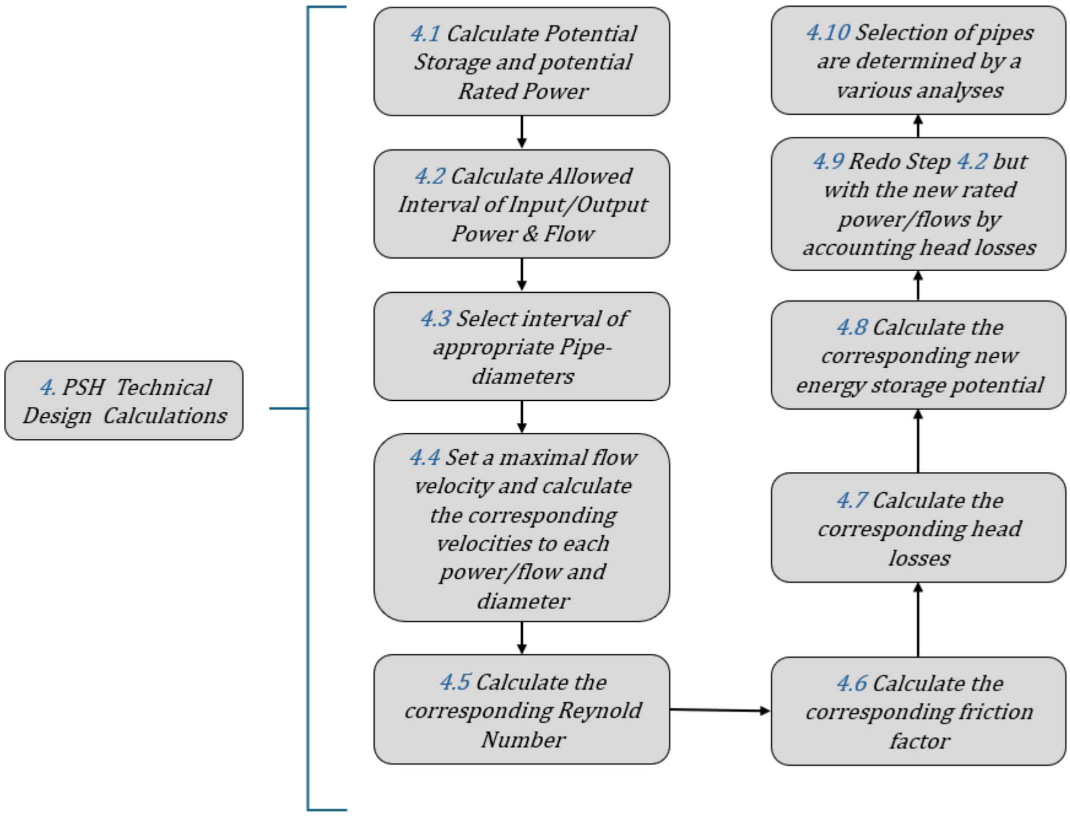

Figure 3.8: Method of "Step 4 from Figure 3.1 with various sub-steps for the technical design of the *PSH* system.

3.4.1 Calculation of Potential Rated Power & Storage

The calculation of the potential rated power and storage was performed without accounting for losses, as losses will be determined through an iterative process, assuming the rated input parameters as the real values. This was done in the report from [9] where no head loss is assumed when the acceptable range of rated power is determined. The maximum potential storage of the *PSH* system was determined from equation 3.1.

$$\mathrm{E_p} = mg\Delta h \tag{3.1}$$

$$\mathrm{E_p} = \mathrm{V_r}\rho_\mathrm{w} g\Delta h$$

Where the water density is given by $\rho_\mathrm{w} = 1000 kg/m^3$, $\Delta h = (\mathrm{h_{r,upper}} - \mathrm{h_{r,lower}})$ and gravity by $g = 9,81 m/s^2$. From the set input parameters in Table 3.1 in Section 3.1, equation 3.1 will yield the following relation.

$$\mathrm{E_p} = 405000\ m^3 \cdot 1000\ kg/m^3 \cdot 9,81\ m/s^2 \cdot (170 - 37)\ m \tag{3.2}$$

$$\mathrm{E_p} = 148,44\ MWh$$

Without considering any losses the maximum potential energy storage for the *PSH* system was calculated to $\approx 148\ MWh$. The minimum and maximum interval of the rated power was then determined since the assumed storage time to reach full storage capacity was set at an interval of 6-12 hours. The following calculation for the rated power is presented in equation 3.3.

$$\mathrm{P_r} = \frac{\mathrm{E_p}}{\mathrm{t_s}} \tag{3.3}$$

With $\mathrm{E_p} = 148\ MWh$ and $\mathrm{t_s} = (6 - 12)\ h$ the following result in equations 3.4 and 3.5 was obtained for the max/min value of the rated power.

$$\mathrm{P_{r,max}} = \frac{148\ MWh}{6\ h} \tag{3.4}$$

$$\mathrm{P_{r,max}} = 24,75\ MWh$$

$$\mathrm{P_{r,min}} = 12,37\ MWh \tag{3.5}$$

The results of sub-step 4.1 are provided in Table 3.3 below, which were used as base values for sub-step 4.2.

Table 3.3: Results of sub-step 4.1 of the potential technical ratings of the *PSH*

Potential Technical Ratings		
Rated Storage ($\mathrm{E_p}$)	$148\ MWh$	
Storage Time ($\mathrm{t_s}$)	6 h	12 h
Rated Power ($\mathrm{P_r}$)	$24.75\ MWh$	$12.37\ MWh$

3.4.2 Calculation of Corresponding In- & Output Power & Flow

In this step, the potential flows were calculated from the corresponding rated power interval from table 3.3 in sub-Section 3.4.1. The in- and outputs for the power and flows were now divided into pumping and generation categories.

- Input Power, is defined as the required pumping power for the pump, to pump a volume of water to the upper reservoir. This is denoted as $\mathrm{P_p}$ for future reference.
- Input Flow, is defined as the corresponding volumetric water flow from the pump i.e. $\mathrm{P_p}$ applied with the efficiency of the pump which results in the corresponding water flow. This is denoted as $\mathrm{Q_p}$.
- Output Flow, is defined as the volumetric flow that gravity pulls down through the penstock down to a Francis turbine connected to a generator. In this instance, the flow is the determining factor compared to the pumping mode (input case). The generation flow (output flow) is denoted as $\mathrm{Q_g}$.
- Output Power, is defined as the generated power from the corresponding generation flow $\mathrm{Q_g}$ applied with the efficiency of the Francis turbine. The generation power is denoted as $\mathrm{P_g}$.

The formulas applied for the calculation of the power and flows were taken from the design and performance report [9] and the book [29]. Both of the literature used the same methodology regarding the calculation of power and flows.

The pumping power was first to be determined, by combining equation 3.1 and 3.3 and adding the corresponding pumping efficiency (η_p) the following was obtained for the pumping power. See Equation 3.6.

$$P_p = \frac{V_r \rho_w g \Delta h \eta_p}{t_s} \tag{3.6}$$

$$Q_p = \frac{P_p \eta_p}{\rho_w g \Delta h} \tag{3.7}$$

Given the use of a Francis turbine, the efficiency needed to be determined for both the pumping and generation modes. According to [36] the pumping and generation efficiency for a Francis turbine installed in a *PSH* system could at best operate at 90% and 95% respectively with an overall round-trip efficiency of 86%. However, it was mentioned that most systems operate at a round-trip efficiency between 75-80%. A report from AFRY advocated a round-trip efficiency between 70-80% for a *PSH* system [37]. Based on the literature, the round-trip efficiency (η_t) was set to 77% with the pumping efficiency (η_p) at 85% and generation efficiency (η_g) at 90%. When substituting the variables in Equation 3.6 and 3.7 with their corresponding given values, the obtained results are presented in Table 3.4 with a calculation example in Equation 3.8 and 3.9.

$$P_p = \frac{405000\ m^3 \cdot 1000\ kg/m^3 \cdot 9,81\ m/s^2 \cdot (170-37)\ m \cdot 0,85}{12\ h} \tag{3.8}$$

$$Q_p = \frac{P_p \cdot 0,85}{1000\ kg/m^3 \cdot 9,81\ m/s^2 \cdot (170-37)\ m} \tag{3.9}$$

Table 3.4: Results of sub-step 4.2 of the interval of the pumping power/flow and the generation power/flow for the *PSH* system accounted with efficiency but without accounting for losses,

$t_s[h]$	$P_p[MW]$	$Q_p[m/s^3]$	$Q_g[m/s^3]$	$P_g[MW]$
12	14.55	9.37	11.14	9.38
11	15.88	10.23	12.15	10.23
10	17.46	11.25	13.36	11.25
9	19.4	12.5	14.84	12.5
8	21.83	14.06	16.7	14.06
7	24.95	16.07	19.08	16.07
6	29.11	18.75	22.27	18.75

3.4.3 Selection and Calculation of Optimal Pipe Diameters

In this sub-step (4.3), the objective was to identify the allowed pipe diameter depending on the resulting velocity in the penstock. Some conditions and limitations were set for the selection of pipe diameter which are presented below.

- The thickness of the pipe was not considered in the evaluations and therefore was ignored in the calculation steps. This was noted in both the performance report [9] and the fluid dynamics literature [10].
- The maximum allowed velocity (v_{max}) in the penstock was set to 5 m/s which was concluded with the supervisor from the university. An article from the chemical engineer states that the

rule of thumb for max velocities in penstocks can be calculated by the following relation $v_{max} = 1,5 + \frac{\text{diamater in inches}}{10}$ and in this instance allows up to 10 m/s [38]. Other sources such as [39] and [40] claim 6 m/s and $5 - 7$ m/s respectively.

The subsequent stage involved selecting a suitable pipe diameter range for analysis, set between 0.75 and 3 meters with increments of 0.25 meters. This decision yielded 10 distinct pipe variations. Considering the storage time of the PSH system set between 6 and 12 hours, this led to the examination of 70 configuration combinations across different pipe diameters and storage durations. Since there are two separate modes (pumping and generation), the total configuration combinations amounted to 140. The following formula was used to determine the velocity in the pipe which also is used in the literature [9] and [29]. See Equation 3.10.

$$v_{pen} = \frac{Q}{0.25\pi d^2}, \quad \text{where} \quad Q = \begin{cases} Q_p \\ Q_g \end{cases} \tag{3.10}$$

The following results for the velocity configuration combinations were then obtained by using Equation 3.10, see tables 3.5 and 3.6 for the pumping and generation mode.

Table 3.5: Velocity configuration for each combination between Pipe Diameter and generation Flow

Pumping Flow [m^3/s]	9,37	10,23	11,25	12,5	14,06	16,07	18,75
Storage Times [h]	12	11	10	9	8	7	6
Possible Diameters [m]	**Pumping Velocities [m/s]**						
0.75	21,21	23,16	25,46	28,29	31,83	36,38	42,44
1	11,93	13,03	14,32	15,92	17,9	20,46	23,87
1,25	7,64	8,34	9,17	10,19	11,46	13,1	15,28
1,5	5,3	5,79	6,37	7,07	7,96	9,09	10,61
1,75	3,9	4,25	4,68	5,2	5,85	6,68	7,8
2	2,98	3,26	3,58	3,98	4,48	5,12	5,97
2,25	2,36	2,57	2,83	3,14	3,54	4,04	4,72
2,5	1,91	2,08	2,29	2,55	2,86	3,27	3,82
2,75	1,58	1,72	1,89	2,1	2,37	2,71	3,16
3	1,33	1,45	1,59	1,77	1,99	2,27	2,65

Table 3.6: Velocity configuration for each combination between Pipe Diameter and Pumping Flow

Generation Flow [m^3/s]	9,37	10,23	11,25	12,5	14,06	16,07	18,75
Storage Times [h]	12	11	10	9	8	7	6
Possible Diameters [m]	**Generation Velocities [m/s]**						
0.75	21.23	23.16	25.46	28.29	31.83	36.38	42.44
1	11.94	13.03	14.32	15.92	17.9	20.46	23.87
1.25	7.64	8.34	9.17	10.19	11.46	13.1	15.28
1.5	5.31	5.79	6.37	7.07	7.96	9.09	10.61
1.75	3.9	4.25	4.68	5.2	5.85	6.68	7.8
2	2.99	3.26	3.58	3.98	4.48	5.12	5.97
2.25	2.36	2.57	2.83	3.14	3.54	4.04	4.72
2.5	1.91	2.08	2.29	2.55	2.86	3.27	3.82
2.75	1.58	1.72	1.89	2.1	2.37	2.71	3.16
3	1.33	1.45	1.59	1.77	1.99	2.27	2.65

Studying the results in the tables 3.5 and 3.6, multiple velocity configurations were greater than v_{max} = 5 m/s. It was concluded that the pipe diameters between 0.75 and 1.5 were ineligible compared to the set condition of v_{max}. But certain configurations were within the limit of v_{max}, especially for pipe diameters with either 1.75 or 2 m, but that only applied for certain storage times since the corresponding flow is higher when the storage time is lower. To simplify the analysis of the various configurations, it was determined that the velocities to the corresponding storage times must be ≤ 5 m/s for a pipe diameter to be eligible with the condition. The final selection of the eligible pipe diameter can be seen in Table 3.7 below.

Table 3.7: Acceptable output range of diameters with corresponding cross-section area and relative roughness with a material of carbon steel

Range of Pipe Diameters [m]	**Acceptable Output**	**Cross section Area [m^2]**	**e/d**
0.75	NO	-	-
1	NO	-	-
1.25	NO	-	-
1.5	NO	-	-
1.75	NO	-	-
2	NO	-	-
2.25	YES	3.98	0.0000222
2.5	YES	4.91	0.00002
2.75	YES	5.94	0.0000182
3	YES	7.07	0.0000167

3.4.4 Calculation of Reynolds Number

The next step of the process was to determine the Reynolds number of the selected range of diameters with its corresponding velocities, calculated in sub-Section 3.4.3 in Table 3.7. The Reynolds number is defined by the following relation in equation 3.11 and was obtained from [10].

$$Re = \frac{\rho_w v d}{\mu} \tag{3.11}$$

Where $\mu_w = 0,0010005\ Pa \cdot s$ and is the dynamic viscosity for water at a temperature of 20°C. Utilizing velocity tables 3.5 and 3.6 for pumping and generation mode respectively, the Reynolds number could be calculated. See Tables 3.8 and 3.9.

Table 3.8: Reynolds Numbers for the pumping mode configuration for each combination between Pipe Diameter, generation Flow, and corresponding velocity

Q_p **[m³/s]**	9,37	10,23	11,25	12,5	14,06	16,07	18,75
t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Reynolds Numbers [-]**						
0,75	15899550	17361319	19085457	21206897	23860570	27271364	31814093
1	11924038	13023488	14312844	15912044	17891054	20449775	23858071
1,25	9545227	10419790	11456772	12731134	14317841	16366817	19090455
1,5	7946027	8680660	9550225	10599700	11934033	13628186	15907046
1,75	6821589	7433783	8185907	9095452	10232384	11684158	13643178
2	5957021	6516742	7156422	7956022	8955522	10234883	11934033
2,25	5307346	5779610	6364318	7061469	7961019	9085457	10614693
2,5	4772614	5197401	5722139	6371814	7146427	8170915	9545227
2,75	4342829	4727636	5194903	5772114	6514243	7448776	8685657
3	3988006	4347826	4767616	5307346	5967016	6806597	7946027

Table 3.9: Reynolds Numbers for the generation mode configuration for each combination between Pipe Diameter, generation Flow, and corresponding velocity

Q_g **[m³/s]**	9,37	10,23	11,25	12,5	14,06	16,07	18,75
t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Reynolds Numbers [-]**						
0.75	15914543	17361319	19085457	21206897	23860570	27271364	31814093
1	11934033	13023488	14312844	15912044	17891054	20449775	23858071
1.25	9545227	10419790	11456772	12731134	14317841	16366817	19090455
1.5	7961019	8680660	9550225	10599700	11934033	13628186	15907046
1.75	6821589	7433783	8185907	9095452	10232384	11684158	13643178
2	5977011	6516742	7156422	7956022	8955522	10234883	11934033
2.25	5307346	5779610	6364318	7061469	7961019	9085457	10614693
2.5	4772614	5197401	5722139	6371814	7146427	8170915	9545227
2.75	4342829	4727636	5194903	5772114	6514243	7448776	8685657
3	3988006	4347826	4767616	5307346	5967016	6806597	7946027

3.4.5 Calculation of Friction Factor

In this sub-step. the friction factor was to be calculated and could be determined by three different methods per the performance report [9] or by two methods from the fluid dynamics book [10]. The methods presented in [10] were deemed reliable when comparing the origin of the source. The two remaining methods that could be utilized are presented below in Equations 3.12 and 3.13.

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{\varepsilon/d}{3.7} + \frac{2.51}{Re\sqrt{f}} \right) \tag{3.12}$$

$$\frac{1}{\sqrt{f}} = -1.8 \log \left[\left(\frac{\varepsilon/d}{3.7} \right)^{1.11} + \frac{6.9}{Re} \right] \tag{3.13}$$

According to [10], utilizing Equation 3.12 (called *Colebrook formula*), required an iterative solution since its dependence on the relative roughness ε/d, Re and f. Since Section 3.1 is a whole iterative solution itself regarding the selection of pipes with the corresponding head losses, Equation 3.13 (called *Haaland equation*) was deemed the relevant formula for its simplicity to determine the friction factor. Applying the the Reynolds numbers from Tables 3.8 and 3.9 and the relative roughness from Table 3.7 into Equation 3.13 the following results for the various friction factors for pumping and generation mode was obtained in Tables 3.10 and 3.11.

Table 3.10: Friction factors for the pumping mode configuration for each combination between Pipe Diameter, Pumping Flow, and corresponding velocity

Q_p **[m^3/s]**	9,37	10,23	11,25	12,5	14,06	16,07	18,75
t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Friction factors [-]**						
0.75	0.01127	0.01126	0.01125	0.01124	0.01123	0.01121	0.01120
1	0.01080	0.01078	0.01076	0.01075	0.01073	0.01071	0.01069
1.25	0.01050	0.01048	0.01045	0.01042	0.01039	0.01037	0.01034
1.5	0.01031	0.01027	0.01024	0.01020	0.01016	0.01013	0.01009
1.75	0.01019	0.01014	0.01010	0.01005	0.01001	0.00996	0.00991
2	0.01011	0.01006	0.01000	0.00995	0.00989	0.00983	0.00977
2.25	0.01006	0.01001	0.00994	0.00988	0.00981	0.00975	0.00968
2.5	0.01005	0.00998	0.00991	0.00984	0.00977	0.00969	0.00961
2.75	0.01005	0.00998	0.00990	0.00982	0.00974	0.00965	0.00956
3	0.01006	0.00998	0.00990	0.00981	0.00972	0.00963	0.00953

Table 3.11: Friction factors for the generation mode configuration for each combination between Pipe Diameter, Pumping Flow, and corresponding velocity

Q_g **[m^3/s]**	9,37	10,23	11,25	12,5	14,06	16,07	18,75
t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Friction factors [-]**						
0.75	0.0113	0.0113	0.0112	0.0112	0.0112	0.0112	0.0112
1	0.0108	0.0108	0.0108	0.0107	0.0107	0.0107	0.0107
1.25	0.0105	0.0105	0.0104	0.0104	0.0104	0.0104	0.0103
1.5	0.0103	0.0103	0.0102	0.0102	0.0102	0.0101	0.0101
1.75	0.0102	0.0101	0.0101	0.0101	0.0100	0.0100	0.0099
2	0.0101	0.0101	0.0100	0.0099	0.0099	0.0098	0.0098
2.25	0.0101	0.0100	0.0099	0.0099	0.0098	0.0097	0.0097
2.5	0.0100	0.0100	0.0099	0.0098	0.0098	0.0097	0.0096
2.75	0.0100	0.0100	0.0099	0.0098	0.0097	0.0096	0.0096
3	0.0101	0.0100	0.0099	0.0098	0.0097	0.0096	0.0095

3.4.6 Calculation of Head losses

The objective of the proposed iterative process was to identify the major losses that occur when the *PSH* system is pumping or generating electricity by the water transmission. The losses are directly proportional, to the friction factor, length of penstock, penstock velocity, pipe diameter, and gravity. The corresponding formula called the *Darcy-Weibach equation* applied for the major losses ($h_{L,major}$) of the water flow and is presented in Equation 3.14 and was utilized by the performance report [9] and also established in the fluid dynamics literature [10].

$$h_{L,major} = f \frac{L}{d} \frac{v^2}{2g} \tag{3.14}$$

Minor losses were also a phenomenon that occurred in the process and from [10] it is defined by the losses from the entrance/exit, bends, and valves in the pipe. See Equation 3.15 for the definition of the minor losses $h_{L,minor}$.

$$h_{L,minor} = K_L \frac{v^2}{2g} \tag{3.15}$$

Where K_L is defined as a loss coefficient depending on the pipe characteristics as mentioned above (valves, bends, etc.). Using the loss coefficient values presented in the fluid dynamics literature [10] the loss coefficient was set to the following: K_L= 6,23. The total head loss is defined by Equation 3.16.

$$h_{L,tot} = h_{L,major} + h_{L,minor} \tag{3.16}$$

$$h_{L,tot} = \left(K_L + f \frac{L}{d}\right) \frac{v^2}{2g}$$

Since all values in Equation 3.16 are calculated in previous steps, the following results for the head losses are determined and are presented in Tables 3.12 and 3.13.

Table 3.12: Total Head losses for the Pumping mode configuration for each combination between Pipe Diameter and corresponding variables presented in Equations 3.14 and 3.15

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Total head losses [m]**						
0.75	1073.12	1278.52	1543.88	1904.71	2409.35	3142.55	4273.38
1	256.72	305.78	368.75	455.42	574.86	749.89	1019.12
1.25	86.00	102.34	123.44	152.09	191.92	250.41	339.92
1.5	35.49	42.24	51.00	62.64	79.18	103.03	139.96
1.75	17.02	20.14	24.35	29.96	37.81	49.12	66.73
2	9.00	10.73	12.89	15.87	20.03	26.05	35.28
2.25	5.20	6.14	7.41	9.09	11.50	14.91	20.26
2.5	3.18	3.75	4.53	5.58	7.00	9.10	12.35
2.75	2.05	2.42	2.90	3.57	4.52	5.88	7.95
3	1.38	1.63	1.95	2.40	3.03	3.92	5.30

Table 3.13: Total Head losses for the generation mode configuration for each combination between Pipe Diameter and corresponding variables presented in Equations 3.14 and 3.15

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Total head losses [m]**						
0.75	1077.63	1282.46	1537.93	1898.83	2403.78	3140.12	4273.38
1	257.15	306.24	369.88	453.67	573.54	749.32	1019.90
1.25	86.00	102.49	122.98	151.86	192.07	250.98	338.89
1.5	35.59	42.33	50.85	62.64	79.41	102.80	140.06
1.75	17.03	20.09	24.35	30.07	37.78	49.26	66.68
2	9.05	10.76	12.89	15.82	20.04	26.00	35.35
2.25	5.21	6.14	7.39	9.10	11.49	14.86	20.29
2.5	3.17	3.75	4.53	5.57	7.01	9.11	12.34
2.75	2.04	2.42	2.90	3.56	4.51	5.86	7.97
3	1.38	1.63	1.95	2.40	3.02	3.91	5.29

3.4.7 Adjustment of the new Energy Storage potential

With the newly calculated losses in sub-Section 3.4.6, the storage potential could be adjusted accordingly to the corresponding pipe diameters and flows. The same method presented in sub-Section 3.4.1 was implemented for the calculation of the adjusted energy storage. The final storage values for the *PSH* system accounted with the potential head losses are presented below in Tables 3.14 and 3.15.

Table 3.14: Adjusted Energy Storage for the pumping mode configuration for each combination between Pipe Diameter and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Adjusted Energy Storage [MWh]**						
0.75	-1035.88	-1262.57	-1555.43	-1953.65	-2510.58	-3319.76	-4567.77
1	-134.89	-189.03	-258.53	-354.17	-485.99	-679.16	-976.29
1.25	53.52	35.50	12.20	-19.41	-63.37	-127.92	-226.70
1.5	109.27	101.83	92.15	79.30	61.05	34.73	-6.02
1.75	129.65	126.22	121.56	115.38	106.71	94.23	74.79
2	138.51	136.59	134.21	130.92	126.33	119.68	109.50
2.25	142.70	141.66	140.26	138.40	135.75	131.98	126.07
2.5	144.93	144.29	143.44	142.27	140.72	138.40	134.80
2.75	146.17	145.77	145.23	144.50	143.45	141.95	139.66
3	146.91	146.64	146.28	145.78	145.10	144.12	142.59

Table 3.15: Adjusted Energy Storage for the generation mode configuration for each combination between Pipe Diameter and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Adjusted Energy Storage [MWh]**						
0.75	-1040.86	-1266.92	-1548.86	-1947.16	-2504.43	-3317.07	-4567.77
1	-135.36	-189.54	-259.78	-352.24	-484.54	-678.53	-977.15
1.25	53.52	35.33	12.71	-19.16	-63.54	-128.55	-225.57
1.5	109.16	101.73	92.31	79.3	60.8	34.99	-6.13
1.75	129.64	126.27	121.56	115.26	106.75	94.07	74.85
2	138.45	136.56	134.21	130.98	126.32	119.74	109.43
2.25	142.69	141.66	140.28	138.39	135.76	132.03	126.04
2.5	144.94	144.29	143.44	142.29	140.7	138.39	134.81
2.75	146.18	145.77	145.23	144.51	143.46	141.97	139.64
3	146.91	146.64	146.28	145.78	145.11	144.13	142.6

3.4.8 Adjustment of the new Powers and Flows

In this sub-step, additional adjustments for the powers and flows in both pumping and generation modes could be made by applying the revised calculations for the storage potential of the *PSH* system, as computed in Sub-section 3.4.7. Recalling the allowed selection of the pipe diameters, which in Sub-section 3.4.3 was concluded between 2,25-3 m, smaller data result samples could be analyzed. See Tables 3.16, 3.17, 3.18 and 3.19 for the revised power and flow for pumping and respectively generation mode.

Table 3.16: Adjusted Power P_p for the pumping mode configuration for each combination between Pipe Diameter, Pumping Flow, and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Power** P_p **[MW]**						
2.25	13.99	15.15	16.5	18.09	19.96	22.18	24.72
2.5	14.21	15.43	16.88	18.6	20.69	23.26	26.43
2.75	14.33	15.59	17.09	18.89	21.1	23.86	27.38
3	14.4	15.68	17.21	19.06	21.34	24.22	27.96

Table 3.17: Adjusted Flow Q_p for the pumping mode configuration for each combination between Pipe Diameter, Pumping Flow, and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Flow** Q_p $[m^3/s]$						
2.25	9.01	9.76	10.63	11.65	12.86	14.29	15.92
2.5	9.15	9.94	10.87	11.98	13.33	14.98	17.03
2.75	9.23	10.04	11.01	12.17	13.59	15.37	17.64
3	9.28	10.1	11.09	12.28	13.75	15.6	18.01

Table 3.18: Adjusted Power P_g for the generation mode configuration for each combination between Pipe Diameter, and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Power** P_g **[MW]**						
2.25	10.7	11.59	12.63	13.84	15.27	16.98	18.91
2.5	10.87	11.81	12.91	14.23	15.83	17.79	20.22
2.75	10.96	11.93	13.07	14.45	16.14	18.25	20.95
3	11.02	12	13.17	14.58	16.32	18.53	21.39

Table 3.19: Adjusted Flow Q_p for the pumping mode configuration for each combination between Pipe Diameter, and corresponding variables in 3.1

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Generation Flow** Q_g $[m^3/s]$						
2.25	6.89	7.47	8.14	8.92	9.84	10.94	12.18
2.5	7	7.61	8.32	9.17	10.2	11.46	13.03
2.75	7.06	7.69	8.42	9.31	10.4	11.76	13.5
3	7.1	7.73	8.48	9.39	10.51	11.94	13.78

Recalling the initial set potential power and flow intervals in Table 3.4 and comparing these values to Tables 3.16, 3.17, 3.18 and 3.19, the magnitude of all the power and flows decreased, which was expected since the total loss ($h_{L,tot}$) was applied. The presented results in sub-sections 3.4.7 and 3.4.8 are final and will be utilized when conducting the analyses in sub-Section 3.5 when choosing the final pipe dimensions.

3.5 Analysis of the adjusted values

After determining the pipe diameter and its corresponding storage capacity, power, and flow for both pumping and generation modes, various analyses were conducted. One option is to select the largest pipe diameter, which would minimize head loss and nearly maximize storage capacity. While theoretically effective, this approach would significantly increase costs in practical applications. The following parameters of the results in sub-sections 3.4.8 and 3.4.7 were investigated.

- Velocity configuration combinations
- Head loss to the corresponding diameter in pumping and generation mode
- Techno-economic analysis compared to overall energy loss

3.5.1 Analysis of the Velocity configuration combinations

As previously mentioned the optimal pipe diameters were concluded and yielded an interval of $2.25-3\ m$ per the set maximum velocity $v_{max} = 5\ m/s$. A flow velocity chart was constructed for the pumping and generation mode. The flow velocity was plotted against the pumping power whereas for the generation mode, the velocity was plotted against the generation flow. See Figures 3.9 and 3.10.

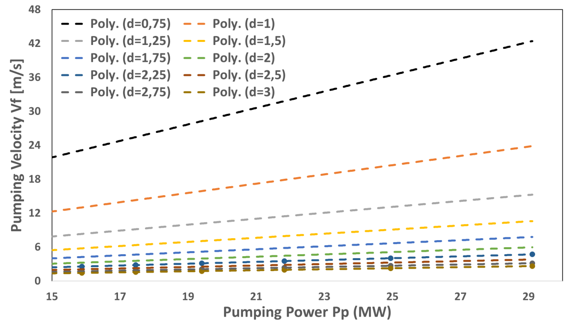

Figure 3.9: Pumping Flow Velocities Charts for various pipe diameters

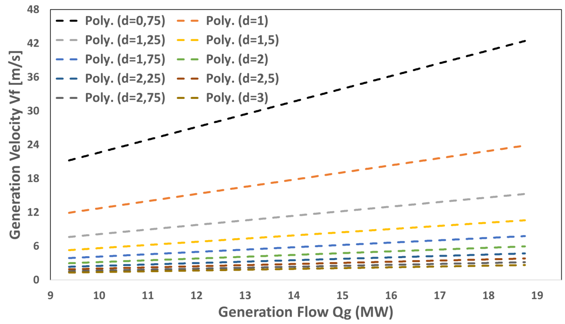

Figure 3.10: Generation Flow Velocities Charts for various pipe diameters

The analysis showed that pipes with smaller diameters produced higher flow velocities, while pipes with larger diameters entailed lower flow velocities.

3.5.2 Analysis of the Head Loss

The head loss for the pumping mode was plotted against the required pumping power (P_p) but for the generation mode, the head loss was plotted against the generation flow (Q_g). This is applied for all the set pipe diameters where the various plots are visualized in Figure 3.15.

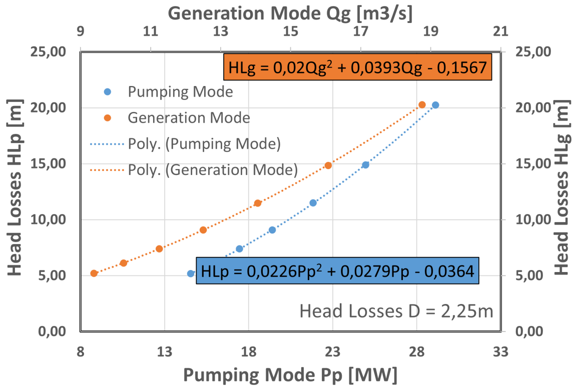

Figure 3.11: Head loss during pumping and generation mode with $d = 2,25m$

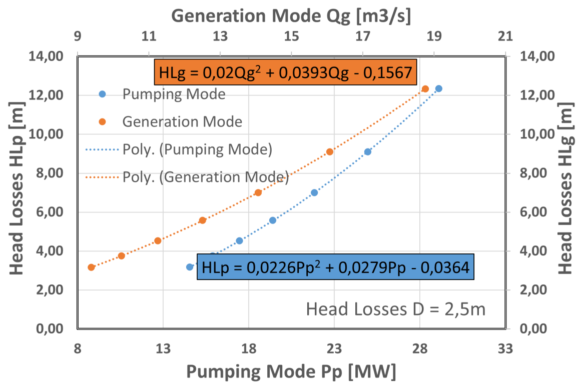

Figure 3.12: Head loss during pumping and generation mode with $d = 2,5m$

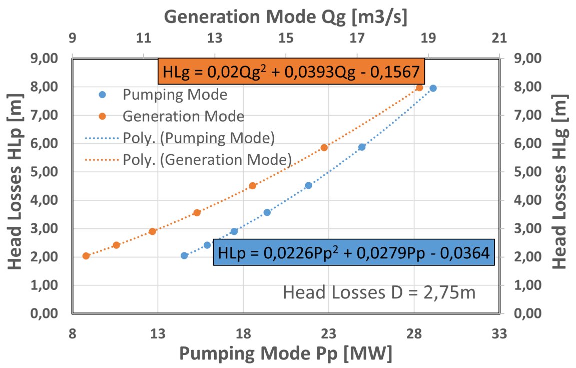

Figure 3.13: Head loss during pumping and generation mode with $d = 2,75m$

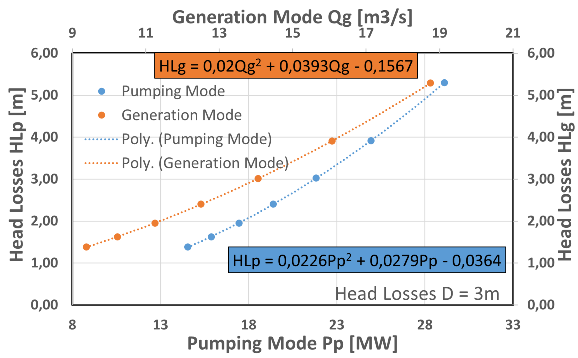

Figure 3.14: Head loss during pumping and generation mode with $d = 3m$

Figure 3.15: Overall Comparison between the various head losses depending on the pipe diameter

Analysis of the various plots revealed a consistent pattern, with the only difference being the magnitude of the head loss. As anticipated from previous results, head loss decreased as pipe diameter increased. Based on the calculations, it was concluded that the primary factor affecting head loss was the pipe diameter selection.

3.5.3 Technoeconomic analysis in relation to Energy Loss

In this last sub-step, a techno-economic valuation of the pipe selection was made by comparing the cost of the pipe to the energy loss to the corresponding diameter. The energy loss was compared to the maximum potential energy storage which was calculated in sub-Section 3.4.1 where only pumping mode was considered since the input power is greater than the output power, i.e. $P_p > P_g$. Recalling the adjusted energy storage calculated in sub-Section 3.4.7, the energy loss from the head losses was calculated with Equation 3.17 below.

$$E_{loss} = E_{p,adj} - E_p \tag{3.17}$$

With $E_{p,adj}$ as the adjusted energy storage accounting losses and E_p as the potential energy storage without losses, the total energy loss E_{loss} could be determined, see Table 3.20.

Table 3.20: Energy Loss for the pumping mode configuration for each combination between Pipe Diameter and corresponding variables in 3.17

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Energy Loss** (E_{loss}) **[MWh]**						
1.75	-18.79	-22.22	-26.88	-33.06	-41.73	-54.21	-73.65
2	-9.93	-11.85	-14.23	-17.52	-22.11	-28.76	-38.94
2.25	-5.74	-6.78	-8.18	-10.04	-12.69	-16.46	-22.37
2.5	-3.51	-4.15	-5	-6.17	-7.72	-10.04	-13.64
2.75	-2.27	-2.67	-3.21	-3.94	-4.99	-6.49	-8.78
3	-1.53	-1.8	-2.16	-2.66	-3.34	-4.32	-5.85

The cost of energy loss was then determined, the cost of the energy loss is defined by Equation 3.18.

$$C_{E,loss} = -E_{loss}E_{gen}ACoE \tag{3.18}$$

Where the average cost of electricity ($ACoE$ = 42 EUR/MWh) and the generated energy from the *PSH* system were set at (E_{gen} = 22026 MWh/year). The utilized data for $ACoE$ and E_{gen} were determined from the operation simulations per Section 3.8. See Table 3.21 for the results of the energy loss cost ($C_{E,loss}$).

Table 3.21: Cost of Energy Loss for the pumping mode configuration for each combination between Pipe Diameter and corresponding variables in 3.18

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Energy loss Cost** ($C_{E,loss}$) **[MEUR]**						
1.75	17.38	20.56	24.87	30.58	38.60	50.15	68.13
2	9.19	10.96	13.16	16.21	20.45	26.61	36.02
2.25	5.31	6.27	7.57	9.29	11.74	15.23	20.69
2.5	3.25	3.84	4.63	5.71	7.14	9.29	12.62
2.75	2.10	2.47	2.97	3.64	4.62	6.00	8.12
3	1.42	1.67	2.00	2.46	3.09	4.00	5.41

The next step was to calculate the pipe's material cost since it was previously concluded that the head loss decreased when the pipe diameter increased. A journal on structural engineering examined a surface penstock made out of the material, Carbon Steel (JIS SS400). The penstock had been used for 50 years and the analysis entailed a strong and positive correlation between the carbon content and the strength of the material. [41] The cost of the pipe is defined by Equation 3.19.

$$C_{pen} = m_{pen}C_{cs} \tag{3.19}$$

Where (m_{pen}) is the mass of the pipe in $[kg]$ and (C_{cs}) is the cost of the carbon steel which was set to $0,523\ EUR/kg$ in accordance with [42]. Equation 3.19 can be rewritten to Equation 3.20.

$$C_{pen} = v_{pen}\rho_{cs}C_{cs} \tag{3.20}$$

$$C_{pen} = \frac{\pi\ L_{res}}{4}\rho_{cs}t_{pen}C_{cs}$$

Where t_{pen} is the thickness of the penstock and is unknown since only one overall penstock diameter has been considered in this thesis. The thickness was estimated using the same literature [41] that examined carbon steel and provided a sample of inner diameters and pipe thickness. The dimensions were recalculated and the sample was defined as outer diameter and thickness instead. Applying a polynomial equation between the data set provided a trend function to be used, see Figure 3.16.

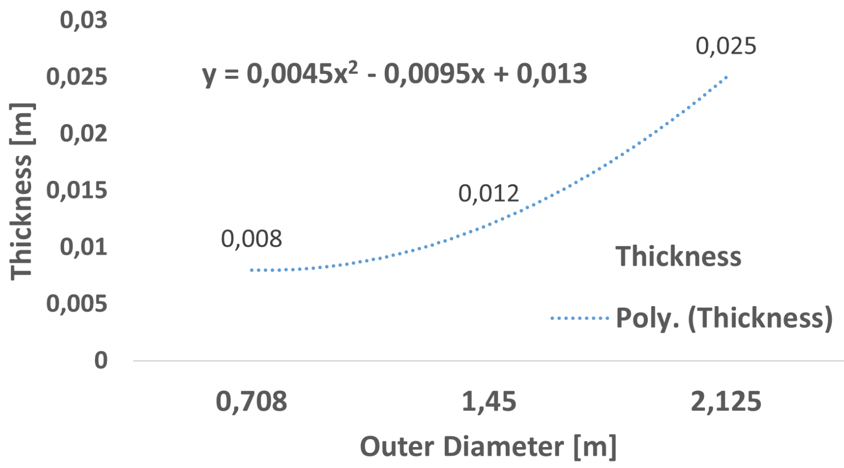

Figure 3.16: Polynomial function estimated for thickness as it relates to the outer diameter.

Utilizing Figure 3.16 the thickness values of the various pipe diameters were determined. The density of carbon steel was set to 7840 kg/m^3 in accordance with [43]. The cost of the pipes was then determined in Table 3.22.

Table 3.22: Cost of pipe for the pumping mode configuration for each combination between Pipe Diameter and corresponding variables in 3.19

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Pumping Pipe Cost (C_{pen}) [MEUR]**						
1.75	5.2183	5.2183	5.2183	5.2183	5.2183	5.2183	5.2183
2	6.8691	6.8691	6.8691	6.8691	6.8691	6.8691	6.8691
2.25	8.8319	8.8319	8.8319	8.8319	8.8319	8.8319	8.8319
2.5	11.1354	11.1354	11.1354	11.1354	11.1354	11.1354	11.1354
2.75	13.8080	13.8080	13.8080	13.8080	13.8080	13.8080	13.8080
3	16.8780	16.8780	16.8780	16.8780	16.8780	16.8780	16.8780

The total cost of the energy loss and the pipe cost was then calculated which can be seen in Table 3.23

Table 3.23: The total cost of the energy loss and the mass/magnitude of the carbon pipes calculated from Tables 3.21 and 3.22

t_s **[h]**	12	11	10	9	8	7	6
d [m]	**Total cost** (C_{tot}) **[MEUR]**						
1.75	22.60	25.77	30.09	35.80	43.82	55.37	73.35
2	16.06	17.83	20.03	23.08	27.32	33.48	42.89
2.25	14.14	15.10	16.40	18.12	20.57	24.06	29.53
2.5	14.38	14.97	15.76	16.84	18.28	20.42	23.75
2.75	15.91	16.28	16.78	17.45	18.42	19.81	21.93
3	18.29	18.54	18.88	19.34	19.97	20.87	22.29

The following graphical figures could then be implemented for a visual analysis regarding the cost of various cost elements in relation to the selection of the optimal pipe. See figures 3.17, 3.18, 3.19, and 3.20.

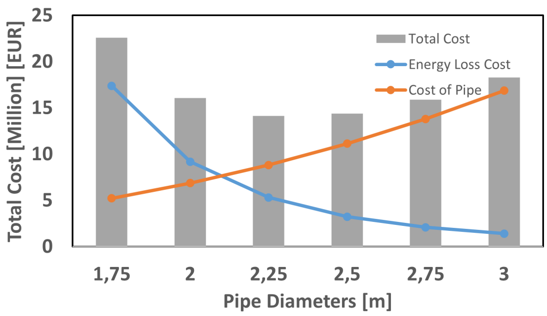

Figure 3.17: Technoeconomical analysis concerning Pipe selection $t_s = 12$

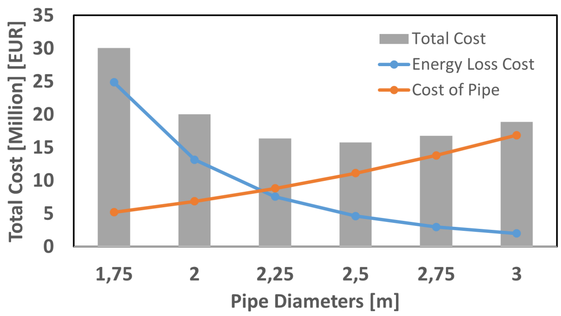

Figure 3.18: Technoeconomical analysis concerning Pipe selection $t_s = 10$

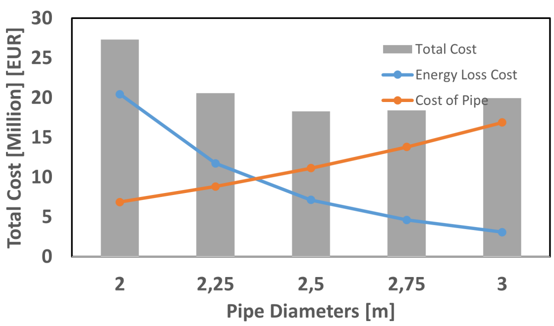

Figure 3.19: Technoeconomical analysis concerning Pipe selection $t_s = 8$

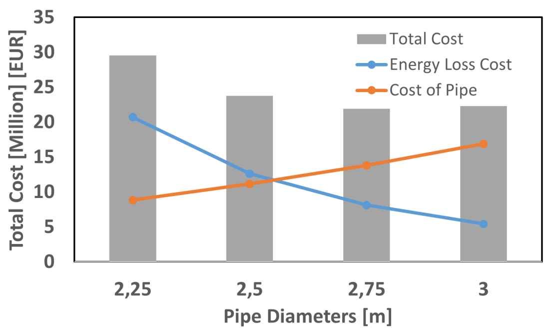

Figure 3.20: Technoeconomical analysis concerning Pipe selection $t_s = 6$

Figure 3.21: Overall Comparison between the various cost elements depending on the pipe diameter

Analysing the various charts in Figure 3.21 it can be seen that the cross-section between C_{pen} and E_{loss} are located between $2 - 2.25$ *m* for Figures 3.17 and 3.18 but for Figures 3.19 and 3.20, located between $2.25 - 2.5$. Based on this analysis, the range of potential pipe diameters decreased to three options i.e. $d_{pen} = (2,\ 2.25\ or\ 2.5)$.

Upon further investigation of the energy and pipe cost calculations, the cost elements were categorized into two distinct groups. The energy cost is variable and depends on the capacity factor of the *PSH* system for the given year. In contrast, the pipe cost can be considered fixed, as it is determined by the pipe's dimensions. Given that energy loss is influenced by the capacity factor, which can fluctuate due to the usage of renewable energy sources *(RES)* as discussed in Section 1.1, it is advantageous to minimize energy costs without significantly increasing pipe costs. A similar conclusion is drawn in an article from Investopedia, which states that higher fixed costs relative to variable costs can lead to greater margins as revenue increases without a corresponding rise in costs [44].

When analyzing the cost elements, especially the total cost, the set storage time of 12 hours entailed the lowest total cost. Applying the logic regarding the fixed and variable costs, the optimal pipe diameter was determined at 2,25 m.

3.6 PSH Design Output Parameters Setup

After the iterative process in Section 3.5 was conducted the finalized output parameters regarding the *PSH* system design were determined. The finalized output parameters are presented in Tables 3.24, 3.25, and 3.26.

Table 3.24: *PSH* system Design parameters concluded from Section 3.5 *Site Hydro* .

PSH design parameters	
Max Velocity [m/s]	5.00
Calculated Velocity [m/s]	2.36
Pumping Flow [m^3/s]	9.01
Generation Flow [m^3/s]	6,89
Pipe Diameter [m]	2.25
Water Temperature [°C]	20
Density [kg/m^3]	997
Dynamic Viscosity [Pa s]	0.0010005
Reynolds Number [-]	5307346
Friction Factor [-]	0.01006
Pipe Material	Carbon Steel JIS SS400
Roughness Coefficient [m]	0.00005

Table 3.25: *PSH* system pumping mode parameters concluded from section 3.5 *Site Hydro* .

PSH Pumping Mode	
Storage Time [h]	12
Energy Stored [MWh]	142.7
Pumping Efficiency [-]	0.85
Power [MW]	13.99

Table 3.26: *PSH* system generation mode parameters concluded from Section 3.5 *Site Hydro* .

PSH Generation Mode	
Storage Time [h]	12
Energy Stored [MWh]	142.69
Turbine and Generator Efficiency [-]	0.90
Power [MW]	10.70

3.7 PSH Operation Strategy & Algorithm Setup

As previously stated in Section 1.2, one of the objectives was to conduct a simulation representing the yearly operation of the *PSHHS* and calculate its potential revenue streams from the *DA* trading, and wind power production. The operation strategy algorithm was set after the *PSH* design was completed as can be seen in 3.1. The operation was then divided into two separate algorithms, one for the operation of the produced wind power regarding whether storage would be necessary. The other algorithm was set for the spot market trading, especially for *DA* market where it was to determine the optimal trading conditions.

3.7.1 Operation of Wind Power Algorithm

The first algorithm established for the operation of the *PSH* was to regulate the generated energy from the wind power park located in the undisclosed location *WPP*. The main objective is to take advantage of hours where the electricity spot price is volatile i.e. buy and store energy when prices are low and sell when prices are high. Theoretically, it is a simple implementation, but since the *PSH* only has finite storage volume, the buy & sell strategy needs to be as optimized and refined as possible. Before constructing the algorithm, certain conditions were also set to emulate a real scenario operation of the *PSH*, as shown below.

- The *PSH* has a finite Storage Capacity i.e. (144 MWh & 12 Hour storage time). It will not be possible to store more than roughly 144 MWh.
- The coupled *WPS* has a certain *PPA* and as mentioned earlier, it is based on the monthly *BL* production. Therefore, a certain amount of energy from the *WPS* needs to be sold to fulfill the *PPA*. The excess energy is then either stored in the *PSHHS* or sold directly to the grid.
- If the produced energy for an hour from the *WPS* is less than the estimated *BL* that is required to be sold to the grid per the *PPA*, the *PSH* needs to compensate with energy from its storage to fulfill the *PPA*.
- If the energy storage of the *PSH* is insufficient and the *PPA* is not fulfilled the operator/company or in this case *PSH* is required to buy the remaining energy from the *DA* market.

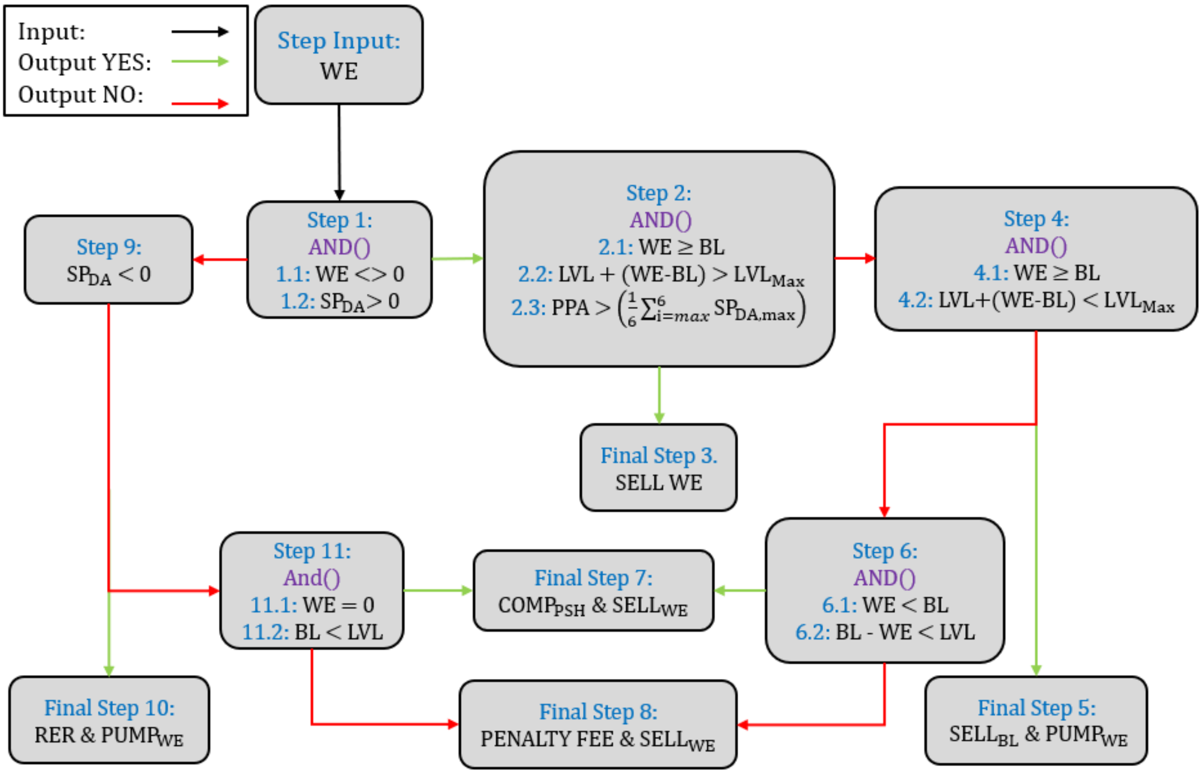

Figure 3.22: Algorithm for Operation Conditions of Produced Wind Power

Figure 3.22 above, illustrates the constructed algorithm regarding the regulation of the produced energy from the wind power station. Steps with "AND" require all criteria to be "TRUE" to yield output "YES", anything else yields "NO". A more in-depth description of the algorithm is presented below which is applied for each hour of a day.

- **Step Input:** The first step in the algorithm is to analyze the input value i.e. the produced energy from the *WPS* and determine its hourly volume in *MWh*.
- **Step 1:** In this step, the wind energy *(WE)* and *DA* spot market price is analyzed. Depending on the output the next step is either "Step 9" or "Step 2". The criteria for "Step 1" can be seen below.
  - **Criterion 1.1:** The produced *WE* from the *WPS* must not be equal to 0 *MWh*.
  - **Criterion 1.2:** The price on the *DA* spot market can not be negative.
- **Step 2:** The objective of this step is to evaluate the produced *WE* and its storage capabilities pr if it should be sold directly to the grid from the *WPS*, An in-depth description of each specific criterion can be seen below.
  - **Criterion 2.1:** The produced wind energy for a specific hour is compared to the base load that is required to be delivered according to the *PPA*. It must be greater or equal to the base load to yield "TRUE".
  - **Criterion 2.2:** The current storage level in addition with the difference between the wind energy and base load must be greater than the maximum storage capacity of the *PSH* system.
  - **Criterion 2.3:** The *PPA* must be greater than the average of the six highest spot price hours for the corresponding day.

- **Final Step 3:** If all criteria are met in ”Step 2” then, all produced *WE* is sold directly to the grid from the *WPS* per the *PPA*.
- **Step 4:** If at least one criterion is not met in ”Step 2”, then criteria 2.1 and 2.2 are tried again to evaluate if the *BL* can be sold directly to the grid and if the excess *WE* can be stored in the *PSH*.
  - **Criterion 4.1:** The same logic as in ”Criterion 2.1” is checked.
  - **Criterion 4.2:** Approximately the same logic as in ”Criterion 2.2” but are now checking if the maximum storage capacity of the *PSH* is greater.
- **Final Step 5:** If all criteria are met in ”Step 4” then, only *BL* is sold directly to the grid, and the excess *WE* is pumped and stored in the *PSH*.
- **Step 6:** If at least one criterion is not met in ”Step 4”, then criteria 4.1 is tried again but now, the *BL* must be greater than the *WE*. The objective of this step is to determine the possibility and if the *PSH* needs to compensate energy to comply with the *PPA*.
  - **Criterion 6.1:** Approximately the same logic as in ”Criterion 4.1” but are now checking if the *BL* is greater than the produced *WE*.
  - **Criterion 6.2:** Analysing if the current storage capacity in the *PSH* can compensate energy to comply with the *PPA*.
- **Step 7:** If all criteria are met in ”Step 6” then, the *PSH* compensates by generating energy to compensate for the insufficient *WPS* production to comply with the *PPA*.
- **Final Step 8:** The final output after ”Step 6” is a required penalty fee as compensation for not delivering the required volume per the *PPA*. According to an economic advisor from BayWa r.e. Nordic AB, the missing energy would be bought on the *DA* market. This would also apply for a case if all of the *BL* would be required to be bought. The insufficient *WE* is sold for the price per the *PPA*.
- **Step 9:** If the output of ”Step 1” yields ”False”, then all of the criteria are required to be analyzed again. In this step, the current hourly spot price in the *DA* market must be less than zero i.e. ”Criterion 1.2” must be false in ”Step 1”.
- **Final Step 10:** If ”Step 9” is ”TRUE” then the value of the *BL* per the *PPA* would be received without selling the produced *WE* to the grid. All of the produced *WE* is then stored in the *PSH* system.
- **Step 11:** If ”Step 9” is ”FALSE” then, the storage capacity is to be analyzed and determine if compensation of energy is possible from the *PSH* to comply with the required *BL* per the set *PPA*. The following criteria are presented below.
  - **Criterion 11.1:** The produced *WE* is set to 0 *MWh* i.e. the *WPS* production is nonexistent for that specific hour.
  - **Criterion 11.2:** The current storage level must be greater than the *BL* that is required to be sold to the grid.

3.7.2 Operation of Day-Ahead spot market trading Algorithm

The second algorithm established for operating the *PSH* system was to identify possible trading hours on the *DA* spot market. As mentioned in section 3.7.1, the main objective is to capitalize on the volatile price on the *DA* spot market. Due to the potential storage of the produced *WE* which the first algorithm established, the storage volume for a specific hour is now, more finite than before. The criteria and optimization of the algorithm would therefore be crucial to finding the optimal operation and trading strategy of the *PSH* system. The algorithm in Section 3.7.1will be referred to as the "*WE* algorithm" and the one in this section, the "*DA* algorithm". Certain conditions were established before constructing the algorithm, as seen below.

- Since the algorithm for the *DA* spot market trading is compiled after the algorithm for the regulation of the *WE*, the established conditions in Section 3.7.1 remain valid.
- During the *PSH* system's pumping/generation mode, trading on the *DA* spot market is possible concerning the regulation of the *WE*, provided that the total pumping/generation is less than or equal to 14/11 *MWh* and the storage capacity permits it.
- To achieve maximum efficiency, the *PSH* system consistently operates at least 2 hours in pumping/generation mode.
- Pumping and generation mode can not be executed at the same hour.

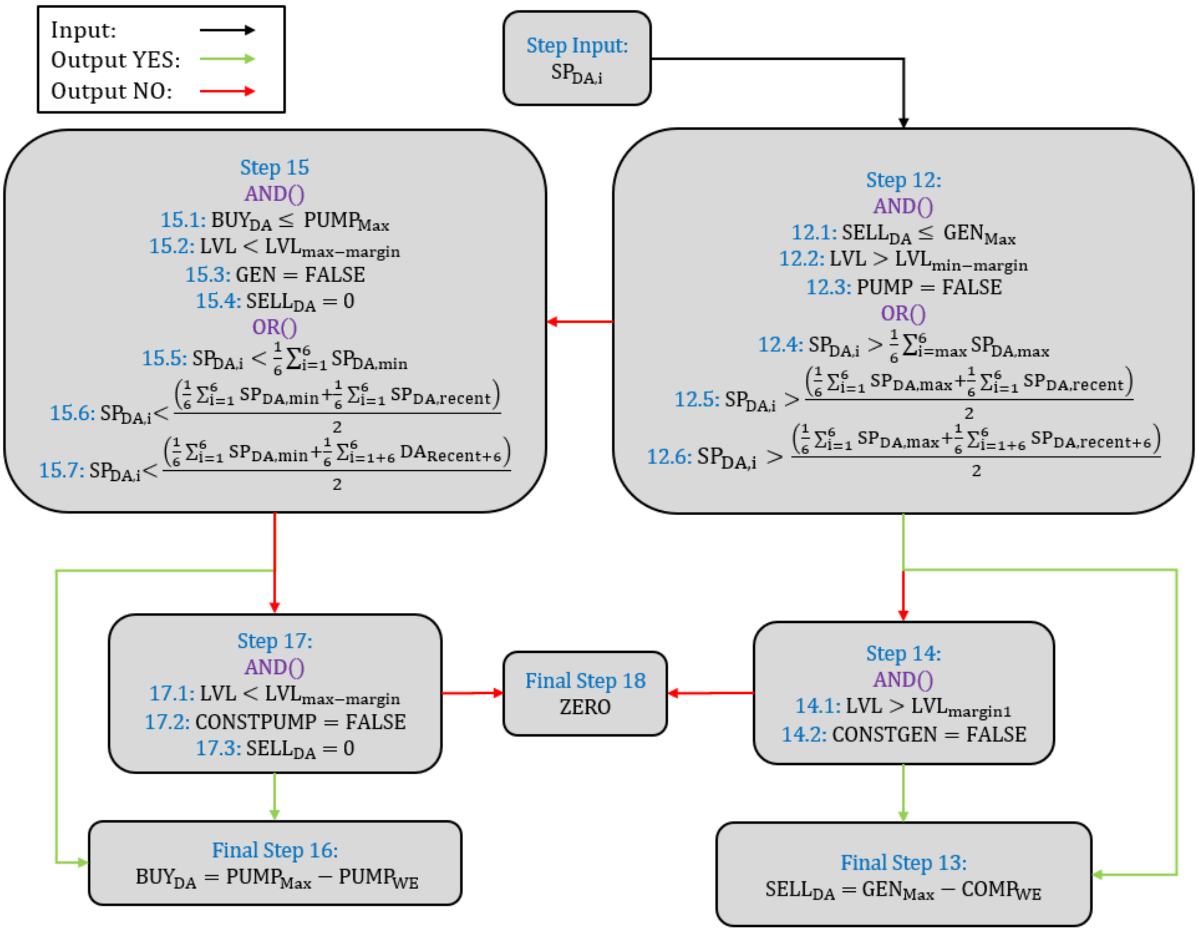

Figure 3.23: Algorithm for Operation Conditions of *DA* trading

- **Step Input:** The first step in the algorithm is to analyze the input value i.e. the hourly spot price on the *DA* market and determine if energy should be purchased and stored or generated and sold directly to the grid.

- **Step 12:** In this step, it is to be determined if the *PSH* system should pump or generate energy i.e. purchase or sell energy on the *DA* market. The storage capacity, operation mode, and the *DA* spot price are to be analyzed. Output "YES" is achieved if criteria 12.1-12.3 are "TRUE" and if at least one of criteria 12.4-12.6 is "TRUE". The following criteria are tested to determine the mode of the *PSH* system.

  - **Criterion 12.1:** The generation mode of the *PSH* is: $\leq$ 10 *MWh* i.e. can not generate more than 10 *MWh*.

  - **Criterion 12.2:** During generation mode, the current storage capacity must exceed the minimum allowed storage capacity, and was set at 12,5 *MWh*.

  - **Criterion 12.3:** The *PSH* system cannot operate pumping mode.

  - **Criterion 12.4:** The spot price ($\mathrm{SP_{DA,i}}$) for the given hour is compared to the mean value of the six highest spot prices on the corresponding day. See equation (3.21).

$$\mathrm{SP_{DA,i}} > \frac{1}{6}\sum_{i=max}^{6} \mathrm{SP_{DA,Max}} \tag{3.21}$$

  - **Criterion 12.5:** The spot price for the given hour is compared to a mean value of two other mean values of the spot price ($\overline{\mathrm{SP}}_{\mathrm{DA,i}}$ & $\overline{\mathrm{SP}}_{\mathrm{DA,Recent}}$), see equation (3.22).

$$\mathrm{SP_{DA,i}} > \frac{\overline{\mathrm{SP}}_{\mathrm{DA,max}} + \overline{\mathrm{SP}}_{\mathrm{DA,Recent}}}{2} \tag{3.22}$$

where

$$\overline{\mathrm{SP}}_{\mathrm{DA,Recent}} = \frac{1}{6}\sum_{i=1}^{6} \mathrm{SP_{DA,Recent}} \tag{3.23}$$

The first term ($\overline{\mathrm{SP}}_{\mathrm{DA,i}}$) in equation (3.22) is found in equation (3.21) the other term ($\overline{\mathrm{SP}}_{\mathrm{DA,Recent}}$) is calculated by the current and the next 5 oncoming spot prices, see equation (3.23).

  - **Criterion 12.6:** The logic is mostly the same as in criterion 12.5 the main difference in equation (3.24) is the second term ($\overline{\mathrm{SP}}_{\mathrm{DA,Recent+6}}$) as seen in equation (3.24).

$$\mathrm{SP_{DA,i}} > \frac{\overline{\mathrm{SP}}_{\mathrm{DA,Max}} + \overline{\mathrm{SP}}_{\mathrm{DA,Recent+6}}}{2} \tag{3.24}$$

where

$$\overline{\mathrm{SP}}_{\mathrm{DA,Recent+6}} = \frac{1}{6}\sum_{i=1+6}^{6} \mathrm{SP_{DA,Recent+6}} \tag{3.25}$$

In equation (3.25) the new interval for ($\overline{\mathrm{SP}}_{\mathrm{DA,Recent}}$) is offset with 6 hours, then the next oncoming hours would be used in the calculation.

- **Final Step 13:** If the necessary criteria are met, energy is then generated from the *PSH* system and sold directly to the grid in accordance to the current *DA* spot price ($SP_{DA,i}$). As mentioned in Section 3.7.1, if the *PSH* system compensated energy to comply with the set *PPA* then, the potential generation for one hour is reduced since the maximum output is 10 *MWh*.
- **Step 14:** Checks whether the *PSH* system should remain in generation mode if it has been generating for one hour. This step will override the optimal trading criteria to achieve optimal generation for at least two hours, as specified in Section 3.7.2.
  - **Criterion 14.1:** Criterion 12.2 is verified again.
  - **Criterion 14.2:** Verifies that the *PSH* system has not been generating for one hour.
- **Step 15:** Output ”YES” is achieved if criteria 15.1-12.4 are ”TRUE” and if at least one of criteria 15.5-15.7 is ”TRUE”. The following criteria are tested to determine the mode of the *PSH* system.
  - **Criterion 15.1:**The pumping mode of the *PSH* is: ≤ 14 *MWh* i.e. can not pump more than 14*MWh*.
  - **Criterion 15.2:** During pumping mode, the current storage capacity must be less than the maximum allowed storage capacity, and was set at 12 *MWh*.
  - **Criterion 15.3:** The *PSH* system cannot operate in generation mode.
  - **Criterion 15.4:** The selling criteria in step 12 must be ”FALSE”.
  - **Criterion 15.5:** The spot price ($SP_{DA,i}$) for the given hour is compared to the mean value of the six lowest spot prices on the corresponding day. See equation (3.26).

$$SP_{DA,i} < \frac{1}{6}\sum_{i=min}^{6} SP_{DA,min} \tag{3.26}$$

  - **Criterion 12.6:** The spot price for the given hour is compared to a mean value of two other mean values of the spot price ($\overline{SP}_{DA,min}$ & $\overline{SP}_{DA,Recent}$), see equation (3.27).

$$SP_{DA,i} < \frac{\overline{SP}_{DA,min} + \overline{SP}_{DA,Recent}}{2} \tag{3.27}$$

where

$$\overline{SP}_{DA,Recent} = \frac{1}{6}\sum_{i=1}^{6} SP_{DA,Recent} \tag{3.28}$$

The first term ($\overline{SP}_{DA,min}$) in equation (3.27) is found in equation (3.21) the other term ($\overline{SP}_{DA,Recent}$) is calculated by the current and the next 5 oncoming spot prices, see equation (3.28).

- **Criterion 12.7:** The logic is mostly the same as in criterion 15.6 the main difference in equation (3.29) is the second term ($\overline{\text{SP}}_{\text{DA,Recent+6}}$) as seen in equation (3.29).

$$\text{SP}_{\text{DA,i}} < \frac{\overline{\text{SP}}_{\text{DA,Min}} + \overline{\text{SP}}_{\text{DA,Recent+6}}}{2} \tag{3.29}$$

where

$$\overline{\text{SP}}_{\text{DA,Recent+6}} = \frac{1}{6}\sum_{i=1+6}^{6} \text{SP}_{\text{DA,Recent+6}} \tag{3.30}$$

In equation (3.30) the new interval for ($\overline{\text{SP}}_{\text{DA,Recent}}$) is offset with 6 hours, then the next oncoming hours would be used in the calculation.

- **Final Step 16:** If step 14yields the output "YES", the available excess energy is bought to the specific hourly spot price. The *PSH* system pumps the available excess energy to the upper reservoir.
- **Step 17:** Checks whether the *PSH* system should remain in pumping mode if it has been pumping for one hour. This step will override the optimal trading criteria to achieve optimal pumping for at least two hours, as specified in Section 3.7.2.
  - **Criterion 17.1:** See criterion 15.2.
  - **Criterion 17.2:** Checks that the *PSH* system has not been pumping for one hour.
  - **Criterion 17.3:** See criterion 15.4.
- **Final Step 18:** If steps 14 and 17 yield "NO", nothing happens, and the *PSH* system is idle from this point until the next hour.

3.8 PSH Operation Outputs

The output design parameters concluded in sub-Section 3.6 were implemented in the constructed logic and operation algorithm set in Section 3.7, which provided various simulation data outputs, see the following list.

- The average buy price in the *DA* spot market $[EUR/MWh]$
- The average sell price in the *DA* spot market $[EUR/MWh]$
- The amount of buying hours $[h]$
- The amount of selling hours $[h]$
- The total Generation from the *PSH* and *WPS* $[MWh]$
  - Generation from *PSH*
  - Generation from *WPS*
- Annual Revenue Streams $[EUR]$

The constructed simulation model in Excel provided various results depending on the external input parameters such as different yearly data samples for the *DA* spot market and produced electricity from *WPS*for various years. These two, data categories were set as two of the variable factors that contributed to the fluctuating generation output for the different operation outputs i.e. the generation output from *WPS* and the *PSH* system. This also indicated that the algorithm established in Section 3.7 performed as intended since the implemented criteria analyzed the *DA* spot price and the produced electricity from *WPS*.

The other contributing factor to the operation output was the set Base load *BL* per the established power purchase agreement for the *WPS*. Depending on the expected base load to be delivered for a hour for a specific month the generation and the revenue stream again fluctuated, which was expected per the implemented criteria in the operation algorithm. The following operation outputs for the pumped hydro storage hybrid setup system *(PSHHS)* are presented below where Table 3.27 displays various generations of electricity for different years with the corresponding annual revenue streams in Table 3.28.

Table 3.27: Technical generation outputs for the Pumped Hydro Storage Hybrid system

Technical parameter Outputs Hybrid Setup						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
Delta Price	€	4,74	41,26	21,38	15,17	15,25
CF PSH	-	0,25	0,19	0,25	0,24	0,25
Generation PSH to Grid	MWh	13120	4396	8640	8517	8696
Generation PSH to Wind	MWh	10322	13265	14423	14161	14384
Total Generation PSH	**MWh**	**23443**	**17661**	**23063**	**22678**	**23079**
Generation Wind to Grid	MWh	52013	39770	34320	37534	37525
Generation Wind to PSH	MWh	167	1931	6564	3832	3840
Total Generation Wind	**MWh**	**52180**	**41701**	**40884**	**41366**	**41364**
Generation Wind Penalty	MWh	-8165	-7742	-9198	-9434	-9226
Total Generation Wind+PSH	**MWh**	**67458**	**51621**	**54749**	**54610**	**55218**

Table 3.28: Corresponding Revenue Stream outputs to the generation for the *PSHHS* system

Annual Revenue Streams Output Hybrid Setup						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
PSH Buy from Grid	k€	-273	-504	-762	-779	-784
Generation Revenue PSH to Grid	k€	190	311	530	434	445
Generation Revenue PSH to Wind	k€	413	663	577	566	575
PSH Annual Delta	**k€**	**330**	**470**	**345**	**221**	**237**
Generation Revenue Wind to Grid	k€	2081	1989	1373	1501	1501
Generation Revenue Wind to PSH	k€	7	77	263	153	154
Generation Revenue Wind Penalty	k€	-160	-533	-504	-412	-400
Wind Annual Delta	**k€**	**1928**	**1533**	**1131**	**1243**	**1254**
Total Annual Revenue	**k€**	**2257**	**2003**	**1477**	**1464**	**1491**

In Table 3.27 multiple generation outputs can be seen and the following list explains the results.

- **Delta Price:** This is the difference between the buying and selling price from the trading on the *DA* spot market.
- **CF PSH:** Defined as the capacity factor for the *PSH* generation alone without considering the generation from the *WPS*.
- **Generation *PSH* to Grid:** Defined as the total generation from the *PSH* to the grid by the *DA* spot market trading.
- **Generation *PSH* to Wind:** Defined as the total generation from the *PSH* to the *WPS* as a compensation for not being able to deliver to the required *BL* per the *PPA*.
- **Generation Wind to Grid:** Defined as the total generation from the *WPS* to the grid by sending it directly from the cite to the main grid.
- **Generation Wind to *PSH*:** Defined as the total generation from the *WPS* to the *PSH* system per the set algorithm in sub-Section 3.7.1. This is done by the connected transmission line.
- **Generation Wind Penalty:** Defined as the total generation penalty that is bought on the *DA* spot market to comply with *PPA* since the *WPS* has not produced enough electricity to meet the required quota of the *BL*.

The generation outputs in Table 3.27 were divided into smaller generation categories to identify the origin of the generation since this was further investigated in Chapter 4 regarding the calculation of LCOS and IRR. This was also implemented for the annual revenue streams which can be seen in Table 3.28. The results were also compared to a case where the *PSH* system and *WPS* were operating as separate entities i.e. not connected. The same operation output was determined by using the same inputs regarding the design and operation algorithm for the separate *PSH* system. The outputs for the separate *WPS* were calculated per the same *PPA* and its required *BL*. The following operation outputs for the separate case are presented in Tables 3.29 and 3.30 below.

Table 3.29: Technical generation outputs for the Pumped Hydro Storage and *WPS* as a separate entity

Technical parameter Outputs Seperate Setup						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
Delta Price	€	19,24	25,17	25,55	24,35	24,58
CF PSH	-	0,31	0,31	0,31	0,31	0,31
Total Generation PSH	**MWh**	**28552**	**28509**	**29087**	**28199**	**28071**
Total Generation Wind	**MWh**	**52302**	**42042**	**42042**	**42042**	**42042**
Penalty Generation	MWh	-14953	-19667	-19667	-19667	-19667
Total Generation Wind+PSH	**MWh**	**65901**	**50884**	**51462**	**50574**	**50446**

Table 3.30: Corresponding revenue stream outputs to the generation for a *WPS* as a separate entity

Revenue Streams Output Seperate Setup						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
PSH Annual Buy	k€	-837	-1034	-1409	-1384	-1391
PSH Annual Sell	k€	1189	1508	1821	1745	1753
PSH Annual Delta	**k€**	**352**	**474**	**411**	**361**	**362**
Wind Annual Sell	k€	2193	2227	1782	1782	1782
Wind Annual Penalty Fee	k€	-484	-1072	-1072	-1072	-1072
Wind Annual Delta	**k€**	**1710**	**1155**	**710**	**710**	**710**
Total Annual Revenue	**k€**	**2062**	**1629**	**1121**	**1071**	**1072**

To analyze the results, a simple comparison between the hybrid and separate setups was conducted. The generation differences are shown in Table 3.31, and the differences in revenue streams are shown in Table 3.32.

Table 3.31: Generation outputs when comparing the Hybrid setup vs the separate setups for Wind and *PSH*

Generation Comparison Hybrid vs Separate Outputs						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
Net Generation PSH	MWh	-5110	-10848	-6024	-5521	-4991
Net Generation Wind	MWh	-122	-341	-1158	-676	-678
Net Generation Penalty	MWh	6787	11925	10469	10233	10441
Total Generation Comparison	**MWh**	**1556**	**737**	**3287**	**4036**	**4772**

Table 3.32: Revenue Stream outputs when comparing the Hybrid setup vs the separate setups for Wind and *PSH*

Revenue Stream Comparison Hybrid vs Separate Outputs						
Simulation Years	**-**	**2020**	**2023**	**20XX**	**20XY**	**20YY**
PSH Comparison	k€	-23	-4	-66	-140	-126
Wind Comparsion	k€	218	378	422	533	545
Tot Comparison	**k€**	**195**	**374**	**356**	**394**	**419**
Penalty Comparison	k€	324	539	568	660	672

A visualization of the operation output regarding the fluctuation of the storage capacity (when the *PSH* system operates in pumping or generation mode) in comparison to the *DA* spot price and the buying and selling patterns produced from the operation algorithm can be seen in Figure 3.24 below.

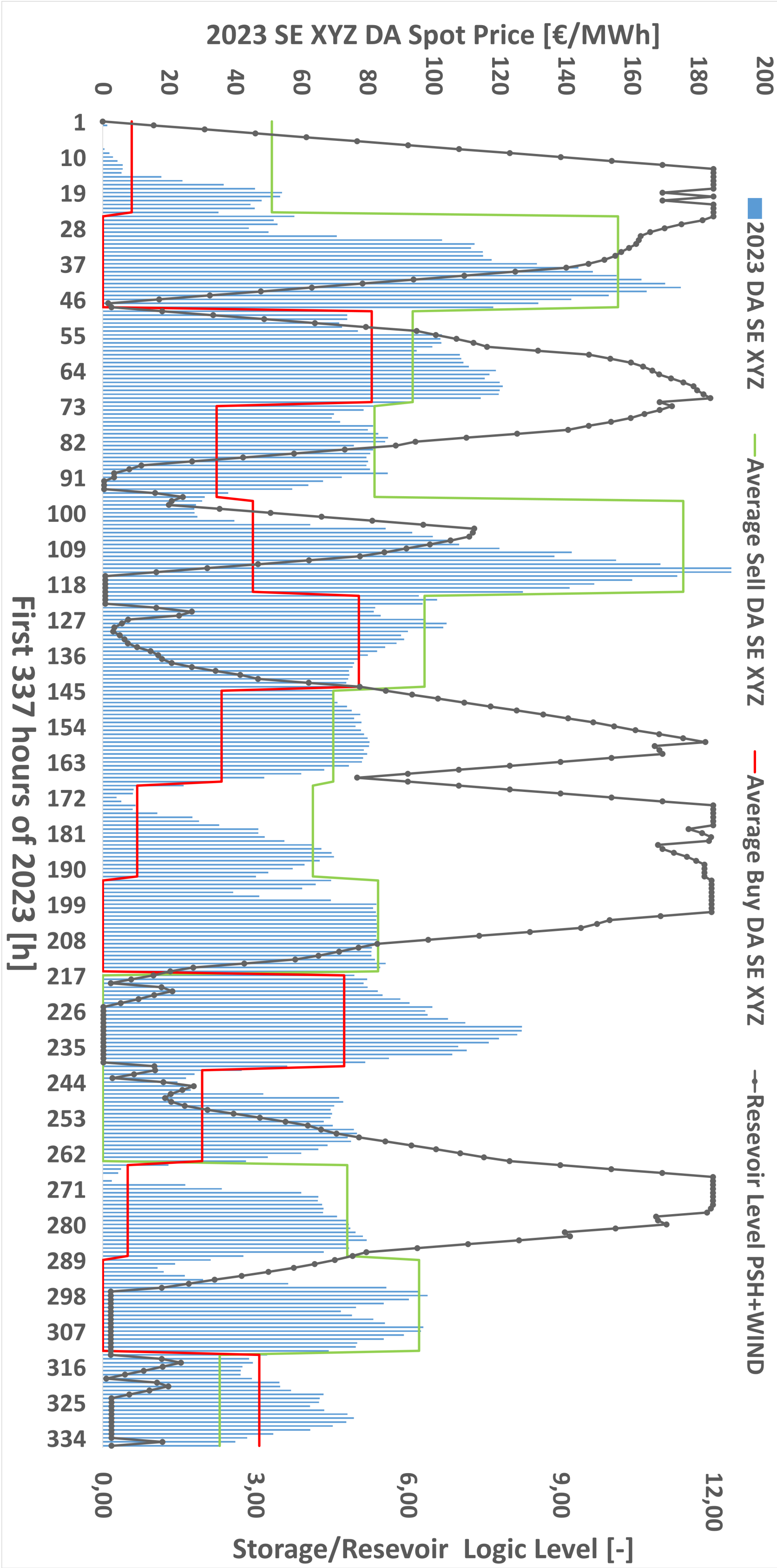

Figure 3.24: Storage Level of the *PSH* in a Hybrid setup with the Wind Power (*PSHHS*)

4 PSHHS Economic Setup & Analysis

In this chapter the economic aspect of the PSH hybrid setup is to be investigated including investment costs such as CAPEX and OPEX and how they can be reduced to optimize the annual costs. A business model will also be presented for the PSHHS system where KPIs such as Levelized Cost of Storage (LCoS) and Internal rate of return (IRR) will be analyzed with a sensitivity analysis. The sensitivity analysis will contain various outcomes regarding the potential change of input factors affecting the net results of the KPIs.

4.1 PSH CAPEX Estimation

In sub-Section 1.4 various reports were introduced and set as the base reference when estimating the *CAPEX* cost. As mentioned in Section 2.2 the *PSH* system can have multiple designs that affect the overall cost of the project. Utilizing the estimated capital cost categories from Tables 2.3 and 2.4 established in Section 4.1, the following *CAPEX* estimation in Table 4.1.

Table 4.1: Estimated *CAPEX* with the Three-point method for the *PSH* system

Base Reference	Black & Veatch (2012)		Small PSH Modeled (2022 USD)		ENTURA 2019		Project Hybrid 2024	
Power (MW)	500		116		377		14	
	2024 (EUR)	Percentage	2024 (EUR)	Percentage	2024 (EUR)	Percentage	2024 (EUR)	Percentage
Reservoir (€/kW)	754 (b)	34%	233 (m)	8%	349 (a)	21%	169,6	8%
Waterway (€/kW)	118 (a)	5%	321 (m)	12%	204 (b)	12%	179,3	8%
Powerhouse Civil (€/kW)	70 (a)	3%	0 (m)	0%	97 (b)	6%	27,8	1%
Powerhouse structure, BOP electromechanical (€/kW)	748 (m)	34%	848 (b)	30%	390 (a)	24%	705,0	32%
Total ($/kW)	**1692**	**77%**	**1402**	**50%**	**1040**	**63%**	**1081,8**	**48%**
EPC (€/kW)	134 (a)	6%	1200 (b)	23%	546 (m)	33%	586,3	26%
Owner's cost (€/kW)	365 (m)	17%	810 (b)	20%	58 (a)	4%	388,0	17%
Grid Fees (€/kW)				6%			175,0	8%
Total with Indirect costs (€/kW)	**2190**	**100%**	**2782**	**100%**	**1645**	**100%**	**2231,1**	**100%**
Contingency as percentage of total project cost	15%	15%	33%	33%	20%	20%	19%	19%

The proposed literature was combined with an old report that collaborated with BayWa r.e. from LTH, where in this report, *CAPEX* was estimated using the three-point estimation method [32]. The three-point estimation is calculated using the formula in Equation 4.1. The following estimations and assumptions were made.

$$E = (a + 4\,m + b)/6 \tag{4.1}$$

Where (a) is defined as the best case, (m) as the most likely case, and (b) as the worst case.

- The reservoir cost was estimated by evaluating the cost elements from the literature in Table 4.1. For this instance, [16] was assumed as the worst-case estimate (b) since it had the highest reservoir cost since the reservoirs were artificially constructed. The small *PSH* model [15], was estimated as the most likely case (m) since the cost was based on a small *PSH* system. The cost from the Entura report [13], was assumed as (a).

- The same assumptions were made for the Waterway since both the reports from Entura and Black & Veatch associate the cost for the waterway with tunnel costs. In this study, a surface penstock is assumed which also is mentioned in the ORNEL report for small modeled *PSH*.

- The same estimation parameters were chosen for the powerhouse civil cost as for the reservoir and waterway costs. In the report from Black & Veatch, the powerhouse was constructed underground and was, therefore, less likely to be a cost element for this study. In the report from Entura, the civil cost was assumed to be volatile, with an estimate of 30% over/under the real value. Since the small *PSH* model from the ORNEL report used a surface penstock, it was assumed to be the most likely scenario.

- The cost of the powerhouse structure from the Black & Veatch report was considered the most accurate estimate (m), as it directly aligned with the categorization used in this study. The cost from the Entura report was considered too small when compared to other external literature in Table 2.2 and was estimated as (a).

- The *EPC* cost from the ORNEL report was set as the worst case (b) since the cost was significantly higher when compared to the base references in Table 2.2. Conversely, the *EPC* cost from the (Black & Veatch) report was assumed to be low and thus categorized as the best-case scenario (a). The most likely estimation (m) for the *EPC* cost was taken from the ENTURA report.

- The owner's cost from the (Black & Veatch) report was estimated to be roughly 20% of the total and *EPC* costs and was chosen as the most likely outcome, given that (Black & Veatch) has been used as a base reference in other literature such as [12], [13], etc. The cost from the NREL report was considered high compared to the literature referenced in Table 2.2 and was estimated to (b). The opposite was assumed from the Entura report and was assumed to (a).

4.2 PSH OPEX Estimation

As mentioned in Section 2.2.3 the fixed and O&M costs were estimated in Tables 2.5 and 2.6 respectively using the ESGC report [12].

4.3 WPS Cost Estimation

To conduct the business model for the *PSHHS*, cost estimations for the *WPS* was to be estimated. Such cost elements were divided into both *CAPEX* and *OPEX* as for the *PSH* system. A financial report from [45] was used as a base reference when estimating the various cost elements. Table 4.2 displays the estimated cost elements for the *CAPEX* and *OPEX* where only the fixed O&M cost is estimated since the *WPS* does not contain variable O&M cost element per [45].

Table 4.2: Estimated *CAPEX* & Fixed *O&M* cost for the *WPS*.

Cost Element	**Unit**	**Value**
CAPEX	€/kW	1228
Fixed O&M	€/kW	33.84

4.4 Business Case

The outputs from Section 3.8 present various simulated results regarding annual revenue streams and generation from the *PSH* and *WPS* hybrid setup *(PSHHS)*. To evaluate its profitability a business case was constructed where the internal rate of return *(IRR)* and leveleized cost of storage *(LCoS)* were investigated to evaluate the feasibility of *Project Hybrid*. The setup of the business case included the following input parameters and used the simulation year 2023 as the base reference, see Table 4.3.

Table 4.3: Input parameter for the business case for *Project Hybrid*.

Input Parameter	**Unit**	**Value**
Rated Generation Power *PSH*	MW	10.7
Capacity Factor *PSH*	-	0.19
Total Fixed O&M (*WPS* & *PSH*)	€/kW	76.89
Variable O&M *PSH*	€/MWh	0.4815
Total CAPEX (*WPS* & *PSH*)	€/kW	3459,1
Total Revenue Stream (*WPS* & *PSH*)	€	1348000
Buying Fee *PSH*	€	504000
Combined Tax rate	%	21%
Depreciation	%	20%
Economic Life	Years	30

The assessed *KPIs* for the business case were the internal rate of return *(IRR)* and the levelized cost of storage *LCoS*. The results for the simulation year 2023 yielded the following results in Table 4.4 where the results of cumulative cash flow are presented in Figure 4.1.

Table 4.4: Output parameter for the business case for *Project Hybrid*.

Input Parameter	Unit	Value
IRR	%	-0.44%
LCoS	€/MWh	105
Payback time	years	NULL

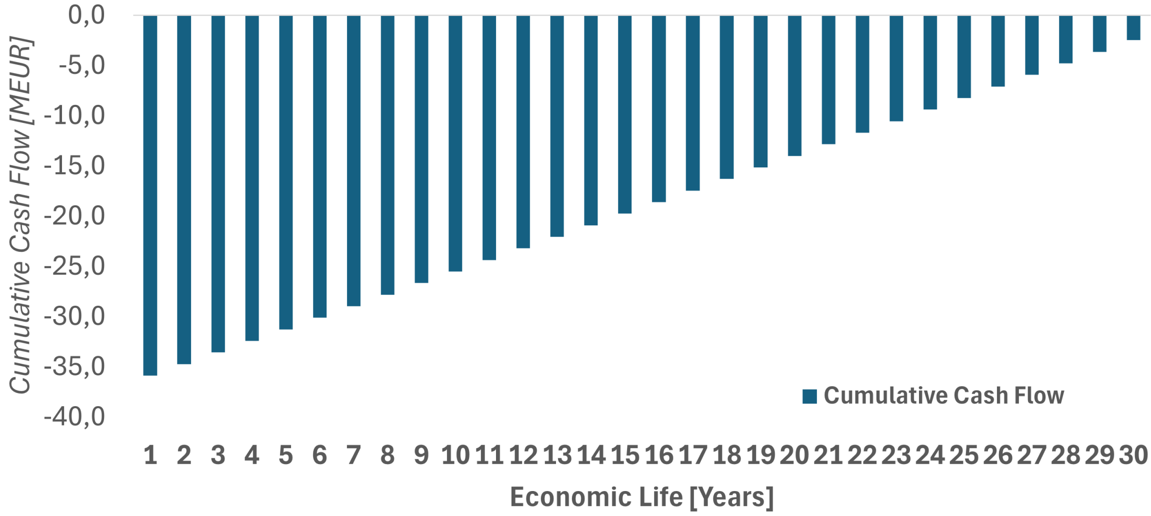

Figure 4.1: Cumulative cash flow from the business case for the simulation year 2023.

The results above indicate a non-profitable business case for *PSHHS* setup where the *IRR* was calculated to -0.44% with a negative cumulative cash flow for the whole economic life. The *LCoS* was calculated to be 105 €/MWh.

4.5 Sensitivity Analysis of PSH Input Parameters

Since the business case from the previous section yielded a non-profitable case a sensitivity analysis was conducted to investigate the various *PSH* input parameters used when calculating the *IRR* and *LCoS*. Furthermore, it was also necessary to identify what potential changes could yield a positive profitable business case.

4.5.1 Financial Impact of CAPEX

The first investigated parameter was the *CAPEX* element since this was one of the driving forces of the cost. Four different intervals were chosen as an overall percentage change and the following results are presented in Tables 4.5 and 4.6.

Table 4.5: Input parameters used for the sensitivity analysis with change in *CAPEX*

Input Change in Capex Elements					
Categories	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
Revenue k€	1051	1051	1051	1051	1051
CAPEX (EUR/MWh)	1115,5	1896,35	2231	2565,65	3346,5
Varible O&M	0,4815	0,4815	0,4815	0,4815	0,4815
Fixed O&M	43,05	43,05	43,05	43,05	43,05

Table 4.6: Output in *KPIs* of change in *CAPEX*

Output Change in Capex Elements					
KPI	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
IRR (%)	1,6%	0,1%	-0,44%	-1,0%	-2,0%
LCOS	90,1	100,6	105	109,5	120

From the results above, it can be seen that the *IRR* does not indicate a profitable case for any scenario when its value is changed. On the other hand, the *LCoS* responded more favorably to the changes, with the lowest value calculated at 90,1€/MWh following a 50% reduction in *CAPEX*.

4.5.2 Financial Impact of Fixed O&M

The next investigated parameters were the fixed *O&M* costs and as seen in the OPEX estimation the labor cost of the fixed *O&M* cost increased when the power capacity of the *PSH* decreased. Investigating the change in this cost was therefore conducted to analyze the change in the *KPIs*.

Table 4.7: Input parameters used for the sensitivity analysis with change in fixed *O&M*

Input Change in Fixed O&M Elements					
Categories	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
Revenue k€	1051	1051	1051	1051	1051
CAPEX	2231	2231	2231	2231	2231
Varible O&M	0,4815	0,4815	0,4815	0,4815	0,4815
Fixed O&M	21,53	36,59	43,05	49,51	64,58

Table 4.8: Output in *KPIs* of change in fixed *O&M*

Output Change in Fixed O&M Elements					
KPI	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
IRR (%)	0,61%	-0,07%	-0,44%	-0,83%	-1,79%
LCOS	101,2	103,9	105	106,2	109

The fixed *O&M* seemed to follow the same pattern with *KPIs* as the *CAPEX* change did, the major difference being the change of *LCoS* barely changing for the different cases.

4.5.3 Financial Impact of Variable O&M

Since the Variable *O&M* cost is bound by the generation of the *PSH* system it was assumed that no noticeable change would be made and this was also the case by analyzing the Tables below where the change of the *IRR* and *LCoS* was minimal.

Table 4.9: Input parameters used for the sensitivity analysis with change in variable *O&M*

Input Change in Varible O&M Elements					
Categories	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
Revenue k€	1051	1051	1051	1051	1051
CAPEX	2231	2231	2231	2231	2231
Varible O&M	0,24075	0,409275	0,4815	0,553725	0,72225
Fixed O&M	43,05	43,05	43,05	43,05	43,05

Table 4.10: Output in *KPIs* of change in variable *O&M*

Output Change in Varible O&M Elements					
KPI	Very Optimistic	Optimistic	Base Case	Pessimistic	Very Pessimistic
Percent Scenarios	50%	85%	100%	115%	150%
IRR (%)	-0,42%	-0,43%	-0,44%	-0,45%	-0,46%
LCOS	105	105	105	105,1	105,1

4.5.4 Financial Impact of the Revenue Streams

The last parameter to be checked was the revenue streams, specifically the trading from the *DA* spot market and the excess electricity generated from the *WPS*. In practice, increasing the revenue streams would involve optimizing the operation strategy described in Section 3.7. The following values were calculated based on various scenarios of changes in the revenue streams.

Table 4.11: Input parameters used for the sensitivity analysis with change in Revenue Streams

Input Change in Revenue Streams					
Categories	Very Pessimistic	Pessimistic	Base Case	Optimistic	Very Optimistic
Percent Scenarios	50%	85%	100%	115%	150%
Revenue k€	525,5	893,35	1051	1208,65	1576,5
CAPEX	2231	2231	2231	2231	2231
Varible O&M	0,4815	0,4815	0,4815	0,4815	0,4815
Fixed O&M	43,05	43,05	43,05	43,05	43,05

Table 4.12: Output in *KPIs* of change in Revenue Streams

Output Change in Revenue Streams					
KPI	Very Pessimistic	Pessimistic	Base Case	Optimistic	Very Optimistic
Percent Scenarios	50%	85%	100%	115%	150%
IRR (%)	-3,9%	-1,3%	-0,44%	0,3%	1,8%
LCOS	280	123,5	105	91,6	70,1

As expected, decreasing the revenue streams resulted in a significantly worse *IRR*, which yielded -3,9% in the Excel calculations. Conversely, a 50% increase in revenue streams indicated a profitability of 1,8%, which is still considered low for a business case assessment for a new project. Since the revenue streams are directly tied to the generation output from the *PSH* and *WPS* systems the *LCoS* could also be calculated but by changing the generation inputs which followed the same patterns as the *IRR* yielding a *LCoS* of 70,1 €/MWh for the profitable case.

5 Discussion

In this chapter, an assessment and discussion will be made on the results/outputs from chapters 3 and 4. Furthermore, the set limitations and conditions will be assessed regarding their implications for the various results.

5.1 Technical Design of the PSH system

The input values in Table 3.1 were estimated using the available data from [46] and [47]. Therefore the estimated input parameters should be considered hypothetical since various legal and practical factors may change the magnitude and dimensions in an actual application.

5.1.1 Estimation of Design Input Parameters

Estimating the available amplitude of the upper reservoir, since according to [48] an unmeasured lake regulation amplitude may vary between 1-3m. An advisor from BayWa r.e. mentioned, possible implications with the regulation of lake amplitudes since it may affect various environmental elements such as ecological and chemical. The uncertainty regarding the allowed amplitude regulation entailed a conservative estimation of the allowed amplitude regulation of the upper reservoir, reducing the maximal potential of storage capacity. This was noted from the generation and revenue outputs from Section 3.8 since the accumulated penalty hours still were noticeable, further investigations showed that the magnitude of electricity generated from the *WPS* was significant compared to the maximal rated storage capacity of the *PSH*.

Another implication regarding the input parameters was the set distance between the reservoirs. The waterway was estimated visually and may in practical situations look different when considering geological factors such as ground, terrain, and accessibility, which was difficult to assess when investigating the reservoir's input parameters. As seen in the estimation of potential losses in Sub-section 3.4.6, the major head loss depends on various factors including the set distance between the reservoirs. An increase in the length would therefore increase the loss and reduce the potential storage capacity when recalling the formula for the potential storage calculation.

5.1.2 Calculation of the Technical Design

As seen in Section 3.1 the technical design of the *PSH* was conducted by utilizing an iterative method from [9] in combination with [10]. The iterative method establishes a potential input power and flows without regarding any specific losses where the losses iteratively are calculated step by step. However, since the scope is to conduct a feasible study of the *PSH* the general design estimation is assumed to be enough. In other cases, more complex methods and tools are used when estimating losses including complex *CFD* or fluid calculations.

5.2 Operation Strategy

The operational strategy of the *PSH* and *WPS* hybrid system had some limitations, especially regarding the logical usage of the *DA* spot market. In practical cases, market bids can only be submitted until 12:00, and the spot price is known only after the auction closes. In the algorithm, however, it was assumed that prices were known one day in advance to simulate hypothetical generation and revenue streams. A trend analysis could be conducted by studying the previous year's spot prices and identifying recurring hours or trends of low or high prices. However, this would require more time and in-depth statistical analysis, which was considered outside the feasibility scope of this study.

As seen from the operation strategy, only the *DA* market was considered. This decision was made because implementing the *WPS* system introduced complications regarding the logical construction of the hypothetical storage capacity in Excel. Managing two external generation sources wind power and the *DA* spot market trading, resulted in various outputs. Adding the intraday market and other ancillary services would have further complicated the algorithm, so it was determined that only *DA* and wind power would be considered in the algorithm.

The crucial part of the operational strategy was to develop an optimal algorithm to regulate the generated wind power and decide whether it should be sold, stored, or both. The applied logic when comparing the various outputs was based on the *PPA*, *DA*, and the storage level of the PSH. Continuous generation/pumping was also applied as a criterion since to reach full efficiency, the system needs ramp time which reduces maximal pumping/generation output at the beginning of the operation mode. In practice, the operational algorithm is more complex, involving additional logic criteria for each step and sub-step in the entire process.

5.3 Generation and Revenue streams for PSH & Wind

The results from Section 3.8 indicated that for the Hybrid setup, the overall generation from the *PSH* portion decreased which was expected since a significant portion of the generation from the *PSH* system was accumulated as compensation to reduce the penalty generation for the *WPS*. This was also seen in the revenue streams, especially regarding the penalty fee when comparing the hybrid to the separate wind setup. The overall generation from the *WPS* to the grid decreased for the hybrid setup and this was also expected since some portion was generated to the *PSH* system and accounting efficiency too, the overall generation decreased further for the *WPS*.

The overall pattern when comparing the hybrid setup to the separate case was the optimization of reducing the penalty generation and thus, increasing the overall generation for the hybrid case. Another factor to consider was increasing the reservoir volume by adjusting the regulation amplitude accordingly, one simulation sample for 2023 indicated that the overall net generation increased where the penalty generation decreased even further, thus increasing the revenue streams. One of the main obstacles to this proposal would be the juridical factor since there are multiple regulations regarding changing existing natural reservoirs per the literature [48].

5.4 Economic Aspects

Regarding the economic aspects, such as the cost estimation for *CAPEX* and *OPEX* elements, the business case, and the sensitivity analysis indicated some positive patterns for potential cost reductions to increase profitability.

The estimated *CAPEX* cost had some rather high-cost elements including *EPC* and the powerhouse structure with its corresponding components. One potential factor would be that most of the literature references underground installations of various components including penstocks and the powerhouse structure. This seems to increase the cost even further since indirect costs scale with the direct costs as established in Section 2.2.3. Utilizing existing reservoirs could decrease the overall cost regarding the reservoir cost category in the *CAPEX* estimation.

The costs associated with the grid in both the *CAPEX* and fixed *O&M* cost seem to be a major factor, especially for profitability. The used literature from Table 2.2 seems to disregard the costs associated with the grid, including grid fees related to tariffs for utilizing the main grid and the constructed transmission lines connected to the storage system. As observed in the business case, reducing *CAPEX* and *OPEX* could lead to profitability, as these factors significantly impact the *IRR* and *LCoS*.

Regarding the business case, one potential element that could be changed would be the economic life [12], estimated to be 40 years. However, with guidance from BayWa r.e. a 30-year economic life estimation was advocated as the relevant and most likely estimation since the connected *WPS* has a smaller economic life compared to the *PSH* system. But if possible the *PSH* system could be operated as a regular storage plant after the expected economic life of the *WPS* system. Participation in the intraday market and ancillary services could then generate additional revenue to cover the cost of the *PSH* system.

6 Conclusion

With the rise of renewable energy as the primary energy source of the electric mix, especially in Sweden, increased requirements will be placed for an optimal balance of the supply and demand aspects. Renewables are dependent on the weather and subject to uncertainty regarding increases in volatile and negative prices. Integration of a Pumped Storage Hydro system interconnected with a wind power system *(PSHHS)* would present a viable solution to solve the volatile and negative spot prices that have occurred during recent years.

The simulated model for the projected *PSH* site indicated that spot price optimization is feasible, allowing for storage opportunities when demand is lower and generation when demand is high. By Integrating the Wind power system, the revenue stream was optimized by compensating for hours when the turbines were idle which increased the revenue streams. The ability to compensate for such hours could tend to increase the minimal required base load to be delivered per the price purchase agreement and thus, increase the fixed price of the electricity since a higher volume with certainty could be delivered. The main trade-off is the reduced efficiency of the *DA* spot market trading which was expected.

Adjusting the cite parameters indicated an overall impact on the efficiency and performance of the technical design of the *PSH* system. Optimizing components such as the penstock diameter entailed, an overall improved efficiency since maximal storage capacities are preferred to maximize the revenue streams.

The *PSH* hybrid system looks from a business case perspective, as an unfavorable storage solution in the context of Swedish regulations regarding the usage of natural resources, diverse grid fees and tariffs, and high *CAPEX* and *OPEX* costs. But from a technical perspective, the overall improved efficiency regarding stable generation from the *WPS* was clear with improved revenue streams when comparing a hybrid case *(PSHHS)* with a separate *WPS* and *PSH* system.

6.1 Recommendations for Future Work

It is recommended for further development of this type of storage solution, to the corresponding project site if:

- Further studies regarding the incorporation of other arbitrage markets and ancillary services for external revenue streams are conducted.
- Investigation regarding allowed amplitude regulation and whether it can be increased compared to this study and other environmental impact factors from the *PSH* system.
- Environmental assessments, including chemical, geological, and similar elements that may affect the overall environment.
- Further assessments of the possibility of reducing grid fees/tariffs and reducing *CAPEX* and *OPEX* per the sensitivity analysis.

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