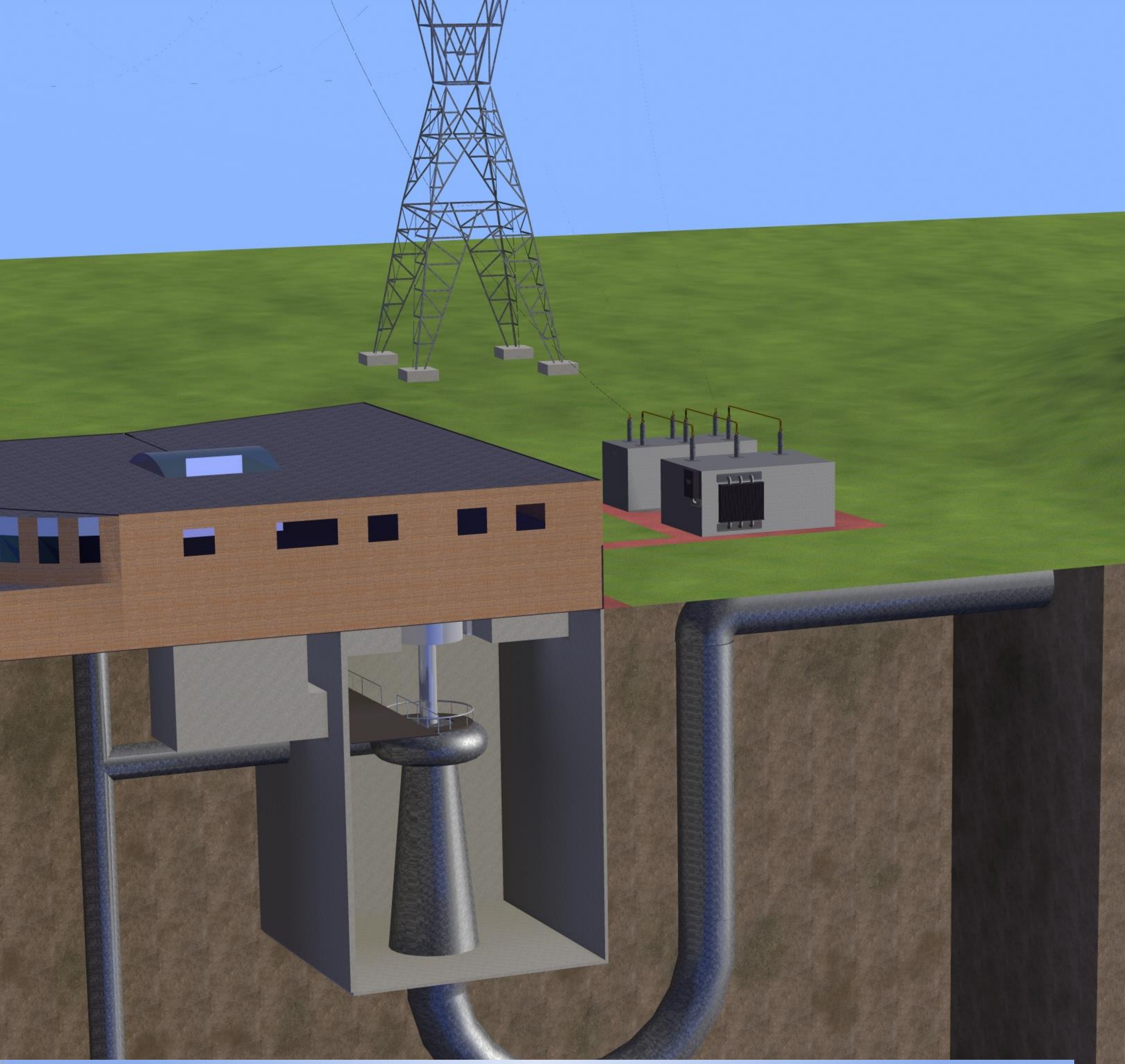

Pumped Hydro Storage: Pressure Cavern

Large-scale Energy Storage in Underground Salt Caverns

Erik van Berchum

November 2014

TU Delft Delft University of Technology

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Title	**:**	**Pumped Hydro Storage: Pressure Cavern** *Large-scale Energy storage in underground salt caverns*

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Type	:	Master Thesis

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Rivers, Delta's and Coasts

AkzoNobel
Industrial Chemicals

Summary

The current electricity market is changing rapidly. The past decades, the market was based on large centralized and monopolized coal- and gas-fueled plants, trying to predict and react to the demand of the market. The production of 'green' energy, subsidized by the government has shifted this market toward decentralized and unpredictable production capacity. The challenge of linking supply and demand of electricity has not been an issue so far, as fossil fuels could be used if needed. This will change in the nearby future, where 40% of electricity demand and 14% of Dutch energy demand is projected to be met by renewables. This situation demands other ways to link supply and demand, as the current solution of back-up fossil fuel facilities is inefficient.

This inefficiency can be solved with the use of energy storage, which is able to store energy when abundant and is able to produce when required. The present storage, which adds up to 140 GW of potential output worldwide (normal day in the Netherlands needs 20 GW) and consists out of Pumped Hydro Storage almost entirely. This storage concept uses abundant energy to pump water from a low to a high reservoir, usually into a self-made basin. When energy is needed, the water runs down into turbines to produce electricity like a normal hydropower facility would. Although successful, the technology is running out of locations because of the large impact that it has on the surrounding environment. Another challenge lies in the need for mountainous areas, which make Pumped Hydro Storage impossible in countries like the Netherlands. Currently, no alternative is able to compete with Pumped Hydro Storage when it comes to scale, efficiency and profitability.

Pumped Hydro Storage: Pressure Cavern

This report shows the operation and the potential of a new alternative, based on known techniques. It uses the underground space left by salt solution mining, called salt caverns. It combines these caverns with the common technology of Pumped Hydro Storage (PHS) into a system which can store energy with minimal construction, surface impact and investment costs.

To understand the concept, more information on the salt cavern is required. Salt caverns are large spaces inside a salt layer. They are a result of Salt Solution Mining and in the Netherlands they are mostly located between 500 and 1200 meters below the ground level of the North-Eastern part of the country. Salt producers like AkzoNobel drill into the salt layers to extract salt. This works by pumping fresh water into the salt layer, where it mixes with the salt. Brine, extremely salt water, is pumped back up and dried to claim the salt. Meanwhile, it leaves a space in the salt layer, which can grow up to the size of millions of cubic meters. These cavities are already used for storage of gas, oil, air (CAES) and nitrogen and will now be used to store pressurized brine. Salt caverns have the promising property to be nearly homogeneous and impervious, which makes them very suitable for storage. On the other hand, these caverns constantly need to be under pressure to prevent the cavern from shrinkage due to creep and fresh water cannot be pumped into the cavern without risking the stability of the cavern itself.

Operating the PHS Pressure Cavern

The concept of the PHS Pressure Cavern differs from conventional Pumped Hydro Storage in one major way. It does not store energy in the form of height difference, but pressurizes the brine inside the cavern to create the needed pressure difference to operate the turbine. It is based on a cavern that is partly filled with brine and partly filled with air. Energy is stored by pumping brine into the cavern. By adding brine, less space is left for the air, which increases the pressure. The maximum pressure allowed is roughly 85% of the geostatic pressure, which is the pressure resulting from all weight above the point in question. This pressure inside the cavern is able to push brine in the shaft all the way to the surface where a Pump turbine is placed. The pressure even exceeds this value, which results in a certain head difference over the Pump turbine. When required, this head difference can be used to create

electricity. The system can be used up to the point where the Pump turbine is not able to efficiently generate electricity any longer. At this point the air inside the cavern is still at 78% of the geostatic pressure, but it would be uneconomical to continue. In a later stage, when energy is abundant again, brine can be pumped in again to close the cycle, as is clarified in Figure 1.

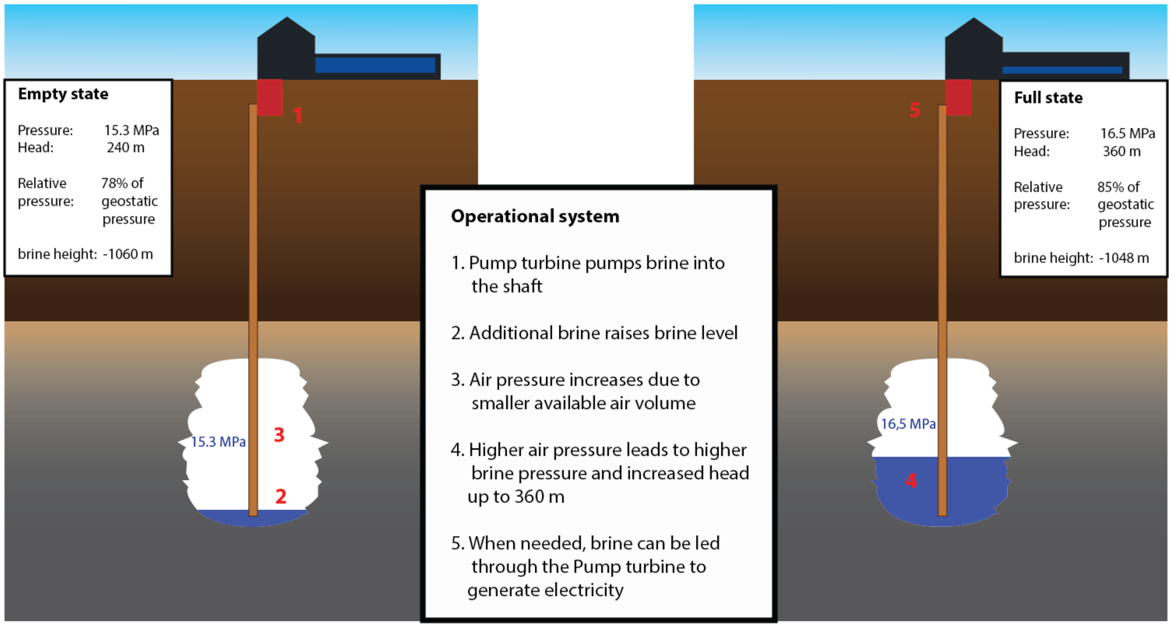

FIGURE 1 - SUMMARY OF THE OPERATIONAL SYSTEM. NOT TO SCALE

The most important structural challenge lies in the construction of the bore shaft. Because of the large diameter (2.0m), a method called Micro Tunneling is required. This method uses a drill head to reach the salt cavern and immediately places the casing behind it. To have a better indication of the potential of the system, an exemplary cavern is defined. This cavern has favorable dimensions and its results are stated below:

TABLE 1 - MAIN CHARACTERISTICS OF THE PHS PRESSURE CAVERN FACILITY

Property	Value	[unit]
Cavern		
Depth of top cavern	900	m
Dimensions(Diameter · h)	150 · 170	m
Size	$3 \cdot 10^6$	m^3
Diameter shaft	2.0	m
Energy storage facility		
Storage Capacity	156	MWh
Design power output	65	MW
Running time	3	Hours
Efficiency	74	%

System risks

Because of the large resemblance to conventional Pumped Hydro Storage, the risks are limited in comparison to other energy storage innovations. The main uncertainties concerning the concept of the Pressure Cavern are linked to the construction of the bore shaft, which uses a technology that is not common on these depths. It can also be challenging to find or construct a salt cavern with the diameter as described. The size of the salt layer below the North-eastern part of the Netherlands and the current salt solution mining market show a potential of tens of caverns to be used as PHS Pressure Cavern.

The economical competitor

When investigating the current Dutch electricity market, it becomes clear that there are multiple opportunities for energy storage to make profit. There are many markets where it can compete with other producing facilities, because of its ability to sell peak capacity at off-peak prices. To estimate the potential financial incentive, the costs need to be compared to the potential revenues. A Pumped Hydro Storage in a salt cavern with a storage capacity of 156 MWh and installed power of 65 MW is estimated to cost roughly 48 million euros. The most important costs consist of the construction and placement of the Pump turbine, as this is highly specialized equipment will take up a third of the total costs. Other expensive components are the bore shaft construction, which still needs additional designing and the connection to the national grid.

There are several parties that will be interested in energy storage. In the first place the Balance Responsible Parties (BRPs), whose main task it is to match supply and demand. As demand is always somewhat uncertain, flexibility can simplify their work and save them a lot of expensive capacity and fines. A second party is the National System Operator TenneT. This government-owned company is responsible for the National Grid and will as such profit from stabilizing facilities like the PHS Pressure Cavern.

To discover its value, the benefits of the system are also estimated. An estimate of the possible benefits, combined with an analysis of the market and reference projects resulted in an estimated yearly revenue of **5-6 million euros**. When comparing the market potential and the possible earlier identified benefits, a Net Present Value of the project of roughly **15-20 million euros** and a payback period of roughly **8-9 years** can be expected. A battery project by AES in design phase claims to use sophisticated market algorithms to be able to make profits with a project that costs €1000/kW power output and €250/kWh storage capacity. This shows the potential for the PHS Pressure Cavern concept, which is valued at €740/kW and €300/kWh.

Several points of the system are still unknown and need further investigation. However, current technical and economic analyses have shown the potential of the concept and conclude that the PHS Pressure Cavern is definitely a business case worth investigating in order to provide the flexibility that the Dutch market is going to need so badly the coming decades.

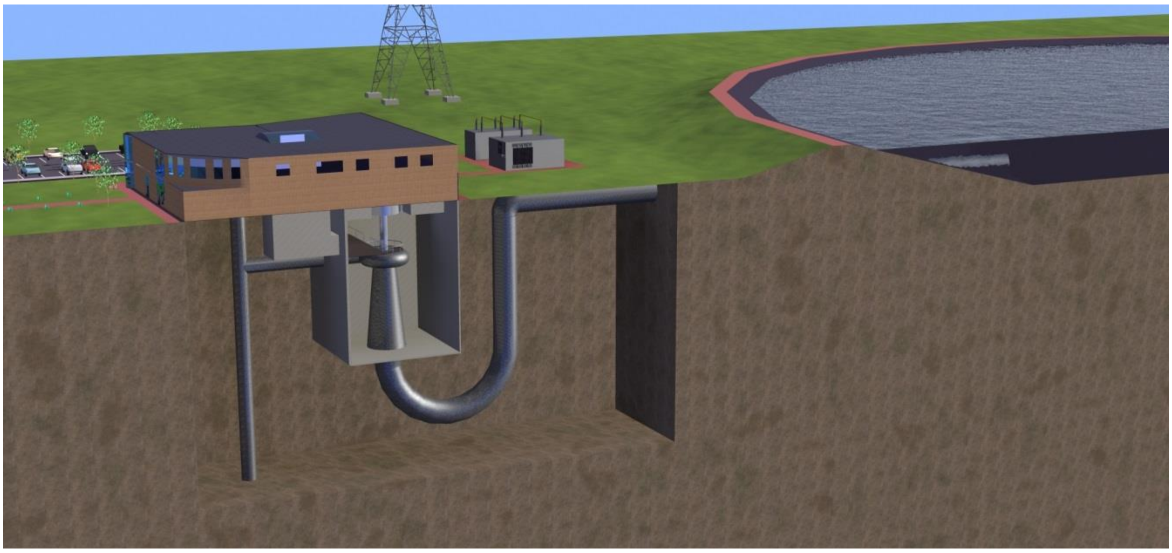

FIGURE 2 - MAIN OVERVIEW OF THE PHS PRESSURE CAVERN-SYSTEM

Preface

This report is the graduation thesis as a part of the Master Hydraulic Engineering at the faculty of Civil Engineering and Geosciences at Delft University of Technology in the Netherlands in cooperation with the companies Royal HaskoningDHV and AkzoNobel.

This feasibility study explains the design of an energy storage facility from the first conceptual idea up to the preliminary design. Because of my technical background, it will mostly be focused around the operational and structural design. However, my desire to evaluate the concept economically in order to create a clear view on its feasibility has enabled me to use my interest and courses in economics and finance as well. In this last phase of my thesis work, I would like to express my gratitude towards everyone that has been valuable to me along the way.

First of all, I would like to thank the members of my assessment committee, for their extensive support and willingness to comment on reports and questions. Prof. Dr. Ir. Bas Jonkman of TU Delft for leading the graduation committee and providing specialized comments; Ir. Ad van der Toorn of TU Delft for his inexhaustible amount of ideas and solutions provided along the way; Ir. Mirjam Walbeek for her supervision during my time at Royal HaskoningDHV and providing the needed contacts; Ir. Sallo van der Woude of TU Delft for his help on underground construction and geotechnical challenges and Dr, Remco Groenenberg of AkzoNobel for his knowledge on salt caverns and by giving the first push towards the concept of the Pressure Cavern. Special thanks are reserved for the regular help and supervision of Ir. Leslie Mooyaart of Royal HaskoningDHV, whose comments and conversations have guided me through the design.

I would also like to thank the many surprisingly helpful people I had conversations with. Dr. Mike Buxton and Dr. Ir. Dominique Ngan-Tillard of TU Delft for their efforts to update me on the state of the art on salt caverns; Ir. Frank Wetzels and Ir. Bas van Rossum for their help from within Royal HaskoningDHV; Ir. Hans Blok of Visser & Smit Hanab for his help with the design of the bore shaft; Ir. Pascal Bovy of Alstom for his comments on Pump turbine design and Ir. Oscar Tessinsohn of TenneT and Drs. Jorrit Lucas of Eneco for their crash course on the Dutch electricity market. Without the help and interest of these people, the thesis would have never had the depth and interesting conclusions that can be found within the report that lies before you.

Finally, thanks to my family and friends for their support and encouragement during this thesis.

Erik van Berchum,

November 2014

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Acronyms

PHS	Pumped Hydro Storage
EES	Electrical Energy Storage
SMES	Superconducting Magnetic Energy Storage.
BRP	Balance Responsible Party
APX-market	Amsterdam Power Exchange
VDD	Vertical Directional Drilling
SCC	Single Completion Cavern.
MCC	Multiple Completion Cavern
CAES	Compressed Air Energy Storage
NPV	Net Present Value
MCA	Multi Criteria Analysis
O&M-costs	Operation and Maintenance costs
PTC-station	Pump Turbine- and Control Station
TSO	Transmission System Operator

Terminology

APX-market	:	Consists of a Day-ahead market and a Spot market, where it is possible to buy electricity capacity for the day after or the same day respectively.
Arbitrage	:	Riskless revenue due to a fault in the financial system. Is used in the current research to signify the rise in value of a certain amount of electricity when storing during off-peak moments and supplying during peak moments.
Balance Responsible Party	:	Institution that links supply and demand of electricity for their customers and is responsible to keep supply equal to the demand.
Base load	:	Minimum constant electricity demand
Blackout recovery	:	The ability of a facility to supply to the grid during an emergency when the supply of conventional plants is cut off.
Borehole	:	Relatively small shaft bored into the earth. Is used in salt solution mining.
Brine	:	Water with relatively high concentration of salt.
Christmas tree	:	Total system of valves, connections and fittings that are placed on top of the well to make operation possible.
Diapirism	:	The geological event where an underlying material (salt) pierces through overlying soil due to pressure. Causes the formation of salt domes.
Electricity supply reserve	:	The use of energy storage to supply during an emergency. This can be on the scale of hospitals up to provinces or islands.
Equilibrium pressure	:	Pressure at which the increase of pressure due to shrinkage is equal to the decrease in pressure due to seepage.
Geostatic pressure	:	The pressure at a certain point within the soil as a result from all soil and fluids above it.
Halmostatic pressure	:	The pressure at a certain point within a non-moving body of brine
Hydrostatic pressure	:	The pressure at a certain point within a non-moving body of water
Homogeneous soil	:	Soil that is uniform in structure and properties.
Intermediate load	:	Daily fluctuation in electricity demand
Load levelling	:	The use of energy storage to totally erase the need for supply fluctuation by storing when demand is lower than supply and by supplying when demand is higher than supply.
Micro tunnelling	:	Small form of Shield Tunnelling. A shaft in the ground is constructed with the use of a small-scale tunnel boring machine.
Net Present Value	:	Valuation tool for financial decisions, based on regular cash flows which can be discounted for time, interest rate and opportunity cost.

Peak load	:	Extreme electricity demand
Peak shaving	:	The use of energy storage to lower the required supply of electricity at peak load moments.
Permeability	:	The ability of a soil type to let water run through.
Pump head	:	The height over which a pump can push water up.
Pump turbine	:	Machine that is capable of pumping water from a low to a high reservoir, but can also be used to generate electricity by running water down from the high reservoir to the lower reservoir.
Pumped Hydro Storage	:	Large-scale and common used way of storing energy. It works by pumping water up a mountain when energy is abundant and producing electricity by running this water through a turbine when energy is needed. *Also called: Pump Hydraulic Storage, Pumped Hydropower Storage, Pumped-storage Hydroelectricity*
PTC-station	:	Station at the surface of the Pump Hydro Storage: Pressure Cavern-system which is used to house the Pump Turbine and the control system, as well as the connection between the salt cavern and the surface reservoir.
Response time	:	An indication for the amount of time needed to turn a facility up or down.
Roundtrip efficiency	:	The ratio between the amount of electricity put into a storage system and the amount of electricity that can be produced with it.
Salinity	:	The relative amount of salt in a solution
Salt cavern	:	Large cavity in a salt layer, which is a result from salt solution mining.
Salt dome	:	Dome of highly pressurized and homogeneous salt in the subsoil, which is the result of salt layers that are pushed through the higher soil types. Can become hundreds of meters high and kilometres in surface area.
Salt Solution mining	:	The extraction of salt from underground salt layers by pumping fresh water into the salt layer and pumping brine back up. No human underground activity is required.
Shaft	:	A long passage sunk into the earth to connect the salt cavern with the surface. Is used to notify the larger diameter compared to the solution mining borehole.
Shotcrete	:	Concrete that can be applied by spraying it on the wanted location.
System Operator	:	Institution responsible for the transmission and the stability of the grid
Time shift	:	The use of energy storage to store energy at moments when electricity demand is low in order to increase supply when demand is high.
Unbalance market	:	A market used by TenneT TSO that is used to stabilize the grid. When an unstable situation occurs, TenneT can buy additional demand or supply.
Vertical directional drilling	:	Drilling technique that uses controlled boring to reach a certain position. Diameters can be increased by running increasingly broader drills through the borehole.

Symbols

A	[m^2]	Surface area
$c_{lubricant}$	[-]	Reduction factor due to brine layer along shaft lining
d_{brine}	[m]	Depth of the brine layer
E_s, E_c	[N/m^2]	Young's modulus of steel and concrete
$E_{storage}$	[Wh]	Energy storage capacity
F_{push}	[N]	Amount of force needed to push drill head into the soil
g	[m/s^2]	the gravity constant (= $9.81\ m/s^2$)
h	[m]	Elevation. Unless stated otherwise measured as vertical distance to the surface.
H	[m]	Pump head. Measures as meters of fresh water column
h_{cavern}	[m]	Height of the cavern
h_{top}	[m]	The depth of the top of the cavern
n	[rpm]	Pump turbine rotation speed
N	[N]	Compressive force
n_s	[rpm]	Specific rotation speed
P	[W]	Power
$p_{atmospheric}$	[Pa]	Atmospheric pressure (= $1 \cdot 10^5\ Pa = 1\ bar = 0.1\ MPa$)
p_{eq}	[Pa]	Equilibrium pressure.
p_{min}	[Pa]	Minimum required cavern pressure
p_{max}	[Pa]	Maximum allowable cavern pressure
R	[m]	Radius
Re	[-]	Reynolds number
S_{brine}, S_{fresh}	[%]	Salinity
t	[m]	Thickness
T	[K]	Temperature
U	[m\s]	Flow velocity
V	[m^3]	Volume
W_{casing}	[N]	Weight of steel casing
W_{steel}	[N]	Weight of cubic meter of steel
Q	[m^3/s]	Discharge
λ	[-]	Friction factor
ΔH	[m]	the difference in elevation
ΔH_{loss}	[m]	Loss of head difference
η	[-]	the efficiency constant, accounting for all associated losses
μ	[$Pa \cdot s$]	Dynamic viscosity
ν	[m^2/s]	Kinematic viscosity
ξ	[-]	Local loss
ρ	[kg/m^3]	Density
σ	[N/m^2]	Stress
ϕ_{cavern}	[m]	Diameter of the cavern

1 Introduction

The world of energy is undergoing major developments. In the past, large scale production of ***energy*** *was mainly controllable. This also applies for one of the main uses of energy,* ***electricity****. Fossil fuels, intended for electricity production, were extracted, stored and used when needed. Only very small amounts of direct accessible energy were needed to be stored. In the current market of increasing amounts of renewable and unpredictable electricity sources, this no longer applies (Oberhofer, 2012). The production companies no longer control the production as the two new renewable power sources, wind and sunlight, do not follow the cycles of electricity demand.*

The result is a challenging situation which can be approached from different angles. One of which is the increase of direct accessible energy storage. The following chapter will describe the challenges faced and the role that this research aims to play within this conversation. First, the ***main research question*** *and the structure of the report will be explained. Subsequently, the overall* ***energy market*** *will be clarified, after which the importance and principles of* ***electric energy storage*** *will be shown.*

Contents:

1.1 Main research question

Before the research is executed, it must be perfectly clear what exactly the goal of this research is and which question it hopes to answer. This is summarized in the main research question. This question will have an important function for this research, as it will act as a guideline for the report.

1.1.1 Problem statement

The amount of electricity produced by renewable energy sources is steadily increasing and most likely will keep growing over the coming decades. Besides all of the advantages, this will also greatly increase the variability of the electricity supply. Natural phenomena, like clouds and drops in wind intensity, will lead to production far below capacity. However, the demand does not depend on the same variables. Large fluctuations and differences between supply and demand will decrease the stability and efficiency of the grid. The market is in need of a solution that can link the demand to the supply with minimal investments and losses.

One way to achieve this is to increase the direct accessible energy storage. The most common way of energy storage, Pumped Hydro Storage, needs large height differences to remain profitable and is running out of possible sites. Other technologies are still in the developing phase, which means that a real alternative to Pumped Hydro Storage has yet to be found.

A potential alternative is to keep the principles of Pumped Hydro Storage and achieve height difference by underground storage. As large caverns, left behind by salt solution mining activities, are already present, this may seem promising. However, several technological challenges appear when trying to combine the worlds of waterpower engineering and salt solution mining. Whether dealing with these challenges is economically feasible requires understanding of both fields and a first conceptual design of a solution. Up to now, no time or research has tried to tackle these problems and the potential of Pumped Hydro Storage in Salt Caverns is still unknown.

1.1.2 Research question

By this research, it is aimed to answer the following question:

- *What is technologically and economically the most feasible way to apply a kind of Pumped Hydro Storage in abandoned salt caverns?*

The main research question is supported by the following sub questions:

- *What is the current state of energy storage and Pumped Hydro Storage?*
- *What are the current uses and opportunities for the use of salt caverns for energy storage?*
- *What challenges appear when using Pumped Hydro Storage in abandoned salt caverns?*
- *Which system configuration can lead to a technically feasible alternative to use Pumped Hydro Storage in abandoned salt caverns?*
- *What economic impact will result from the use of the most promising alternative to use Pumped Hydro Storage in salt caverns?*

1.2 Structure of the report

The questions stated above will be answered in this report. The background and importance of the electricity market and energy storage will be discussed in the remainder of Chapter 1. The next step is to further continue the literature study by investigating the world of energy storage in Chapter 2 and the different alternatives for the use of Pumped Hydro Storage in salt caverns, which can be found in Chapter 3.

The following conceptual design step, which will elaborate further on two promising approaches, is shortly described in Chapter 3, but is described in detail in **Appendix G and H**. After a last comparison, the final alternative will be chosen. This alternative will be investigated further in the preliminary design in Chapter 4. In both the conceptual and the preliminary design, technical and economic analyses will be worked out simultaneously. A visualisation of this process can be seen in Figure 3.

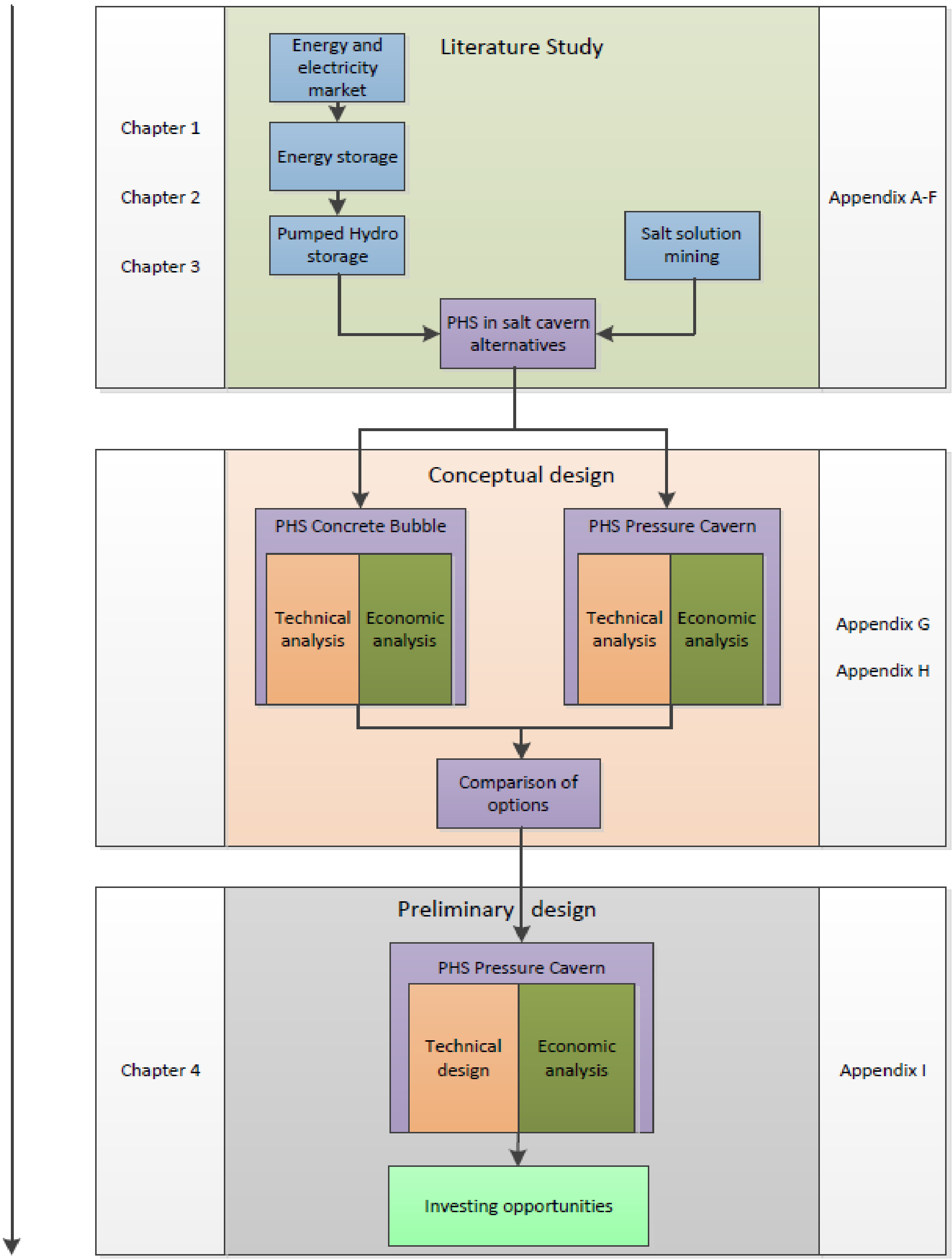


FIGURE 3 - FLOWCHART OF RESEARCH PROCESS, WITH CORRESPONDING CHAPTERS

1.3 The energy market

To make clear what kind of technology is being discussed, a bigger picture is sketched. All following challenges and solutions are part of the energy market, which is the total of supply and demand of energy. In the Netherlands, this market is strongly regulated and controlled. Within this market, strong desires are mentioned towards a less fossil fuel-dependent future. Concrete plans include a target of 14% of national energy usage being accounted for by renewable energy and a reduction of 80 – 95 percent of carbon emissions by 2050 compared to the 1990 levels (Ministry of Economic Affairs Agriculture and Innovation, 2011).

Although wind power and biomass are occupying increasing percentages of the energy supply, the Dutch energy market still has a long way to go, as the percentage of energy consumed from renewable sources has grown from 1.9 in 2004 to 4.5 in 2012 (Eurostat, 2014). Compared to the other European Union member states, the Netherlands is falling behind, as seen in Figure 4.

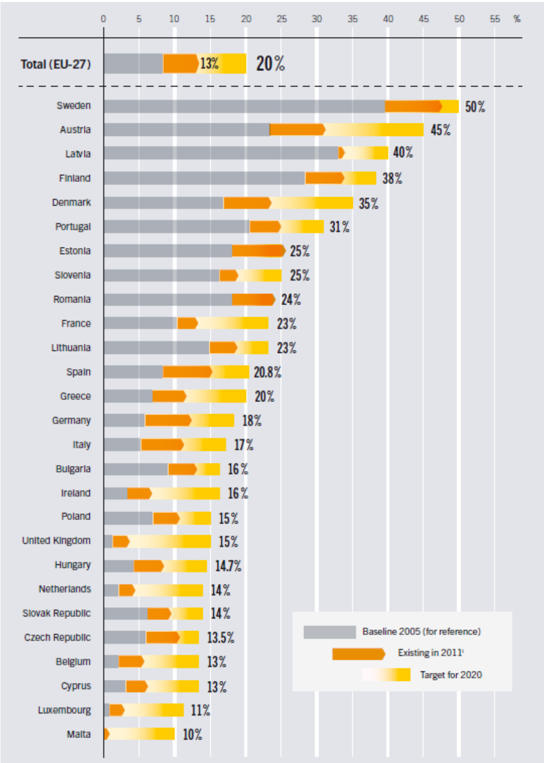


FIGURE 4 - SHARE OF ENERGY FROM RENEWABLE SOURCES PER MEMBER STATE OF THE EU27 (SOURCE: REN21, 2013)

The market of energy can roughly be divided in three separate smaller markets: Transport, Electricity and Heating & Cooling. When considering for example the Netherlands, an important part of the energy market consists of the Heating & Cooling-market, which makes up for almost half the consumption of total energy.

The market that will be considered in this research is the electricity market, which depends on the buying and selling of electric energy. These activities consume around 20 percent of the total energy consumption, which makes it an important part to focus on. All three markets should be changed structurally to reach the goals set on the European level (Ministry of Economic Affairs Agriculture and Innovation, 2011). Therefore, the electricity market is slowly changing due to the wanted rise in renewables.

This is also the case for the Heating & Cooling- and Transport market. These markets have their own solution, where waste heat from industrial processes is increasingly stored for heating of residential areas. The transport market is also rapidly changing with cars being more economical and an increasing amount of hybrids. Both markets have their own challenges and developments, but will not be covered further by this research. Below, more detailed information will be given on the electricity market.

1.4 The electricity market

Both the electricity demand and the electricity production are undergoing changes. Although the demand of electric energy in the Netherlands can be predicted reasonably well[1], the market for Dutch electricity is becoming more complex with the stronger connections to the surrounding countries. In the yearly published 'Energy Trends Netherlands', a new trend is highlighted where the Dutch market is flooded with cheap German electricity on sunny or windy days, due to the large amount of heavily subsidized renewable electricity. (E.-N. ECN, 2013) Instead of an energy-exporting country, the Netherlands is still importing cheaper foreign energy, while the Dutch companies cannot fully utilize their capacity.

Several other developments are emerging, with the biggest one being the transition from a fossil fuel based electricity market to a market based on renewable energy. In order to comply with the goals imposed by the EU, a large increase in production of renewable energy is needed. The current state of this development can be seen in Table 2 and shows that in 2012 12.2% of the electricity is produced by renewable power sources.

Subjects	Gross production electricity and heat			
	Total electricity and heat (TJ)		Electricity	
			Electricity (%)	
Central/decentral production	Total central/decentral production		Total central/decentral production	
Periods	2011	2012	2011	2012
Energy commodities	TJ		%	
Total energy commodities	631248	594340	100.0	100.0
Total fossil fuels	545099	497022	82.5	80.5
Natural gas	432133	376320	60.1	52.7
Hard coal	77558	90346	18.4	23.6
Fuel oil	224	186	0.0	0.0
Other fossil fuels	35184	30170	4.0	4.1
Total renewable energy	50224	56817	10.9	12.2
Solar energy	361	914	0.1	0.2
Wind energy	18361	17935	4.5	4.9
Hydro power	205	376	0.1	0.1
Biomass	31297	37593	6.3	7.0
Nuclear energy	14907	14093	3.7	3.8
Other energy commodities	21018	26408	2.9	3.4

TABLE 2 - ELECTRICITY PRODUCTION BY ENERGY SOURCE (SOURCE: STATISTICS NETHER-LANDS (CBS), 2014)

To make sure that this percentage keeps increasing over the coming years, large wind power projects are being developed. Also other measures like subsidizing solar panels and regulating biomass should have a positive effect on the production of renewable energy. However, it is clear that a large majority of the produced electricity comes from fossil fuels, natural gas in particular due to the presence of gas fields in the northeast of the country.

[1] This is done by TenneT. Examples can be found at http://www.tennet.eu/nl/about-tennet/news-press-publications/publications/technical-publications.html

The fossil fuels also provide the big advantage of flexibility. Natural gas, coal and oil can be stored and used on short notice when needed. This provides the backbone for the current system of flexibility for the electricity network. This grid is managed by the company TenneT, which is owned completely by the Dutch government. To ensure and protect the reliability of the network, every variation and extreme value needs to be dealt with. To describe this, three levels of electricity load are formulated: base load, intermediate load and peak load.

Base load consists of the main constant electricity needs of the grid. These loads come mostly from industries and result in a certain portion of the daily energy being needed all the time. The base load plants are characterised by the relatively expensive construction, but also inexpensive operation costs, meaning that they are most cost-efficient when used constantly and at full capacity (Bogdanowicz, 2011). Examples are coal or nuclear plants. Intermediate and peak load plants are used for the daily variation and extreme electricity needs respectively. They are characterised by higher running costs and faster start-up times. Examples are gas- and most renewable energy plants. The distinction between base load, intermediate load and peak load is clarified in Figure 5.

The total system of constant running, fossil fuelled base load power plants complemented with a variety of standby, highly-reactive intermediate- and peak load plants results in a reliable grid with only a minor chance of supply shortage (TenneT, 2013) . To lower these chances even more, surrounding countries have been linked to the Netherlands to make it possible for one country to meet the other country's needs.

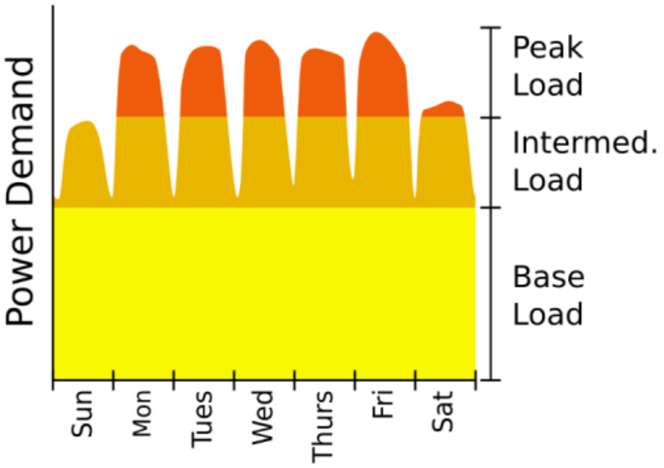


FIGURE 5 - WEEKLY VARIATION IN BASE LOAD (YELLOW), INTERMEDIATE LOAD (ORANGE) AND PEAK LOAD (RED) (SOURCE: BOGDANOWICZ, 2011)

The unpredictable nature and the major development of renewable energy is causing complications (E.-N. ECN, 2013). The large disadvantage of renewable energy is the fact that several forms, like solar power and wind power, are not controlled by humans but by nature. This results in a situation where the supply of electric energy does not comply with the demand in an increasing manner. When increasing the usage of wind power stations far enough, which is occurring in Germany as earlier mentioned, the simple distinction between cheap-to-operate base load plants and expensive intermediate load plants fades or even reverses.

If the Dutch government would choose to increase the amount of wind- or solar power plants, a sunny or windy day could lead to a decrease in electricity prizes. The renewable energy, which is produced regardless of demand, would drop below the price of fossil fuel, forcing a drop in efficiency of the base load plants, because they have to turn down their production.

1.4.1 Future developments

The Dutch situation is characterized by a large amount of fossil fuel power plants, not running on full efficiency. The amount of energy produced with renewable energy is still low and already the effects of its unpredictability are felt. The future plans show a picture that is both promising and challenging. A short summary of the future plans concerning the production of electricity is shown in Table 3.

TABLE 3 - SUMMARY OF FUTURE ELECTRICITY PRODUCTION PLANS (SOURCE: TENNET, 2013)

Plan	Effect in	Effect
Increase of wind farms • **from 2500 MW to 6000 MW on land** • **from 1000 MW to 4450 MW on sea**	2020	• Electricity supply will depend more on natural events; • Difference in reliance on conventional energy sources between Netherlands and surrounding countries decreases;
Additional shutdown of coal-burning plants	2016/2017	• Base load more dependent on gas production; • Recent coal-burning plant shutdowns in America have lowered the price of coal, making it relatively cheap compared to the popular gas-plants;
Tax-discount on solar cells • **Expected output in 2020 of 4000 MW**	2014	• Electricity supply will depend more on natural output; • Increase in decentralized electricity production;
Temporary increased demolition and conservation of production plants	2013-2015	• Decrease in total electricity output; • Shift from old production facilities to new production facilities; • Decrease in current conventional plant efficiency; • Construction of new gas- and nuclear facilities when a larger demand is expected;

The table shown above clearly shows the two main issues of the current electricity market in the Netherlands. Production of gas based electricity is relatively expensive due to its connection to the oil price. On the other hand, coal burning plants have become even cheaper the last years. As several coal burning plants in the US are closing down because of a more sustainable policy, the supply from overseas increases and pushes the prices down. The pollution tax, which will negatively affect the coal production, is still very low, resulting in a situation where coal plants push gas plants out of the market.

The table also shows that this first issue is attempted to be dealt with by dealing with the second issue, the low amount of renewable electricity production, at the same time. Especially wind energy is being enhanced in a large amount by growing from 3500 MW to almost 10500 MW, which in the current production situation (2014) would be enough for approximately 20% of the entire electricity production of the Netherlands. The other interesting statistic is the expected output for solar cells of 4000 MW, which is mentioned in the Quality- and Capacity document of TenneT (I. Janssen-Visschers, 2013). This results from the new Energy Agreement for Sustainable Growth (SER, 2013), which is a large agreement between companies and the Dutch government. Distribution network operator TenneT estimates this goal to be feasible.

Another interesting development concerning the Dutch electricity market is the desire of the Dutch government to strengthen the position of the Netherlands as the power hub of North-western Europe. As addressed in the Energy Agreement for Sustainable Growth (SER, 2013), the new cables connecting the Netherlands with Great-Britain (Britnet) and Norway (NorNed) and the planned cable to Denmark will play a demanding role in the international transportation of electricity, especially between the continental countries to the Southwest and the oversea countries of Great-Britain and Scandinavia. With all current plans executed, the total international capacity will add to 8.1 GW in 2017. The effect of the international connections on the flexibility and the stability of the grid in the various countries have not yet been investigated.

At the moment however, it is still unknown if the development of international trade will provide a solution for the increasing unbalance between supply and demand. The unpredictable nature of the production of electricity from renewable sources may still result in a too large fluctuation of demand for conventional base load plants, resulting in a drop of efficiency and therefore unnecessary loss of raw material. A more fundamental change in the way we manage our energy is therefore needed.

1.4.2 The position of this research

One of the other possibilities is to store energy when there is a surplus, in order to supply additional electricity when needed. At the moment, this sort of storage is hardly used because the system described above had no need for it. However, it will become more profitable with every investment done in renewable energy. Currently, the only technology capable of storing energy meant for electricity production on a large scale is Pumped Hydro Storage. However, the potential sites for this technology are limited and need substantial investments. More information about this and alternative technologies is given in the following chapters. A feasible alternative is clearly needed. Several previous researches have been done to find a profitable solution. These researches include:

- ***Energy Island***; this alternative tries to provide large-scale storage by using a reservoir at sea with a surface area, combined with a small head difference. (Boer, 2007)
  Properties*: 30 GWh energy storage, 2500 MW installed capacity*

- ***Slufter Pumped Hydro Storage***; by transforming an area used as silt depot into a Pumped Hydro Storage system, large amounts of energy can be stored. (Kibrit, 2013)
  Properties: 2.16 *GWh energy storage, 470 MW installed capacity*

- ***Gravity Power Storage***; energy is stored by moving a heavy piston up and down a storage tank filled with a pressurized fluid, which in turn can be used to power a turbine. (Imambaks, 2013)
  Properties: 80 M*Wh energy storage, installed capacity unknown*

- ***Gravity Power Module***; this alternative uses the principle of the Gravity Power Storage and combines it with underground storage to construct large-scale energy storage. (Tarigheh, 2014)
  Properties: 174 M*Wh energy storage, installed capacity unknown*

The alternatives shown above are either only applicable on a small scale or require large investments to develop. Combined with the enlarged risk of an unproven technology, it will be a challenge finding support from investors if another technology than Pumped Hydro Storage is used. This research will look to answer the main question of energy storage by combining the known and proven principles of the Pumped Hydro Storage with the totally different field of Salt Solution Mining. This form of deep underground mining leaves larges caverns, which can be used to provide the needed height difference. These large and abandoned spaces are already used for other purposes, such as storage of gas, oil, air and nitrogen. Although Pumped Hydro Storage has been linked to abandoned mines in other countries before, the use of salt caverns in the search for energy storage in the form of Pumped Hydro Storage has not been considered yet until now.

2 Energy storage

The last chapter showed the developments and the need for a solution that can link supply and demand on the electricity market. The current system, dominated by fossil fuel, where flexibility is provided in the form of fast-reacting overcapacity is inefficient in both capital usage and fuel efficiency. Besides, it may not suffice in a future which is characterized by the significant portion of electricity produced by renewable energy sources.

There are several ways to match demand and supply. The overproduced electricity can partly be exported to countries without an overcapacity of energy or stored in the form of electric, potential or kinetic energy. There are several different incentives to use energy storage and a variety of roles that electric energy storage can play inside a nations grid. A detailed and clear description is given in the white paper of the International Electrotechnical Commission (IEC, 2011).

This chapter will show the ***importance and size of the worldwide and nationwide energy storage****. A few* ***essential terms*** *will be explained in order to understand the ways energy storage can improve the stability of the grid. Subsequently, the most used energy storage facility,* ***the Pumped Hydro Storage-facility****, will be explained.*

More background information can be found in the ***Appendices A-C****. These Appendices are included to give a short overview of the current state of the art on energy storage and their current role and opportunities in the market.*

Contents:

2.1 Energy storage technologies

Energy storage can play different roles inside the current electricity market. Before the technologies are discussed, it is therefore necessary to have a clear view on these roles. Here the four primary roles of energy storage will be discussed. The first function and fastest reacting function that energy storage can play is the assurance of ***power quality*** of the electric energy on the grid. The demand for electric energy varies constantly and the production capacity cannot constantly be prepared for this variation of voltage and frequency. On these short notices, a small amount of energy storage, combined with phase modifiers will keep the voltage and frequencies between allowable boundaries.

The second role that energy storage can play is ***the primary regulation*** of the grid. This part is related to the power quality in the sense that it reacts to changes or errors. When an error occurs on the grid, which happens several times every day, more modification is needed than only the power quality assurance can provide. Larger and slightly slower amounts of energy storage are kept standby to react to these kinds of changes.

As third function, energy storage can be used for ***time shift***. This term explains the intentional over- or under production in order to smoothen the electricity production. The most used application is the overproduction at night or other off-peak moments in order to reduce the else needed production peaks in the morning or evening. This stored energy will be used during the day when the base load is not sufficient. When used in relatively small amounts, this is called ***peak-shaving***, which can reduce costs in different ways. The additional production needed from peak load plants is disproportionally more expensive, which means that the use of time shift would result in the longer and more constant use of cheaper and more efficient production plants. Besides this effect, revenues can be made with the storage by buying of the grid during cheap off-peak moments and selling to the grid during expensive peak moments of the day. When large amounts of energy storage are used, it is theoretically possible to provide electricity to provide electricity during the entire peak during the day by filling the storage during night, resulting in one constant energy production level, which is called ***load levelling***.

The last and most diverse function is ***electric supply reserve***. This can occur on different scales. On the local scale, where certain buildings like hospitals may require electricity continuously up to the national scale, where the temporary loss of a production plant may not lead to power shortage, electric supply reserve may be needed. The above mentioned roles offer solutions and possibilities on different timescales and are called upon different amounts of time. These differences are clarified in Figure 6.

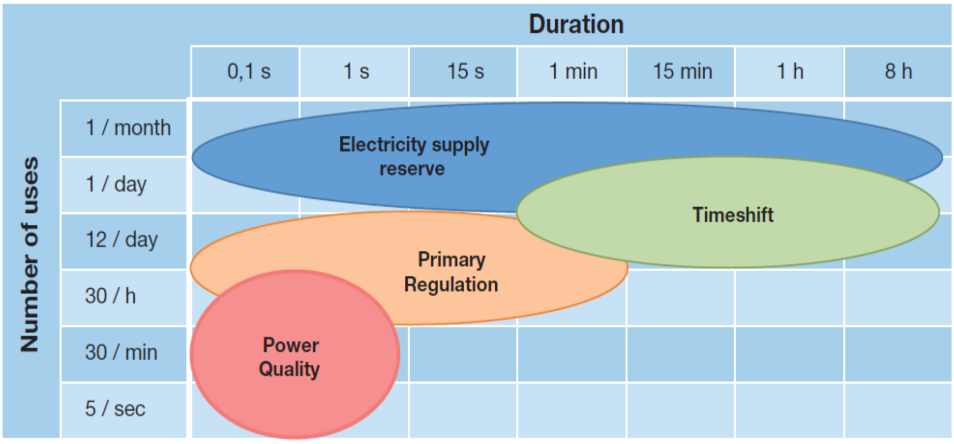


FIGURE 6 - DIFFERENT USES OF ELECTRICAL ENERGY STORAGE IN GRIDS, DEPENDING ON THE FREQUENCY AND DURATION OF USE. (SOURCE: IEC, 2011)

This figure shows the diversity needed by energy storage. On one end, high-frequency short-duration storage is needed, but on the other also storage with a long duration and low storage losses is necessary.

2.1.1 Types of energy storage

Last chapter discussed the many tasks that a form of energy storage may fulfil. This wanted diversity has led to a large variety of energy storage techniques. The following technologies will be discussed below:

- Mechanical Storage
  - Pumped Hydro Storage (PHS)
  - Compressed Air Energy Storage (CAES)
  - Flywheel
- Chemical storage system
  - Batteries
  - Fuel cell
- Electrical
  - Superconducting Magnetic Energy Storage (SMES)

In the figure below, these technologies are listed for their capabilities, especially their ability to produce large amounts of energy and the duration on which they can produce this. As can be seen, the PHS is capable to produce the largest amounts of Power output for the longest amount of time. Batteries can be used for a large variety of purposes, but are especially good at long duration and low output. The flywheel on the other hand is a very specialized system, producing large amounts of output for a short amount of time.

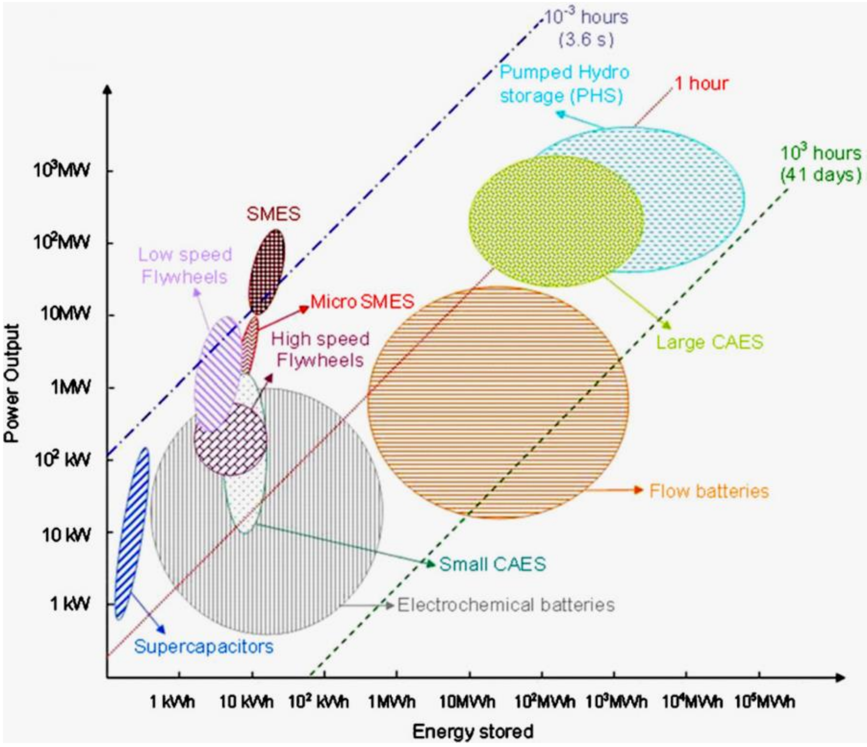


FIGURE 7 - FIELDS OF APPLICATION OF DIFFERENT STORAGE TECHNIQUES ACCORDING TO ENERGY STORED AND POWER OUTPUT. FUEL CELLS ARE NOT INCLUDED, AS THE TECHNOLOGY IS CONSIDERED TO BE IN A DEVELOPING STAGE. SOURCE: (IBRAHIM, ILINCA, & PERRON, 2008)

In this paragraph, these technologies will be introduced swiftly. Subsequently, the Pumped Hydro Storage technology will be explained in more detail. The following figure is shown to provide some additional insight on the current state of the worldwide storage capacities,.

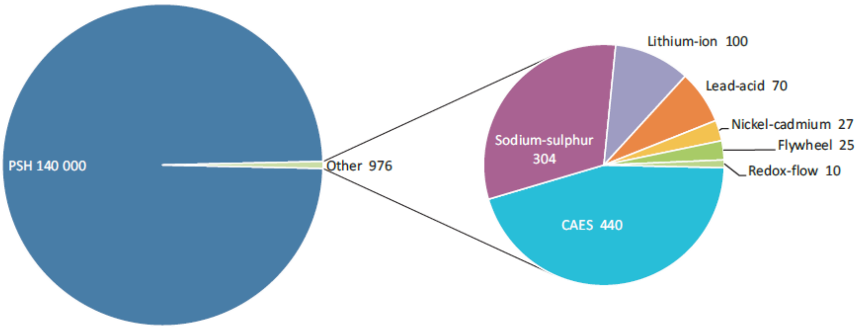


FIGURE 8 - WORLDWIDE STORAGE CAPACITY FOR ELECTRICAL ENERGY (SOURCE: IEA, 2013)

This figure shows that almost the entire global storage capacity is provided by Pumped Hydro Storage. When this technology is not within the reach of the concerning company or country, batteries or Compressed Air Energy Storage would provide a proven technology, although these technologies have other significant drawbacks. Another opportunity is to connect to a country that has PHS abilities, which limits the storage power output by the capacity of the cable and makes the receiving country dependent on the supplying country. Important to note is that the large majority of energy storage technologies is still in a developing phase. Because the storage of electricity is only recently being considered as possibly profitable, these technologies are far behind on other sectors like energy production or thermal storage.

This point is strikingly illustrated by the Technology Roadmap shown below (IEA, 2013). Figure 9 shows the phase of the most popular electricity storage technologies in dark blue, are compared with the most common thermal storage technologies in light blue. The vertical height in the graph shows an approximated combination of the required capital investment and the technology risk. This shows that Pumped Hydro Storage, which needs a considerable capital investment, has a very small risk. Alternative uses of Pumped Hydro Storage, which will be explained in following chapters, are still in a development stage however.

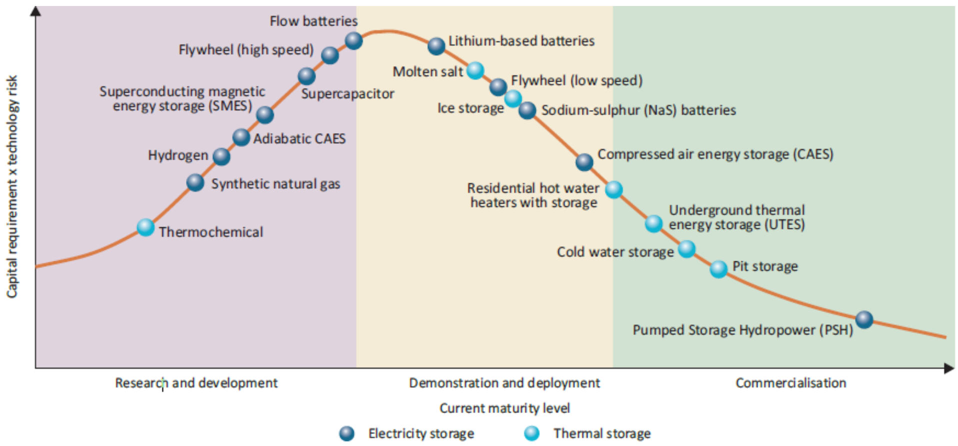


FIGURE 9 - MATURITY OF ENERGY STORAGE TECHNOLOGIES (SOURCE: IEA, 2013)

Also recognizable is that most of the electric storage technologies are still in the Research and Development-phase and will only need more capital investment with increasing risk the coming years. This means that the electricity market needs to be even more promising and profitable than the past years if the technology is to be developed up until the Commercialisation-phase.

A more detailed description of the various developing technologies can be found in **Appendix A**. This will give a short overview of the current state of energy storage and will show the lack of a low-risk, large scale alternative to the conventional Pumped Hydro Storage. Because of the importance of Pumped Hydro Storage and its prominent role in this research, this technology is described further below.

2.2 Pumped hydro storage

The biggest contribution to energy storage is provided by pumped hydro storage plants. These special hydropower plants store energy in the form of potential energy by using surplus electricity to pump water from a low-lying basin to a high-placed basin, either natural or man-made. When a shortage of electricity emerges, this water can be used to power turbines like a conventional hydropower station to produce electricity (Ter-Gazarian, 2011). Hydropower itself is globally by far the most used renewable source of energy with a worldwide power output potential of approximately 990 GW of electricity (REN21, 2013). This means that it accounts for 67% of all the renewables and 16.5% of the total global electricity production. Pumped hydropower storage makes use of this well-tested technology and accounts for a total worldwide power output potential of 140 GW.

There are different ways to accommodate a PHS into the water- and energy system. The most common way is the 'open-loop' system, where the PHS is connected to the existing water system. The other possibility, 'closed-loop', is referring to a PHS-system which is totally independent from water streams nearby. The open-loop configuration can be divided into 'off-stream'- and 'pump-back'-systems.

The off-stream open-loop PHS is the most common sort, where the lower lake or river is part of the water system and the higher lake is isolated away from the stream. This usually means that a higher reservoir is built in a mountainous area, closed off by a dam. The pump-back principle refers to a system where both the top and bottom reservoir are part of the stream. During energy-surplus situations, water is pumped from the lower to the higher reservoir even though there is a net-surplus of water running down from the higher to the lower reservoir.

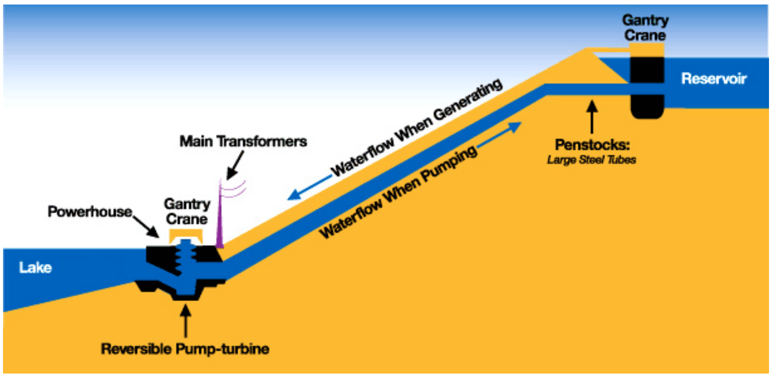


FIGURE 10 - MOST COMMON SET-UP FOR PUMPED HYDRO STORAGE (SOURCE: RICHARD-ROWLAND-PERKINS.COM)

TABLE 4 - MAIN PROPERTIES OF PUMPED HYDRO STORAGE

BASED ON: (BEAUDIN, ZAREIPOUR, SCHELLENBERGLABE, & ROSEHART, 2010; IEA, 2013)

Power Output	100-3000 MW
Efficiency	70-80%
Discharge at capacity	Hours-days
Response time	minutes

The main advantages of the PHS include the relative simplicity, the capacity and the experience of working with hydropower. In the second half of the twentieth century, the first requests for energy storage were made, long before renewable energy became an issue. The rise of nuclear power increased the amount of base load plants and reduced the average flexibility of the electricity production.

To cope with the high peaks, instead of building additional gas plants, investments in adjusting the existing hydropower plants were made (EPRI, 2013). Using the principle of load levelling, the building of additional peak load plants was avoided. This way the profitability and attractiveness of the nuclear plant was increased, because the PHS was able to tackle the most important disadvantages of using nuclear power. The nuclear power plants were very inflexible and expensive to build, making them the perfect example of a base load plant that has to run every minute of the day. The PHS was able to store the nuclear energy during the night in order to generate energy when the nuclear plant was not sufficient. The combination of nuclear production and PHS took off (Manwaring, 2012).

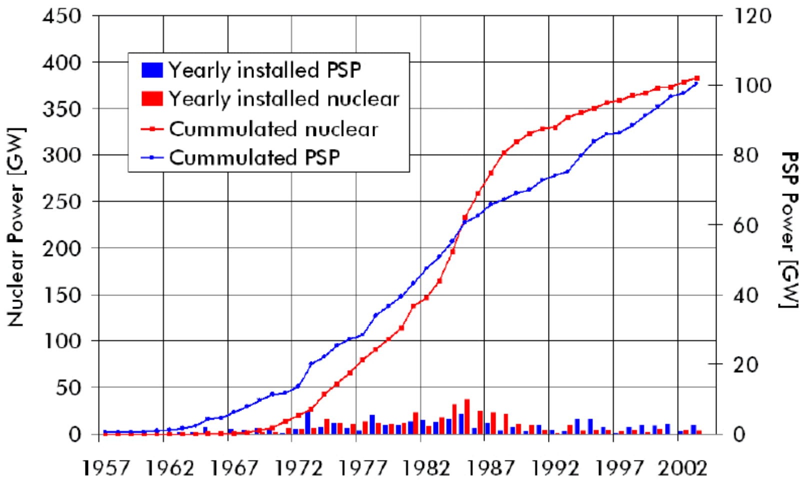


FIGURE 11 - WORLDWIDE INSTALLED CAPACITY OF NUCLEAR PRODUCTION AND PUMPED HYDRO STORAGE (PSP) (SOURCE: MANWARING, 2012)

In the recent years, the role of the PHS is still to support the stability of the grid, but the main components of energy production are shifting. Big, constant-running fossil fuel plants are replaced grouped or decentralized production of renewable energy. Instead of redistributing the constant inflow of energy from nuclear, coal and gas plants, the PHS has to react to the very variable input from renewable energy sources. This required a new approach in which the pump and generator capacity should be able to react and alter much faster (Manwaring, 2012). This was relatively easy to do, which lead to the current situation in which this decades old technology is rendered almost risk free and the highly adjustable PHS has conquered its spot as the first choice with a more than 99% market share of energy storage.

Advantages

- Capable of storing large amounts of potential energy, with largest plant being 3000 MW
- Almost no standby-losses
- Long lifetime, up to 60 years
- Long duration, up to days of electricity production at capacity
- Fast response time

Disadvantages

- Special site needed with river close to mountainous area
- Large environmental influences
- High initial investment

The most obvious and compelling disadvantage of the use of PHS is the large influence on the geographical site. First of all, there need to be mountains. In order to make a closed-loop PHS, no nearby river is needed, but it is still necessary to close off a high-lying area in order to make the higher reservoir. This reservoir should be able to store the designed amount of water, which will lead to large walls and extra costs if the mountains are not arranged in the right way. Nearby, preferable close, enough space for a lower basin should be accessible. Both these places will be entirely occupied by the water, meaning that it should not be inhabited or important for the local natural system, in order to get the right permits. These large restrictions mean that only a small amount of places is suitable for the placement of a PHS plant. The production of electricity from hydropower relies on one important formula, which links the provided power output to the potential energy input:

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot \Delta H \; [W]$$

Where:

- P is the power in [watt]
- η is the efficiency constant, accounting for all associated losses [-]
- ρ is the water density in $[kg/m^3]$
- g is the gravity constant $[m/s^2]$
- Q is the volumetric flow $[m^3/s]$
- ΔH is the difference in elevation [m]

This formula is valid for the production of electricity from the potential energy of water, using a turbine and a generator. The formula shows a few different variables that can be altered to increase output. For example, the efficiency in the current situation can be optimized up to 80%, based on running projects. Only a small increase is possible. Also the water density cannot be altered much, because the use of heavier water like sea water, only changes the density marginally. Besides, a closed-loop system would be necessary to prevent pollution of the nearby surface water with salt water. The gravity constant cannot be altered by definition. This reveals the only workable variables to be the volumetric flow Q and the difference in elevation ΔH.

The power output depends on the amount of discharge, Q, and head difference, ΔH. This can be an advantage as well as a drawback. It means that everywhere where it could be possible to run a large flow over a large vertical distance, large amounts of energy can be generated. The downside is that only one of the two variables needs to be absent in order for the technology, the only proven and commercially produced electrical storage technology, to be almost useless.

Luckily, several sites create ideal circumstances for the construction of PHS plants and the market is still growing with an increasing rate. However, to make energy storage with the use of hydropower on a scale where it would meet the probable future demand of energy storage, other measures are necessary and other types of structures should provide for the flow and height difference, independent of the vicinity of mountains and water. In this field, several researches have been done. Most researches can be divided in two groups:

- Focus on height difference: These researches use underground or underwater space, as this is the only option without mountains. Other substances or states of matter can be used than water, like gas or solid weights. Examples are OPAC, Gravity Power Storage (Imambaks, 2013) and Hydraulic Hydro Storage (Heindl, 2013) and Subsea PHS (Falk, 2013).

- Focus on area: When height cannot be achieved, a certain capacity can only be reached by increasing the area. This way, a large water flow is still possible for a sufficient amount of time. Examples of large-scale reservoirs with minimal height difference are Energy Island (Boer, 2007), the Eleventh Province in Belgium and the Slufter (Kibrit, 2013).

More information about alternatives to Pumped Hydro Storage can be found in **Appendix B**. Most of these options are based on innovative ideas, but lack the economic potential to deal with the large investments and the large risks. If it would be possible to apply the ideas of PHS to already existing cavities, like mines, aquifers or salt caverns, this could lead to a major advantage over other alternatives when considering economic feasibility. Another possibly interesting development is the comparison to large distance storage, where one country stores energy from another country. This is for example the case in the Netherlands, which is connected to the mountainous Norway through a thick power cable. This comparison will be explained further in later chapters.

2.3 Energy Storage Economics

Storing energy is possible, even in the large amounts that will be needed in the short future. Whether it will rise in popularity soon depends on one question: 'Where's the profit?' Most suggested and declined projects are put on hold during the design phase because there were no investors to be found, which is a direct effect of too little financial incentive. Only those who are willing to innovate and take risks can profit from energy storage. This is a result of the sophisticated and unpredictable changes that the energy market is undergoing. Also, the advantages of using energy storage are not always accompanied with financial revenues for the investing party.

A small overview of factors that make the energy market and the possible revenues unpredictable:

- The energy demand depends on numerous factors and growth in energy demand is uncertain as a result of for example smart grid or electric cars
- Energy supply is depending on a lot of different global markets influencing the electricity prices. Most fossil fuels are supplied by markets based in unstable markets. Developments in the mining of fossil fuels or the exploitation of renewable energy sources could have major impacts on the energy supply and prices.
- The energy market is regulated by different governments in a variety of ways. Every government is focussing on the exploitation of fossil fuels and the encouraging of renewable energy differently. This makes it difficult for investors to choose a certain technology, because it might not be profitable in other countries. The government policies are also rapidly changing over time, making it uncertain if a designed technology will be profitable by the time it is built.
- Most of the benefits cannot be expressed directly in financial revenues. This provides difficulties to pay the investors for their services without governmental interference or major company collaborations.

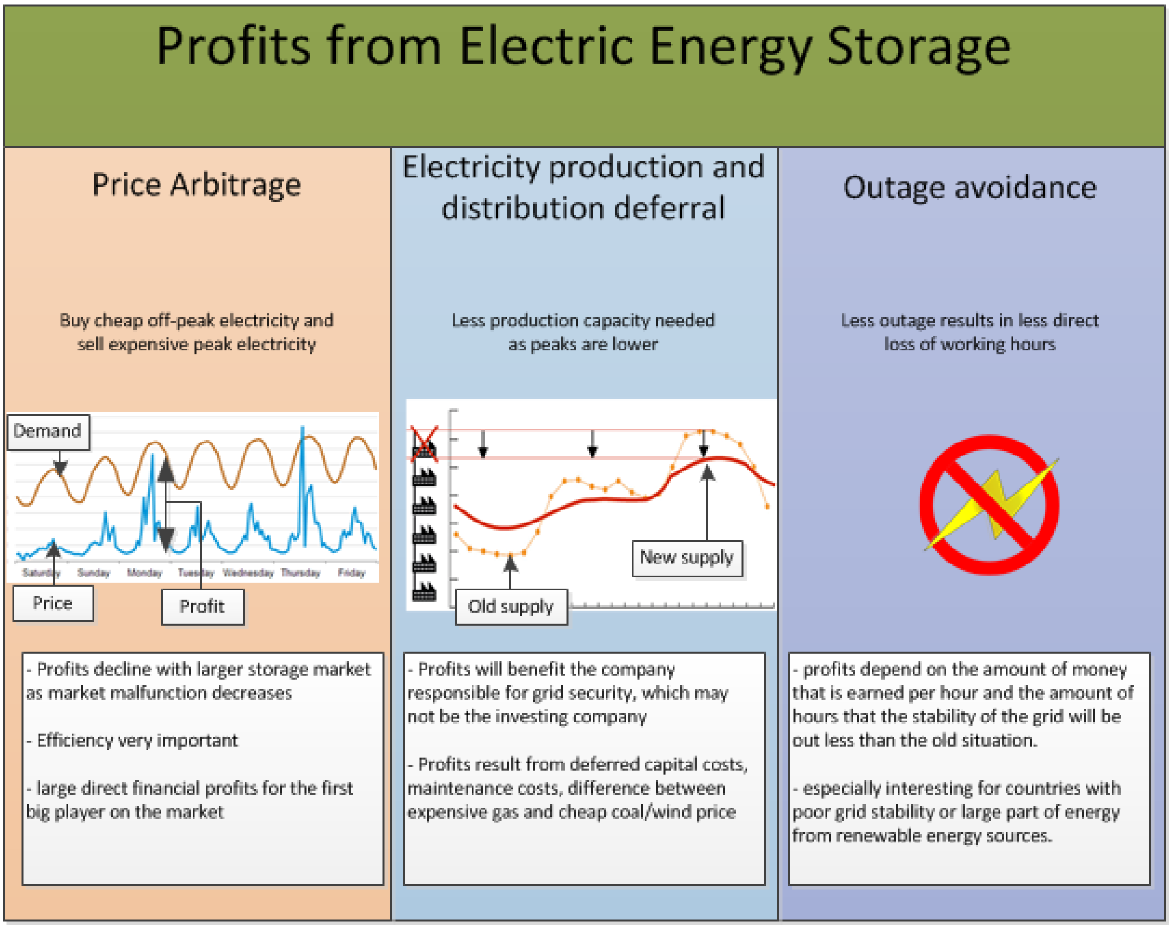
The current (growing) amount of Electrical Energy Storage (***EES***) shows that governments and an increasing amount of private investors are willing to take the risk and make use of the services that EES provides. Powered by the governmental aid, future prospects and current revenues, an increasing amount of money is invested in innovative solutions.

The benefits from Electrical Energy Storage can be divided in mainly three groups (Zhang, 2013):

- Price arbitrage; buying off-peak cheap energy and selling on-peak expensive energy
- Electricity production and distribution deferral; Storage capacity can handle the peaks, which make peak plants redundant as a stability measure. Base load plants are able to increase their efficiency and work rate, thereby increasing the profitability of the entire system.
- Fuel revenues; Instead of expensive gas, electricity will be produced with the use cheaper coal or even cheaper renewable energy sources. Problems can arise when calculating the amount of gas replaced in coal for a certain company, as both the production capacity and the energy storage facility are connected to the grid instead of being connected to each other directly.

From these three arguments, only the price arbitrage can be directly converted to financial revenues. The benefits of EES will be further explained in **Appendix C**.

TABLE 5 - DIFFERENT KINDS OF PROFITS THAT CAN BE MADE FROM THE USE OF ENERGY STORAGE



Most of the existing alternatives, whether or not using PHS, are lacking the financial incentive to be implemented on large scale. When concentrating on underground energy storage, a lot of early investment is needed to investigate the soil and create the cavity. The large capital investment needed and the enlarged uncertainties of surface impact have discouraged investors. This can be resolved by reducing the risk, increasing the hit rate (amount of useable sites as a portion of the amount of investigated sites) or reducing the needed investments.

The use of existing underground space

Because of the large capital investments required to construct an underground space, a large cost reduction can be achieved by using existing cavities, like abandoned mines, aquifers or salt caverns. Use of these cavities will force the investing parties to use the given shape and circumstances.

The aquifer will most likely be the least suitable storage facility, due to the permeability of the aquifer. A lot of research and investments are needed to provide a sufficiently impermeable underground space. A mine could be a suitable host for PHS, when the circumstances are right. An important downside to mines is the differences between them. Every mine is different and will therefore need separate initial research and specially made solutions for every mine.

Salt caverns, large cavities underground as a result of salt solution mining, have a strong advantage when it comes to standardisation. Because of the homogeneous nature of the salt layers and especially the ***salt domes*** (which will be explained in later chapters), most solutions will be applicable to multiple salt caverns. Also, the caverns can be much larger than most mine chambers and the shape is more similar between caverns. They combine a large height difference with a large size, leading to a large possible energy storage capacity.

3 Pumped Hydro Storage in Salt Caverns

*The storage of energy can provide solutions to a few of the major challenges concerning the greatest change in the landscape of electricity since the creation of the grid. This third chapter tries to utilize the findings from the world of energy storage by combining the only successful energy storage technology with another proven practice: storing energy in **used salt caverns** with the use of **Pumped Hydro Storage**.*

*This alternative is based on the idea of looking down instead of up, into the ground. The earth has been used for a variety of purposes, mostly for extracting materials or fuel, leaving gaps that can be used for the necessary height difference which is so critical in the usage of Pumped Hydro Storage. A special kind of mining is the **salt solution mining**, which is among other places done in the east of the Netherlands. This leaves a closed off, deeply positioned cavern when abandoned, making it very promising to serve as a reservoir for energy storage.*

*First, **the principles of salt solution mining** will explained. Subsequently, different possibilities of using PHS in salt caverns will be presented with in total **four approaches**. From these four, a **qualitative analysis** will choose the most promising solution, which will be worked out further in later chapters.*

Contents:

3.1 The principles of salt solution mining

The main idea of salt solution mining involves the **pumping of fresh water** into a borehole to a salt layer. At depth the fresh water dissolves the salt to form **brine**, which is then pumped back up. At the surface, the brine is transported to a processing facility where it is purified. After purification, the water is evaporated from the brine, thus producing salt. The mining of salt with the use of this method has been done for a long time, also in the Netherlands.

This method grew over course of the twentieth century, resulting in the current situation where salt solution mining is the main source of salt production in the Netherlands (Mollema, 2011). At the moment, there are four places where salt is being solution mined in the Netherlands, all located in the **eastern- and northern part of the country**. [2] More information on salt solution mining can be found in **Appendix D**.

3.1.1 Construction

The process of solution mining is fairly simple. Water is pumped through a pipe into an underlying salt layer, where it reacts with the surrounding rock salt. This creates a cavity in the layer filled with brine, which is basically water saturated with salt.[3] This brine is pumped back up, after which it is purified and the water evaporated to produce salt. To keep this process constantly going, a well with different casings is used. Currently, a well with three casings is customary, where one part will pump the water down, the second part will pump the brine up and the third will apply and remove a thin oil layer on top to control the formation of the cavern.

First, a pipe with usually a diameter of 24.5 cm is drilled and cemented into the soil. Two pipes with a smaller diameter will be lowered down inside this pipe. In the first phase, water is pumped into the lowest part of the targeted area without the use of an oil (blanket) layer. This creates the cavern sump. After this, the oil layer will be applied and the water will be forced to flow to the sides, adding to the width of the cavern rather than the height.

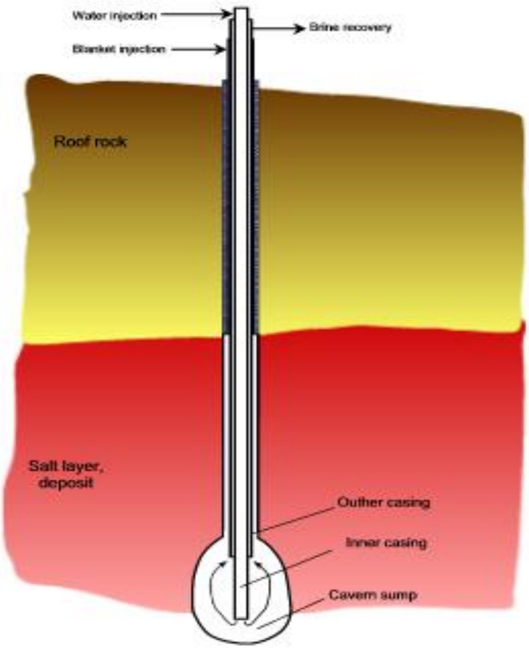


FIGURE 12 - FIRST STAGE OF FORMING OF SALT CAVERN. THE WATER IS PUMPED IN TO FORM THE FIRST PART. SOURCE: SOLUTION MINING PRESENTATION, K-UTEC. ACCESSED ON 31-3-2014

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[2] Based on: State Supervision on Mines. www.sodm.nl/onderwerpen/zoutwinning. Accessed on 31-3-2014

[3] Salt concentration can reach up to 25%, which is comparable to the Dead Sea. saltworks.us/salt_info/si_DeadSeaSalt_Info.asp. Accessed on 31-3-2014

When the desired width is achieved, the blanket level is pulled up and the same process starts again. This process can be seen in Figure 13. The cavity is filled at all times with increasing amounts of brine, to prevent drops in pressure.

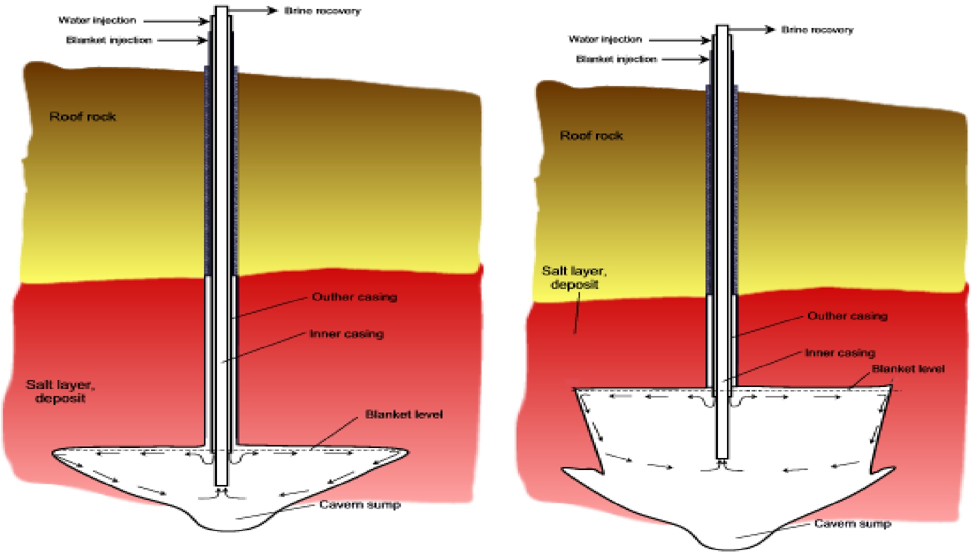
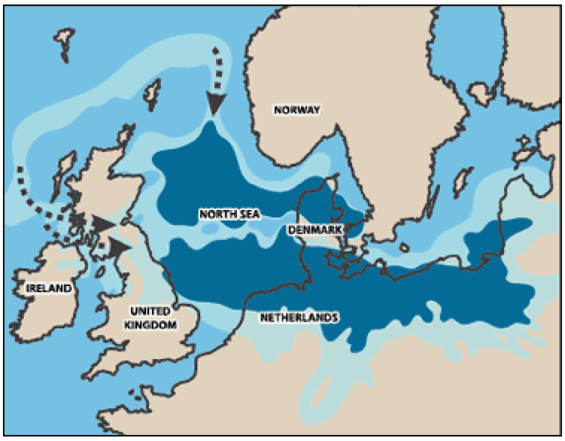


FIGURE 13 - THE SECOND AND THIRD STAGE OF SOLUTION MINING. WITH USE OF MEASURING MATERIAL AND CONTROL OF THE BLANKET LEVEL, THE EXACT FORM OF THE CAVERN IS BEING CONSTRUCTED. (SOURCE: SOLUTION MINING PRESENTATION, K-UTEC. ACCESSED ON 31-3-2014)

The solution mining stops when the top of the salt layer is reached. The brine will remain to keep the pressure at an allowable load. After this, the cavern can be closed off or used for another purpose.

3.1.2 The geology of the Netherlands

To find the origin of the salt-packed layers, time has to be set back around 250 million years. The continents were not formed yet and the landmass consisted of the supercontinent Pangaea. During the Middle- and Late-Permian period (271-251 million years ago), a collection of geological layers called the Zechstein formed on the bottom of the Zechstein Sea. This shallow part, close to the equator of the supercontinent was flooded during a severe de-glaciation at the end of the Early-Permian period. The following millions of years, different layers of salt were deposited and later topped by the ground layers of the 250 million years of history (Sannemann, 1968).



In this time period the Pangaea continent split up in the several continents that we know today and the Zechstein layers moved with the corresponding tectonic plates to the north, where it is currently placed in a part of the North Sea and the northern parts of Germany and The Netherlands.

FIGURE 14 - MAP OF CURRENT NORTH-WESTERN EUROPE, WITH THE EXTENT OF THE ZECHSTEIN SEA SHOWN IN BLUE (SOURCE: ZECHSTEINMAGNESIUM.COM. ACCESSED ON: 07-04-2014)

As mentioned above, the deep ground layers can vary depending on the location. This can lead to major differences in the thickness of the salt layer. These differences are results from the characteristics of rock salt on the long time scale and a concept called diapirism. As hard as it may be, when subjected to a certain amount of force, rock salt will react and deform plastic. This means that on a long time scale, rock salt will act as a fluid (Fokker, 1995).

When a light fluid is located beneath a heavier fluid, the lighter fluid will push through the upper layers in the form of bells or bumps.[4] Because the rock salt is relatively light in comparison to the heavy sediment on top, salt domes will form. The layered structure of a few hundred meters thick is pushed together to form kilometres thick, homogeneous salt domes. When using these salt domes instead of the original layers for the mining of salt, the salt caverns will be able to be bigger and more stable. These can also more easily be used for secondary purposes, when the salt cavern is depleted.

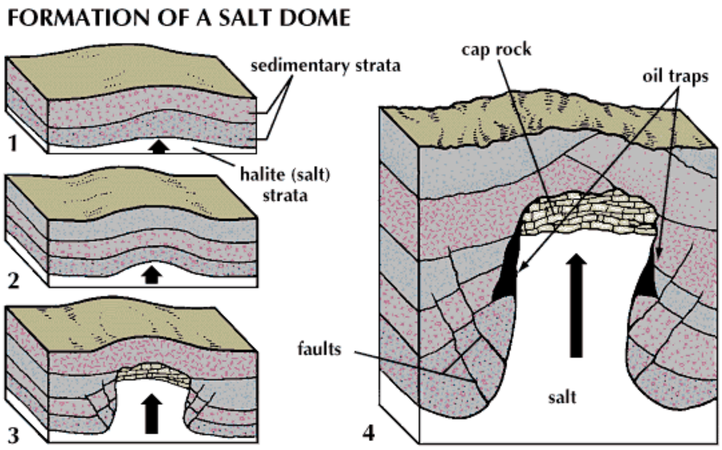


FIGURE 15 - DIFFERENT STAGES OF THE CREATION OF A SALT DOME. (SOURCE: ENCYCLOPÆDIA BRITANNICA KIDS, KIDS.EB.COM. ACCESSED ON 31-3-2014)

A disadvantage of the rock salts fluid behaviour is the necessary pressure, which was already briefly mentioned before. At the depth of some kilometres, the pressure can be very high, making the rock salt act as a fluid on the long term. When this pressure would drop locally, for instance by excavating a cavern, this cavity would close over time. The surrounding rock salt would be pushed into the large cavern, possibly resulting in minor, but noticeable drops of the ground level above the cavern. To counter this phenomenon, pressure should be applied back to the rock salt at all time. During solution mining, this will mean that the cavern should always be filled with brine. The specific weight of the brine isn't sufficient to provide definite support, but the closing of the cavern will occur with such slow speeds, that it will hardly be noticed on the ground above.

When the brine is left behind in the closed-off salt cavern, the pressure from the brine onto the salt cavern wall is less than the geostatic pressure from the salt dome. This means that the walls will eventually creep into the cavern. Pressure will increase beyond the standard pressure of the static brine, due to the smaller space that has to accommodate the same amount of brine. At the moment the cavern is left behind after the salt solution activities stopped, the pressure in the cavern is solely based on the brine weight, resulting in a pressure called the ***halmostatic pressure***, as mentioned in related literature (Berest, 2001).

[4] A well-known example is the lava lamp

This pressure is slightly more than normal hydrostatic pressure and can be seen as:

$$p_h = \rho_b \cdot g \cdot H = 0.012 \cdot H; \;\; [MPa]$$

Where:

- P_h is the halmostatic pressure at depth h in [MPa]
- H is the average cavern depth in [m]
- ρ_b is the density of the brine, which is assumed at $1200\ kg/m^3$ [kg/m^3]
- g is the gravitational acceleration, which is assumed at 9.81 m/s^2 [m/s^2]

This is significantly lower than the geostatic pressure which is acting upon the salt dome through the surrounding soil:

$$p_g = 0.0216 \cdot H; [MPa]$$

Where p_g is the geostatic pressure at depth H in [MPa]. The constant is an assumed value from reference projects. The difference between the halmostatic and the geostatic pressure will result in creep of the cavern sides, because of the ring pressure and therefore shrinkage of the cavern, which can be viewed as a cavity. The shrinkage will increase the pressure in the brine, which will decrease the difference in pressure and therefore decrease the resulting creep. Pressure build-up in the brine will also increase due to the thermal expansion of the brine. Water from the surface is left in the cavern, which can be approximately $50°C$, depending on the depth. This will increase the pressure.

One would think that, when the pressure in the brine is equal to the geostatic pressure, the creep would stop. This is however not the case, because it is impossible to make the brine pressure equal to the geostatic pressure at all heights. This would most likely have led to fracturing, which is not the case due to another important characteristic of the salt, its long-term permeability. Although salt is impermeable for every engineering standard, it can be seen as permeable when considering very long time scales (at least decades) and increased pressure. As has been found by Berest in (Berest, 2001), a final equilibrium will form where the pressure increase due to creep will be balanced by the pressure decrease due to brine leakage through the permeable salt dome. To give an indication for this equilibrium, the research has found with the use of a test cavern that:

$$p_{eq} = 0.014 \cdot H \;\; [MPa]\,; \text{ which is 13 MPa at 950 m depth.}$$

Where p_{eq} is the equilibrium pressure in the brine. The equilibrium pressure is relatively low compared to the geostatic pressure. The brine leakage in this test was equal to 1.4 $m^3/year$, what will lead to a slow demise of the cavern taking thousands of years (the reference research stated this to take 50 centuries) before the cavern is closed completely. The leakage and equilibrium pressure depend greatly on the creep and permeation, which have to be calculated in-situ (Brouard, 2007).

3.2 Characteristics of a PHS-facility in a salt cavern

The lack of energy storage is bound to develop into a major concern over the coming decades if not properly addressed in time. Early solutions have been initiated by increasing the international electricity trade capacity and increasing the energy storage in the form of Pumped Hydro Storage. However, the potential sites for Pumped Hydro Storage are running out and other technologies are still in the development phase, unable to take over the necessary growth.

A salt cavern can provide the needed solution. A large capacity closed space with a relatively large head difference as main characteristic. Both Pumped Hydro Storage and Solution Mining of salt caverns are proven technologies. Combining these two projects while changing as little as possible to the original concepts will result in a low-risk, easy-to-predict energy storage plant. Several conceptual estimates are done below.

First estimate

The size of a cavern depends on the location and sort of salt cavern. When using a salt cavern in a salt dome, the size can easily exceed millions of cubic metres. This is not nearly as big as the largest conventional Pumped Hydro Storage facilities in the mountains, which can reach up to as much as 20-40 million cubic metres for the biggest ones.[5] To estimate the power output, a head difference of 900 metres is used. Also, the efficiency is chosen at 70%, which is somewhat lower than present PHS-plants. When a total capacity is required to run at full capacity for three hours, this results in the following discharge and power output:

$$\Delta H = 900\ m; \quad C = 1 \cdot 10^6 m^3; \ \eta = 70\%; \ Q = \frac{1 \cdot 10^6}{3 \cdot 3600} = 92.6\ m^3/s$$
$$P = 92.6 \cdot 0.7 \cdot 1000 \cdot 9.81 \cdot 900 = 430 \cdot 10^6\ W = 572\ MW$$
$$S = P \cdot d = 572 \cdot 3 = 1720\ MWh\ per\ cycle$$

Where:

- ΔH is the difference in height between the two reservoirs	[m]
- C is the capacity of the salt cavern	[m^3]
- η is the efficiency of the system	[-]
- Q is the average discharge through the turbine	[m^3/s]
- P is the resulting average power output	[MW]
- S is the total amount of energy stored per cycle	[MWh]
- d is the duration	[h]

If for example this facility is used for day-night time shift (emptied during the night, filled during the day), the capacity would be enough to store electricity for approximately 180 thousand households every day.[6] The average daily production consists of:[7]

$$\frac{98.4 \cdot 10^3}{365} = 270\ GWh\ per\ day$$

[5] A list of the largest Pumped Hydro Storage plants in the world can be found at : *http://en.wikipedia.org/wiki/List_of_pumped-storage_hydroelectric_power_stations*

[6] The average yearly household electricity usage in the Netherlands is 3500 kWh

[7] Total production in the Netherlands = 98.4· 10^3 GWh (2013). Production from renewable energy sources= 11.4· 10^3 GWh (2013) Source*: Energiebalans* **statline.cbs.nl** accessed on: 2-5-2014

This means that the daily storable energy of one dome will account for 0.6% of the total yearly production of the Netherlands or 5.3% of the current yearly produced renewable energy. These numbers indicate that large scale energy storage is within reach, would the technology prove to be potentially profitable.

3.2.1 Main characteristics

The construction of a Pumped Hydro Storage plant inside a used salt cavern will bring some additional challenges compared to conventional PHS. These extra challenges will change the design, components and construction. However, the main idea is the same and could provide a first indication about the facility and all that is linked to it.

First of all, a Pumped Hydro Storage facility needs the following components:

- Two water bodies in the form of a reservoir or connection to the surface water system
- Pump and turbine, can be separate or a combined system
- Pipelines to connect the previous components
- Main control building which controls the in- and output and connection to the grid

The initial situation will consist of a small shed connected by a well of about 25 cm diameter with a large cavern approximately 700-1200 metres below. These caverns generally have a diameter of 50-125 metres and a height of 100-400 metres, filled with brine.

The diameter of the borehole most likely has to be enlarged to facilitate the discharge and potential equipment that has to be lowered into the cavern. If conventional Pumped Hydro Storage is used, the Pump turbine-Station has to be placed at the lower end, which means that a room has to be constructed at cavern depth. The room will need to be accessed by a maintenance crew and will probably be tens of metres long in every direction. If the use of this underground Pump turbine space has to be avoided, a change of the total Pumped Hydro Storage operational system is required. The bore shaft can be incorporated into the well or can be dug separately and should be in the order of a metre in diameter. A short overview can be seen in Figure 16.

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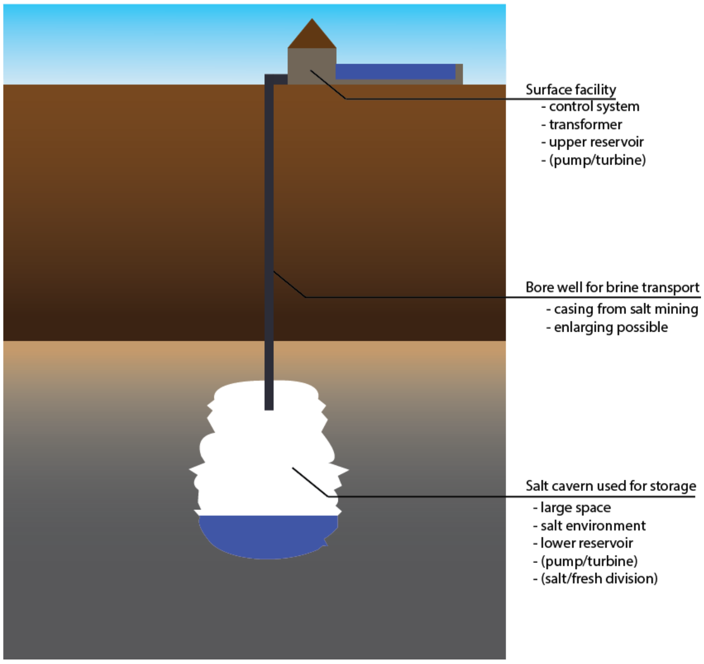


FIGURE 16 - MAIN CHARACTERISTICS OF A PUMPED HYDRO STORAGE-FACILITY IN A SALT CAVERN

When a system has to be designed within the frame of a salt cavern, the following requirements need to be taken into account:

- Well sizes exceeding a diameter of half a metre are unusual for drilling. In the order of meters, shaft sinking is necessary. Salt solution drill diameter is usually around 25 cm.
- Atmospheric pressure inside the cavern is not an option, because of cavern shrinkage.
- Everything placed inside the brine of the cavern needs to be able to withstand the equilibrium pressure of the brine (approximately 14 MPa per kilometre depth)
- Everything placed between the insides of the cavern wall needs to be able to withstand the geostatic pressure (approximately 22 MPa per kilometre depth)
- A substance that dissolves salt cannot be used inside the cavern without separation from the walls
- A Pump turbine-station has to be accessible for maintenance.
- The Pump turbine and the bore shaft have to be adjusted to cope with the extremely salt brine.

Also, the following considerations should be mentioned as well:

- The use of dangerous or polluting materials or substances should be discouraged due to longer permit periods and decreased support from surrounding residents.
- Surface space is limited. As salt solution mining needs minimal space, these facilities can be close to residents.

3.2.2 Pitfalls of PHS in Salt Caverns

Sadly, implementing of Pumped Hydro Storage does have a few challenges to address before a working and profitable version can be designed. The ones that require the most attention are:

- The salt cavern needs a minimum pressure to keep the cavern from closing too fast for economical standards, due to the geostatic pressure from the surrounding ground layers.

- Using fresh water will result in an unwanted increase in salt cavern size, while salt water still needs to be processed later.

- Additional underground space is needed to accommodate the pump and turbine

- A second reservoir is needed with a comparable capacity to the salt cavern, which would result in a salt-water lake or the requirement for a very shallow salt cavern nearby. This provided that salt water is used to counter the previous point.

More detailed descriptions of these challenges for the use of Pumped Hydro Storage in salt caverns can be found in **Appendix E**.

The occurrence of these problems is the result of this combination never being tried before. All other uses for salt caverns rely on the storage of different kinds of energy, besides potential energy. The only comparable technology is CAES, which stores energy in the form of potential energy in the form of pressure. Most of the problems stated above are avoided by using a substance that does not react with the salt dome, without losing the minimum pressure.

3.3 Possible solutions

Despite the many challenges faced by the current technology, it is technically most certainly possible to use Pumped Hydro Storage in Salt Caverns. None of the problems stated before cannot be fixed or anticipated on with the use of already existing technology. The challenge is to find the economically most promising solution and test whether it is sufficiently profitable in comparison to the risk. After all, this is one of the most important measures to grade whether the project should be executed.

Below, four possible solutions are stated. They all approach the challenges at a different angle and are therefore a good resemblance of the large variety of possibilities. A short introduction:

- *PHS Concrete Bubble*; the first approach is to form a protective shell with the use of concrete. This makes open-loop fresh water PHS possible.

- *PHS Pressure Cavern*; The cavern is closed off and practically turned into a large piston, as only half the cavern is filled with brine. Surplus energy pumps brine into the cavern, increasing the brine level and the air pressure. This pressure pumps the brine back up when needed.

- *PHS Pressure Barrels*; the third option uses a developing concept where connected barrels are lowered into the cavern. These barrels will act as the needed storage.

- *PHS Abandoned Mine*; the last option widens the view by not only looking at salt caverns. Several problems faced by working with salt caverns are not- or significantly less present when using traditional mines, although others may rise

All four possibilities will be further explained below. Attempts are made to clearly state the pros and cons of each approach to enable the development of a choice based on sound arguments.

3.3.1 PHS Concrete Bubble

The Concrete Bubble-approach is the closest to conventional Pumped Hydro Storage of all the possibilities. The big advantage is the use of fresh water, which makes a second reservoir redundant.

Below in Table 6, the main characteristics and components of this facility are stated. As can be concluded from the table, most cavern-related problems are eliminated by the use of a concrete shell. Rather than applying the shotcrete unto the moving cavern walls with its diverse shape along the cavern, a pressurized soft bubble is blown inside the cavern, while the cavern is filled with brine.

TABLE 6 - THE MAIN CHARACTERISTICS AND NEEDED COMPONENTS OF THE PHS CONCRETE BUBBLE-APPROACH

Characteristics	**Construction components**
• *Concrete shell divides the water from the cavern* • *Open-loop system with fresh water* • *Brine dampens the pressure on the concrete shell*	• Construction to keep shell in place • Soft bubble for the primary size of the shell • Shotcrete for the strength of the shell when depressurized • Underground station • Connection underground station to surface water system • Pipeline connecting underground station with concrete bubble

When the bubble achieved its final size, shotcrete is applied unto the inside of the bubble to give it its strength. This way, the size and shape of the concrete structure is better controlled and able to withstand larger forces. Also, the pressure from the brine is lower than the geostatic pressure from the cavern would be.

The downside is that the cavern will shrink, but only slowly.[8] This PHS will act the same way as most facilities around the world, which makes this a very safe and proven part of the technology. The efficiency has already been proven to be high compared to other, upcoming forms of large scale energy storage. Together with the potentially large capacity of the cavern this can lead to a large energy storage capacity.

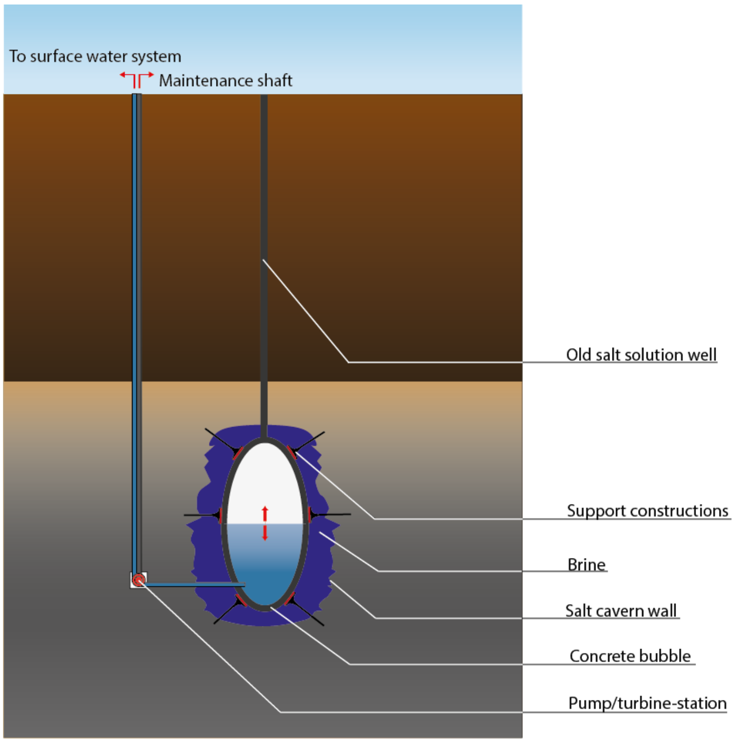


FIGURE 17 - SCHEMATIC OVERVIEW OF THE PHS CONCRETE BUBBLE-APPROACH

The size of the Pump turbine may become problematic. The need for a space reserved for the pumps and turbines will need additional attention. The easiest, but perhaps more expensive solution involves the excavation of another underground space on a comparable level to the cavern. This would give major space restrictions to the amount of pumps and turbines, as it is very expensive to construct such a room. The machines would have to be Pump turbines to save space and a trade-off is necessary with the additional power output of an extra Pump turbine on one hand and the costs of additional space on the other.

Another unknown is the strength of the shotcrete and what kind of dimensions of the concrete shell can be constructed using current technologies. The forces and needed thickness will increase disproportionally compared to the size of the concrete shell.

Concluding, there are several unknowns which need additional research before the PHS Concrete Bubble can be seen as profitable investment. However, it definitely seems promising, as all of these

[8] As researched by (Berest, 2001): Geostatic pressure is 20.5 MPa, stabilised brine pressure: 13.0 MPa. Number of years before cavern is totally closed is expected to be around 5,000 years.

blind spots can be solved with current technology and the main concept of Pumped Hydro Storage is kept simple and completely intact. The challenge will mainly concentrate at the construction phase, as the operation is fairly easy and low-risk. In the following table, the main advantages and disadvantages of the use PHS Concrete Bubble are stated.

TABLE 7 - ADVANTAGES AND DISADVANTAGES OF THE PHS CONCRETE BUBBLE-APPROACH

Advantages of PHS Concrete Bubble
+ Division between substance and cavern wall makes atmospheric pressure possible, which means better efficiency, less risk and no constant air-tight system needed
+ No second reservoir at surface needed
+ Works according traditional Pumped Hydro Storage, proven and low-risk
+ All the water inside shell is usable and optimal head difference possible, which leads to the maximum amount of energy storage capacity.
Disadvantages of PHS Concrete Bubble
- Large construction needed inside salt cavern
- Significant additional research needed (e.g. construction, stabilisers)
- Underground station hard to implement into idea
- Complicated construction phase

3.3.2 PHS Pressure Cavern

Pressure Cavern is a straightforward design that combines the use of gas pressure and the production of electricity through hydropower. With minimal underground adjustments, the salt cavern is turned into a working energy storage facility.

TABLE 8 - THE MAIN CHARACTERISTICS AND NEEDED COMPONENTS OF THE PHS PRESSURE CAVERN-APPROACH

Characteristics	Construction components
• *Cavern partly filled with brine and water. Air-tight well cap keeps the pressure in the cavern.* • *Closed-loop system with brine-reservoir at the surface.* • *Surplus energy pumps brine into cavern, with higher air pressure as a result.* • *Pressure build-up pushes brine past turbine at the surface to generate electricity* • *Minimal underground constructions needed*	• Air-tight well seal • Extended pipe from surface to salt cavern brine • Surface reservoir • Surface constructions with Pump turbine

When Table 8 is compared with Table 6, the most striking difference is clearly the small amount of construction components of the PHS Pressure Cavern-approach. It avoids the underground station and large cavern alterations. The salinity is guaranteed by using brine as liquid. In combination with the trapped air and pressure-measuring devices, this will assure that the pressure will not fall below the minimum needed value.

The concerns of this approach are not linked to the construction part but the operation part. By filling only a part of the cavern, the capacity is limited. This is decreased further by the necessary minimum pressure and the fact that some of the pressure is already needed to push the brine up to the surface where the Pump turbines are. This has an effect on the efficiency and storage capacity and additional research should point out how much profit can be made using this approach.

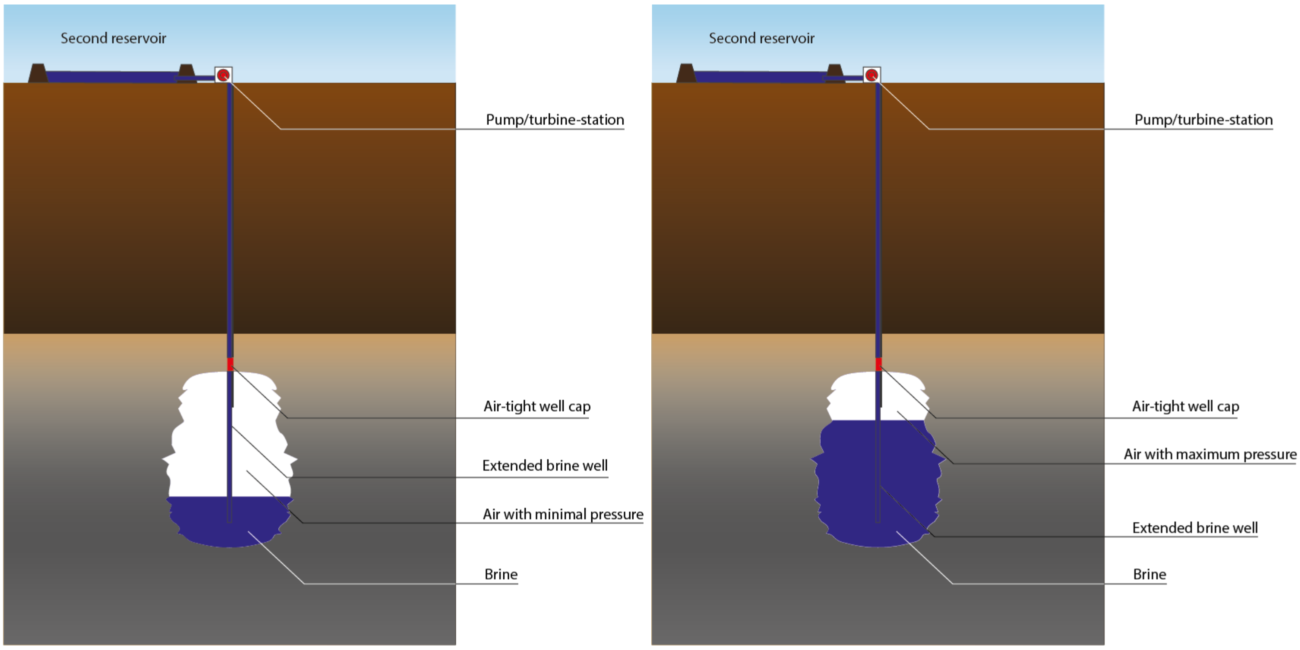


FIGURE 18 - SCHEMATIC OVERVIEW OF THE PHS PRESSURE CAVERN-APPROACH WITH BRINE AT LOW-LEVEL AND BRINE AT HIGH-LEVEL

Construction, which is mostly on the surface, is easier and faster. This limits the idle time of the salt cavern and the time between investment and first profit. The investment costs will also be relatively low, because only known structures and concepts are used. By avoiding underground constructions and placing all constructions on a place where they are easy accessible and maintainable, the project risk is minimized. This project risk is also very important when assessing the profitability of a project.

The surface storage reservoir will have to be taken into account. Although it will be significantly smaller than it would have been under normal Pumped Hydro Storage circumstances, it still demands considerable space. In conclusion, this approach offers a low cost, low risk solution with a smaller capacity and a larger surface impact. The economic profitability is questionable, but could possibly be optimised further with a better pressure-brine management. The following table shortly restates the main advantages and disadvantages of using the PHS Pressure Cavern-approach.

TABLE 9 - ADVANTAGES AND DISADVANTAGES OF THE PHS PRESSURE CAVERN-APPROACH

Advantages of PHS Pressure Cavern
+ Very limited (underground) constructions needed
+ Low project costs
+ Low project risks
+ No risky/developing construction components needed
Disadvantages of PHS Pressure Cavern
- Small capacity
- Probably low roundtrip-efficiency
- Surface reservoir needed, limits possible locations
- Relatively high surface interference

3.3.3 PHS Pressure Barrels

The third approach is called the PHS Pressure Barrels-approach, which is characterised by flexibility. Based on a developing energy storage system, this approach provides a modular kind of storage, which makes the technology suitable for all kinds and shapes of salt caverns. The PHS Pressure Barrels does not use one big compartment like the PHS Concrete Bubble does. Instead it uses prefab modules, which are lowered down into the cavern, for both the Pump turbine and the storage capacity. This has some important consequences. The most important characteristics are stated below in Table 10.

TABLE 10 - THE MAIN CHARACTERISTICS AND COMPONENTS OF THE PHS PRESSURE BARRELS-APPROACH

Characteristics	Construction components
• *Cavern filled with brine* • *Steel storage modules are let down through extra-large bored shaft* • *Pump turbine module is connected to storage modules. Water is let in when energy is needed and pumped out into the cavern when abundant*	• Extra-large borehole • Storage modules • Pump-turbine module(s) • Connection between modules and between module and surface • Surface reservoir

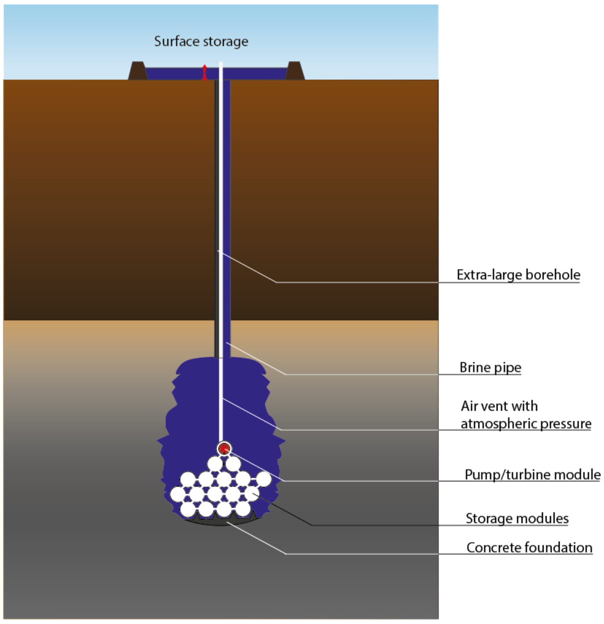


FIGURE 19 - SCHEMATIC OVERVIEW OF THE PHS PRESSURE BARRELS-APPROACH

The most important costs will consist of the construction of the borehole and the modules. The borehole will have to be enlarged significantly, until an entire module can fit through. The optimal size of a module should be calculated by comparing the additional cost of a larger borehole in comparison to the costs and risks of more connections and material. Another decisive factor is the Pump turbine. To maintain the strong points of this approach, the Pump turbine should fit inside one or two of the modules. The result is a system that can easily be applied on different (kind of) salt caverns. No particular size, shape or capacity is needed as the projected module size will most likely be small in comparison to the size of a salt cavern.

This 'one-size-fits-all'-approach will result into a standardized size of drill, construction methods and construction equipment. By using a Pump turbine-module and brine, the underground pump station and the salinity are not an issue. What may cause problems is the need to store the brine when the modules are filled with air, with the additional demand for a sufficiently large water column to provide the pressure of the brine onto the cavern walls and the turbine. This means that when the water is pumped out, the excess water should be stored at surface. Adding to this, a few additional challenges appear. First of all, the barrels should be lowered in a controlled way into the salt cavern, where they have to be connected watertight to avoid losses. Also, the Pump turbine-module has to be able to be taken back to the surface again for maintenance.

Summarizing, the PHS Pressure Barrels-approach can be a very promising mass-production product, where the project costs depend on a few (currently) unknown variables, like the drilling of the borehole, the assembling of Pump turbine-module and the connections. A few smart mechanical solutions could make a significant difference in the costs and profitability of the project. The table below summarizes the PHS Pressure Barrels-approach in comparison to the other solutions:

TABLE 11 - ADVANTAGES AND DISADVANTAGES OF THE PHS PRESSURE BARRELS-APPROACH

Advantages of PHS Pressure Barrels
+ 'One-size-fits-all'-solution, possibility for mass-production advantages
+ Prefab elements
+ Standardized equipment and components
Disadvantages of PHS Pressure Barrels
- Bigger borehole needed
- Several design issues that need to be solved before technology is possible
- Second reservoir

3.3.4 PHS Abandoned Mine

The last option tries to widen the view on Underground Pumped Hydro Storage by including other kinds of man-made underground height differences. The conventional mine is used all over the world in a variety of different ground-types and shapes. No moving walls or saline environment can make this option particularly interesting.

TABLE 12 - THE MAIN CHARACTERISTICS AND COMPONENTS OF THE PHS ABANDONED MINE-APPROACH

Characteristics	**Construction components**
• *Isolated underground chamber is used as lower reservoir* • *Chamber is easy accessible and can be relatively easy transformed* • *Higher chamber can be used as higher reservoir* • *challenges are mostly project-specific*	• Deep-underground chamber, isolated from ground water. • Pump turbine station • Shallow-underground chamber, isolated from ground water • Pipelines connecting the chambers with the Pump turbine

The use of conventional mines can avoid big problems caused by the specific character of the salt dome. If it is possible to find a mine that does not move under atmospheric pressure and does not pollute the water, this would lead to a large advantage over the use of salt caverns.

This will also take away the advantages of salt caverns. Because most salt caverns were constructed in the same manner, a lot of standardization is possible. Also, the geological characteristics are the very similar for most salt caverns. Thirdly, they are also roughly similarly shaped. When these characteristics cannot be taken into account anymore, the market of large-scale underground energy storage will be much more specialized. Every mine has to be investigated separately.

As most problems can only be denoted for individual projects, the most common can be discussed here. First of all, ground water can lead to big problems and a noticeable drop in efficiency. Electricity can be generated when water flows from the higher reservoir to the lower reservoir, but when the lower reservoir will slowly fill with ground water, this process will suffer large efficiency-losses. After all, this water does have to be pumped up as well. The walls can be coated with a water-resistant layer like concrete to deal with this problem. Another option, when coating is not wanted, is to concentrate on mines in geological layers that are impermeable on their own.

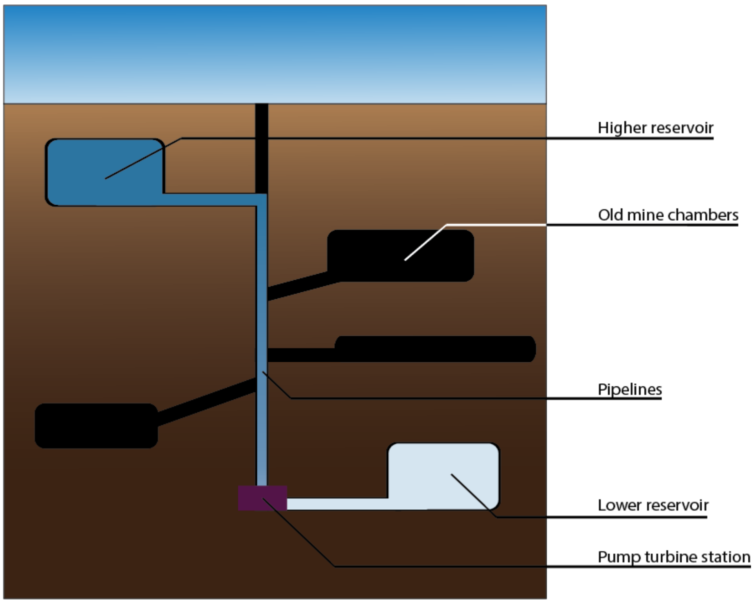


FIGURE 20 - SCHEMATIC OVERVIEW OF THE PHS ABANDONED MINE-APPROACH

One thing that would give the conventional mine an advantage over the salt cavern is the stability of the walls. Atmospheric pressure can be applied on these large depths, which greatly improves the amount of possibilities. But above all, it simplifies the situation. No minimum and maximum pressure makes Pumped Hydro Storage possible in its simplest and most-proven form. When looking at the considerations mentioned above, the PHS in Abandoned Mines can certainly be a possibility and some mines will have the right characteristics for PHS. Whether the advantages of producing without the problems of pressure and salinity is worth it, will mainly depend on the costs and benefits of this and alternative technologies. After all, all the problems and questions stated above can be solved by technology. But not for free. In the following table, the main advantages and disadvantages of the use PHS in Abandoned Mines are stated and compared with the use of PHS in salt caverns.

TABLE 13 - ADVANTAGES AND DISADVANTAGES OF THE PHS ABANDONED MINE-APPROACH

Advantages of PHS Abandoned Mine
+ No pressure-related requirements + No salinity-related requirements + Storage space is accessible to humans + Easier construction and easier maintenance
Disadvantages of PHS Abandoned Mine
- Every mine is different: • Every mine needs its own analysis • Every mine needs its own solution • No standardisation of equipment possible • Disproportional advantage to experienced companies, decreases market forces - Heterogeneous soil layers will make permeability unpredictable - Permeable layers will decrease efficiency

3.4 Comparison of options

The previous chapter introduced four possible approaches to implement energy storage by Pumped Hydro Storage with the use of salt caverns. All of them have certain advantages, disadvantages and several blind spots. As it is currently impossible to develop all the options within the framework of this thesis, a choice has to be made to find out which option is the most promising at this stage of the project. The choice will be particularly hard because of the large amount of unknowns and additional researches needed per option.

The unknown factors of the solutions and the uncertainty in the costs increase the importance of an objective consideration. Because blind spots and uncertainties cannot be quantified, a Multi Criteria Analysis is used to compare the possibilities. In this analysis, both the criteria and the given grades should be clearly clarified in order to find the most promising approach objectively. Because the criteria have different importance, a weight factor is used to make the important criteria count more. The following criteria and weight factors have been used, the percentages is the amount of the total score that comes from the criterion. The percentages are determined by comparing the criteria relative to each other. This shows for example that the lifetime costs were more important than any other criterion:

- Constructability (10%)
- Durability (6%)
- Environmental impact and surface interference (6%)
- Implementation period (4%)
- Large scale applicability (4%)
- Lifetime costs (18%)
- Risk & safety (16%)
- Roundtrip efficiency (10%)
- Storage capacity (14%)
- Technology stage & blind spots (10%)

More information on the criteria and weight factors can be found in **Appendix F**: Multi Criteria Analysis. Here, all four alternatives have been given scores on individual criteria. In the chart below, all these results are summarized.

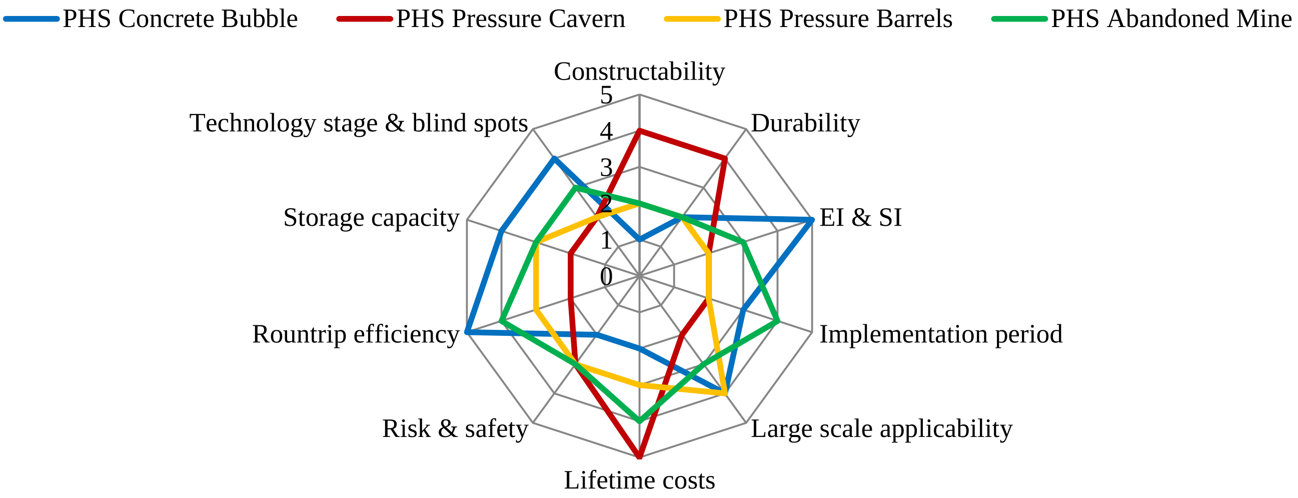


FIGURE 21 - MULTI CRITERIA ANALYSIS RESULTS FOR THE FOUR PHS IN SALT CAVERN ALTERNATIVES. SCORES ARE RATED FROM 1 (WORST) TO 5 (BEST)

After the weight factors are applied, this results in a total score for the alternatives between zero and five. The results can be seen in Table 14.

Alternative	Score
PHS Concrete Bubble	3.00
PHS Pressure Cavern	3.04
PHS Pressure Barrels	2.67
PHS Abandoned Mine	3.16

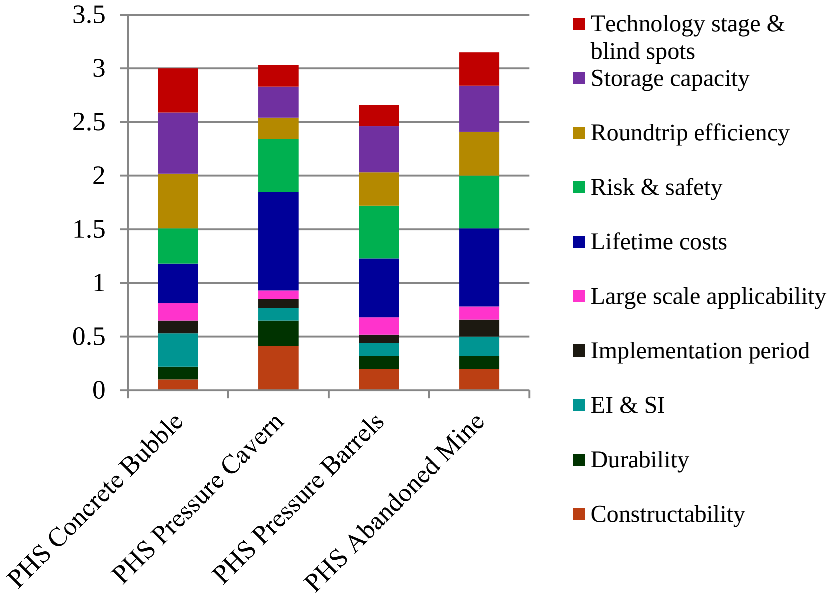


TABLE 14 - THE FOUR ALTERNATIVES AND THE SCORES FROM THE MULTI CRITERIA ANALYSIS

The figure and the table above show the scores of the alternatives and the way their scores are divided between the criteria. The arguments on which these choices are based can be seen in **Appendix F**.

The highest score is achieved by the PHS Abandoned Mine-alternative. This can mainly be explained by the diversity of this option. A good choice of mine can solve most of the problems. Therefore, the mine doesn’t score low on a single criterion. On the other side, the biggest disadvantage is PHS Abandoned Mine cannot be captured within these criteria, which is that every mine needs an individual solution. The use of salt caverns provides a solution that can be easily implemented on different locations. The diversity of conventional mines can lead to a profitable solution when one location is considered, but does not provide a structural, broad applicable solution. Therefore, this solution will not be explained further after all. It does show that more research on this topic can be interesting and the option should not be ignored when a location is set and the opportunity appears.

PHS Pressure Barrels has the lowest score by far. The disadvantages of the solution cannot be compensated by the advantages. After all, the advantage of adaptability isn’t useful when the situation is almost identical for every project. The many blind spots, components and connections make the PHS Pressure Barrels risky. It will therefore not be considered further.

The other two alternatives, PHS Concrete Bubble and PHS Pressure Cavern score almost identical. They both have clear advantages but also some weak points that need to be solved. For PHS Concrete Bubble, this mainly concerns construction and costs. PHS Pressure Cavern on the other hand needs additional research on efficiency and possible storage. Both alternatives however can result in a low-risk solution with the PHS Concrete Bubble focussing on high-efficiency pure Pumped Hydro Storage and PHS Pressure Cavern focussing on easy-to-construct, pressure-based energy storage.

3.5 Preliminary design choice

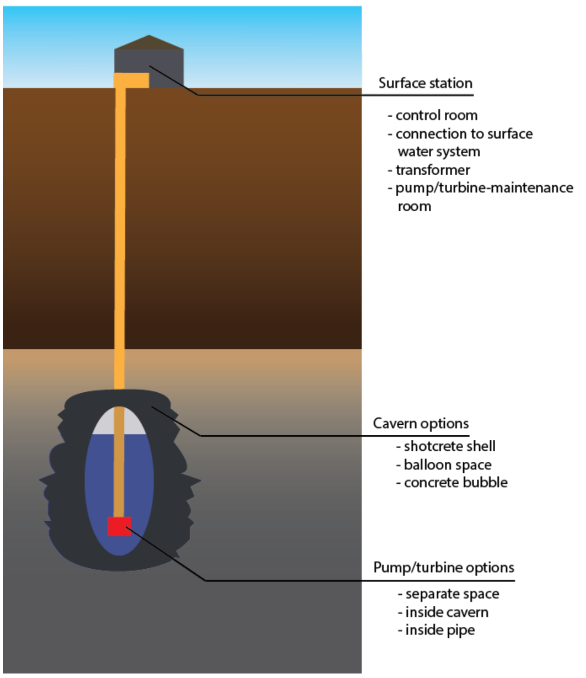
One most promising solution has to be chosen out of these two possible alternatives. The choice can be clarified by further developing both options one design step further. This conceptual design phase will not be mentioned extensively in the main report. Therefore **Appendix G** and **Appendix H** can be consulted for more information about this design step and the choices that lead to the conclusions formulated below.

In short, both alternatives have been developed one design step further, with special care to parts of the project that were marked as bottlenecks earlier. For the PHS Concrete Bubble, this included the structural requirements of the cavern adjustments and its construction. The PHS Pressure Cavern-alternative required more information on the operational scheme and the borehole.

This conceptual stage resulted in a technically challenging and economically unfeasible structural design for the PHS Concrete Bubble. Because of the large pressures acting on the concrete, several meters of concrete is needed to keep the concrete in place. Other measures like struts or a layer of brine could limit the thickness but also lead to significant constructability challenges. The outside forces require large amounts of concrete and limit the amount of water that can be stored inside the cavern, which has significant negative effects on the projects profitability. The costs estimates run up to several hundreds of millions of euros, while the revenues diminish with the smaller amount of water storage.

On the other side, the PHS Pressure Cavern keeps its promising profile. The operational scheme shows that only a small portion of the cavern (about 10%) can be used for storage. On the other hand, the costs are also low because of the small amount of structural components. The placement of the Pump turbine on the surface shall definitely affect the profitability positively. When the costs of the borehole can be limited, this alternative could most certainly lead to a profitable solution to the energy storage problem.

Therefore, the PHS Pressure Cavern-system will be elaborated further in the preliminary design. This design phase will explain the system and its components in more detail in order to be able to estimate its potential even better.



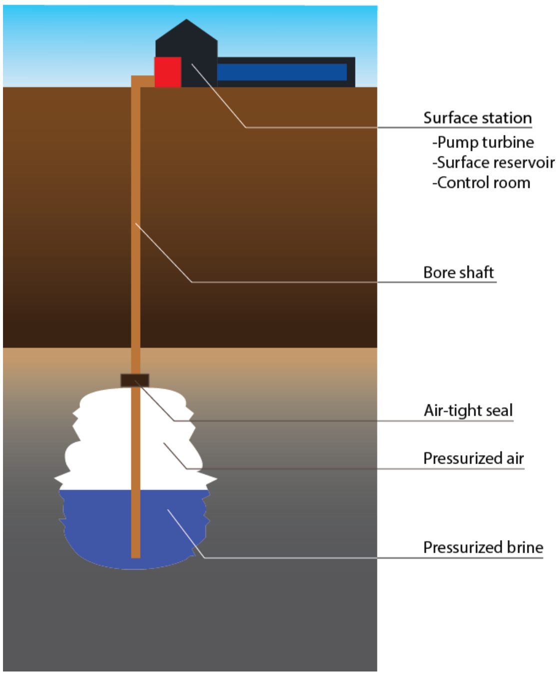


FIGURE 22 - SCHEMATIC OVERVIEWS OF BOTH THE PHS CONCRETE BUBBLE-ALTERNATIVE AND THE PHS PRESSURE CAVERN-ALTERNATIVE

4 Preliminary Design: PHS Pressure Cavern

The most promising alternatives for the use of Pumped Hydro Storage in Salt Caverns were explained in past chapters. This design phase showed that this technology could most certainly be technically possible and economically feasible. However, there are still some unknowns left that could influence the concept. These unknowns will be the main subjects of the ***preliminary design****.*

Focussing on the most promising alternative, the ***PHS Pressure Cavern-system****, this chapter will continue to go one step further. The entire system is clarified up to a level where* ***investing decisions*** *can be made. An important place is reserved for the* ***operational design*** *and* ***the risk analysis****.*

Due to its great importance, the ***economic feasibility*** *will be especially focussed upon in this chapter. Special attention will be put into the possible investing strategies. Who wants these electricity storage facilities and why would they invest? With the use of the more detailed design and a further analysis of the possible benefits, the Cost-Benefit Analysis will also be updated and improved.*

Contents:

4.1 PHS Pressure Cavern-facility

Earlier analysis showed two promising alternatives for the use of salt cavern in the search for suitable **energy storage solutions**. Comparison of the two alternatives showed a clear distinction. Where the projected bottlenecks of the Concrete Bubble-approach turned out to be unacceptable, the unknown factors of the Pressure Cavern did not affect its **potential**. This was decisively revealed with the help of the economic analysis.

Even though this was only the conceptual design and the final costs and revenues could deviate somewhat from a detailed design, the message was clear. The Pressure Cavern **outperformed** the Concrete Bubble with a clear margin.

So what makes this alternative the best solution? It distinguishes itself by relying on a totally **different principle** than the others. Instead of storing energy in the form of a high position relative to a turbine, it stores energy in the form of **pressure**. Although this limits the portion of the cavern that can be used for storage, this is made acceptable by the advantages of the system.

The advantages are numerous and relevant. The first and foremost is its **simplicity**. Besides the construction of a shaft, no underground constructions are needed. All other components are easily accessible, repairable and replaceable. Simplicity limits the costs and the risks. The low project risk is support by the use of **common technologies.** Although the operation is very innovative, the construction is solely based on known methods and commonly used materials.

The same counts for **efficiency**. Although the components have never been used in this configuration before, they have been used individually. Reservoirs, Pump turbines, transformers and shafts have all been engineered and optimized before, which benefits the roundtrip efficiency.

A few challenges remain, which will all be mentioned in the preliminary design phase. As **project-related challenge**, the operational design will be clarified. This will show which pressures will be used and calculates the working head differences, storage capacity and power output. Next to the project-related challenges, the main **market-related challenges** remain. What is the appropriate place for energy storage? Which form of investing will lead to a blooming energy storage market that can last far into the future? The **preliminary design** phase will try to answer all these questions. A more detailed explanation of the system and its components can be found in **Appendix I**.

4.2 Boundary conditions

A project that affects its surroundings on both the surface and deep into the subsoil will naturally be restricted from many different sides. These conditions can be divided into natural restrictions, engineering requirements, project requirements and wishes. The PHS Pressure Cavern will mostly have to deal with natural restrictions because of its pressure-based operational system. On the other hand, also surrounding inhabitants and governments are affected and the current uses of the structural components limit the dimensions and construction methods to be used.

The most important boundary conditions of the PHS Pressure Cavern are stated in Table 15 below. It shows that the natural restrictions indeed dominate the conditions in terms of relevance. The necessary use of brine and the properties of the salt layer are given boundary conditions that cannot be changed easily.

Because no specific location has been indicated as project location, the amount of restrictions from the surroundings is still limited in this phase. The absence of the demands and wishes of the local governments and the surrounding inhabitants shows the necessity of a constantly updated list of boundary conditions, requirements and wishes. However, the preliminary design will be based on the list stated in **Appendix H.1**, of which Table 15 is a short summary.

TABLE 15 - BOUNDARY CONDITIONS, REQUIREMENTS AND WISHES OF THE PHS PRESSURE CAVERN-SYSTEM

Description	Condition	Importance
The underground condition at large depth results in high pressures on every construction. The geostatic pressure can be quantified by assuming the pressure to increase 21.6 kPa per meter depth underground.	BC.1	Natural restriction
Fresh water inside the salt cavern will react with the cavern wall, expanding it. Equilibrium exists by using brine.	BC.3	Natural restriction
The salt cavern walls are impermeable for engineering purposes.	BC.6	Natural restriction
Inside the salt cavern, a minimum and maximum pressure is present, to prevent excessive shrinkage and blowouts. These pressures are linked to the geostatic pressure as 30% and 85% of the geostatic pressure respectively. The choice for these boundaries will be explained in a later subchapter.	BC.7	Engineering requirement
The brine used inside the salt cavern has to be kept separated safely from the surface water system at all times.	BC.10	Engineering requirement
The air- and brine pressure should be monitored accurately to prevent too high or low pressures.	BC.11	Project requirement
The surface space required for the facilities should be limited as much as possible.	BC.12	Wish

The natural restrictions which are explained above in Table 15 show the way in which the salt cavern and the underground conditions affect the project and the operational system in particular. The working pressures are limited by the geostatic pressure and the properties of the salt cavern. The precision with which the reaction of the salt layer and the pressures can be predicted, reveal its largest advantage. The homogeneous nature of the salt beneath the Netherlands has been one of the main reasons to work with this particular layer. This means that most of the natural restrictions will not change when another location inside this or another salt layer is chosen.

Additional requirements that could result from interference from local governments and surrounding inhabitants will most likely result in an increase in project requirements or wishes. These conditions are assumed to mainly concern small additions or changes to the surface construction or lay-out of the facility. Therefore, the current list of boundary conditions is assumed to be sufficiently accurate to design the main concept of the system. More detailed engineering of the surface facility itself and the reservoir are more sensitive for external interference and will therefore be less relevant to work out at this stage of the research.

4.3 System analysis

The facility consists of several different structural components. The way these individual components perform and work together will be crucial in order for the concept to become a technically and economically feasible project. In short, the system consists of five parts:

- Surface reservoir
- Surface station with Pump turbine
- Salt cavern
- Connections between previous parts in the form of pipes and the shaft
- Connection to the national grid

In order to clarify the parts and their roles, a system map can be seen on the next page in Figure 23. The system map shows the three important cycles:

- Brine flow
- Electricity cycle
- Data stream

The first and all-important cycle is that of **brine flow**, denoted with the blue arrows. During one cycle the brine travels from the reservoir in the open air through the Pump turbine and the shaft down into the salt cavern and the same way back to the reservoir. Losses can occur when brine evaporates in the reservoir. This has however no effect on the efficiency of the system. It could become a problem when the amount of brine decreases too much during a long dry period, which is not common in the Netherlands. Water needs to be added in this situation to maintain salinity and to be able to keep pumping the brine.

The second cycle is the **electricity cycle**, which is the most complicated of the three. The efficiency is a very important factor. The efficiency will be investigated further later in the chapter. During the cycle from grid-to-grid, the electricity passes through the transmission tower, the transformer to the pump turbine and back from the generator to the transformer and the transmission tower.

An important service that the energy storage facility could provide is the restart during a blackout. If the grid is down, the pump turbine should be able to be controlled manually in order to provide power to the transformer. The electricity of the PTC-station and most importantly the control panel has to be connected to this transformer if the facility has to be able to run during this situation. This allows the total system to be fully independent of the situation on the grid.

The third network is the **data stream**. The control room has to be able to make decisions based on accurate knowledge of the situation inside the cavern and at the reservoir. Therefore a network of sensors is needed. In the salt cavern, near the top of the cavern, pressure and temperature sensors will provide the cavern information. Both sensors are implemented double in order to detect sensor errors. The reservoir is checked with salinity, temperature and height sensors. Cameras are also fitted to check whether waste might block or contaminate the pipeline and the reservoir.

The system map shows that the facility consists of only a few major components. Most connections can easily be implemented double, limiting the risk of failure to produce. These risks will be quantified later in the chapter. The map reveals the Pump turbine as the heart of the facility and shows that nearly the entire project is located above ground. Simplicity and redundancy will have a positive effect on both the efficiency and risk.

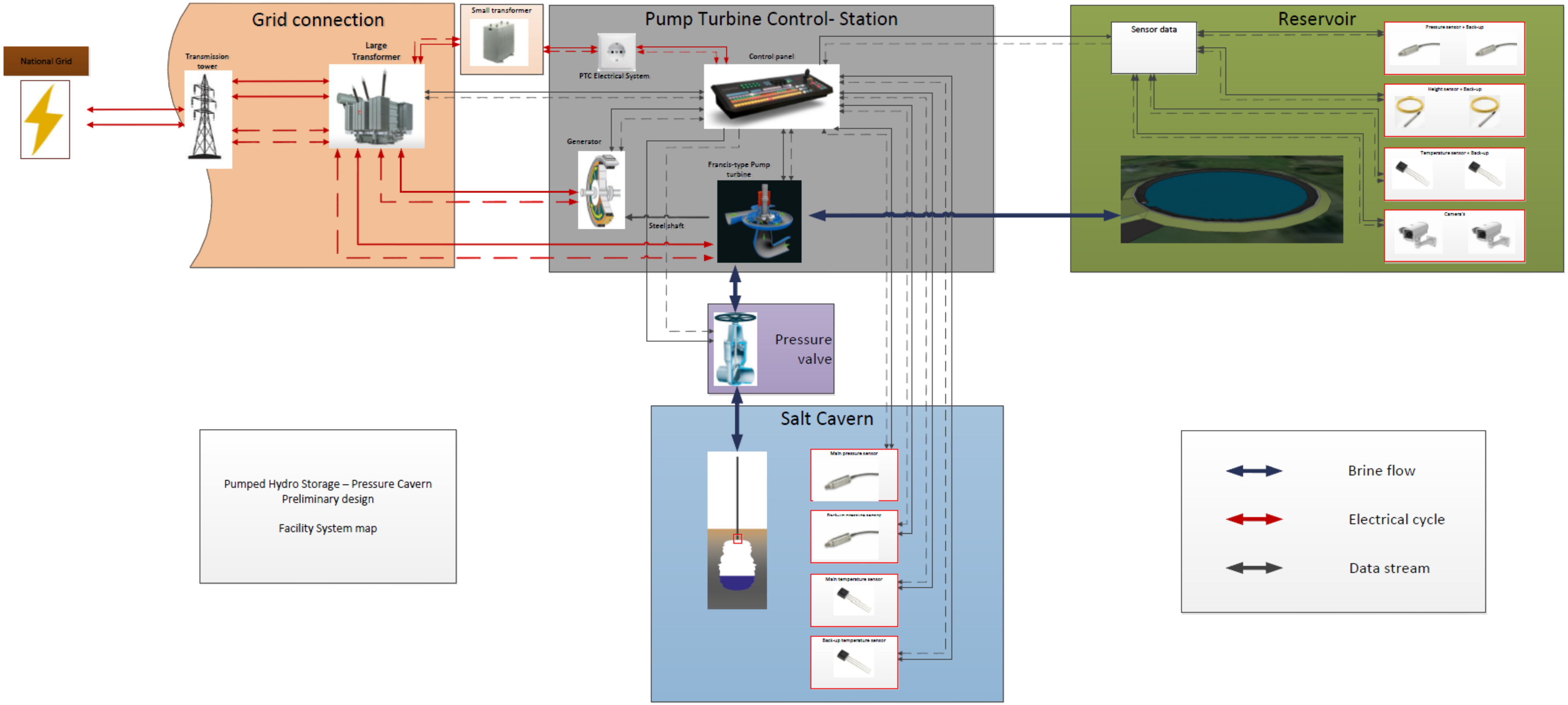


Figure 23 - System map of the components of the PHS Pressure Cavern-facility

4.4 Operational design

The key innovation of the PHS Pressure Cavern is the way it stores energy. Although both conventional PHS and PHS Pressure Cavern use a head difference to power the turbine, other methods are used to create this head difference. This is possible because hydraulic head is built up from height and pressure. Whereas conventional Pumped Hydro Storage increases the height of water to store energy, PHS Pressure Cavern increases the pressure. The facility uses and produces energy by moving between two extreme states: the uncharged, low-pressure state and the charged, high-pressure state. The main objective of the operational scheme is to maximise the amount of water that can be stored inside the cavern and therefore its efficiency. The two extreme states of the salt cavern are defined as follows:

- The uncharged state is the state where no useable energy is stored inside the cavern. The air inside the cavern is at minimum working pressure. The surface reservoir is full.
- The charged state is the state where the maximum amount of storable energy is stored inside the cavern. The air is at maximum pressure. The surface reservoir is at its lowest point.

The facility stores energy by pumping water into the cavern, increasing the amount of brine inside the cavern and the amount of space taken by the brine. This lowers the available space of the air inside the cavern, which in turn increases the air pressure. This can continue until the charged state is achieved. With the use of a cavern with assumed dimensions, a sensitivity analysis is done to reveal what kind of cavern will maximize the profitability. All calculations concerning the brine levels, pressures and head differences, as well as the sensitivity analysis can also be seen in **Appendix H.2.1** and leads to the following conclusions:

- The depth and size of the cavern have a large influence on the amount of storable energy. Especially depth is important, as there is an optimal height based on the depth of the cavern.
- The brine level inside the cavern at uncharged state should be as low as possible. Brine is nearly uncompressible and will not add to the storage space.

Based upon these conclusions, a cavern is defined with the following dimensions. The cavern height will be explained later. The shape of the cavern is assumed to cylindrical. The cavern dimensions are:

- Depth of the top of the salt cavern: $h_{top} = -900\ m$
- Diameter of the cavern: $\phi_{cavern} = 150\ m$
- Height of the cavern: $h_{cavern} = 170\ m$
- Depth of brine layer in uncharged state: $d_{brine} = 10\ m$

Operational stage

The next step is to calculate the work pressures during the operational stage. During its lifetime, the pressure inside the cavern will vary between the charged- and uncharged state. First, the situation during the charged state will be elaborated upon. Later, the uncharged state will be defined. This is more complicated, because of the different conditions that apply for the minimum working pressure. Besides the condition of minimum cavern pressure, the brine also needs to reach the Pump turbine and the pressure on the Pump turbine needs to be enough to work efficiently.

The charged state is the easiest to evaluate. It is limited by the geostatic pressure. When this pressure is exceeded, a blowout could occur. Therefore it is common practice to insert a certain amount of safety to stay below this pressure. In salt solution mining as well as other salt cavern purposes, a limit of 85% of the geostatic is proven to be safe.[9] This geostatic pressure needs to be measured, but can be assumed at

[9] These first estimates, as used by AkzoNobel, are based on an interview with Dr. R. Groenenberg from AkzoNobel Industrial Chemicals B.V. on July 30th 2014.

21.6 kPa per meter depth. The top of the cavern is the most relevant location for the pressure, as an exceeding pressure at this location will most likely cause a blowout.

$$p_{max} = 0.85 \cdot 21.6 \cdot 900 = 16.5 \cdot 10^3 kPa$$

The uncharged state is harder to determine. This follows from a number of restrictions that apply for the minimum working pressure inside the cavern. The first and most obvious restriction is the minimum pressure of the cavern itself. This was set at 30% of the geostatic pressure, or around 5.8 MPa, according to the same calculation as mentioned above. The pressure inside the cavern will push the brine up the shaft. The resulting brine level can be calculated with the formula of Bernoulli:

$$\frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 + p_{c,min} = \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + p_{atmospheric}$$

Where:

- $\rho_1, \rho_2 = the\ density\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively$ $[kg/m^3]$
- $v_1, v_2 = the\ velocity\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively$ [m/s]
- $h_1, h_2 = the\ elevation\ of\ the\ fluid\ compared\ to\ a\ reference\ plane\ at\ position\ 1\ and\ 2\ respectively$ [m]
- $p_{c,min}, p_{atmospheric} = the\ pressure\ at\ position\ 1\ and\ 2\ respectively$ [Pa]

$p_{c,min}$ is defined as the pressure that is needed to ensure the stability of the cavern. The velocities at the interface are chosen at zero, because stationary situations are considered. The situation is illustrated in Figure 24. When the other known parameters are used as input, this concludes to:

$$\rho_1 = \rho_2 = 1.20 \cdot 10^3 kg/m^3; h_1 = -1060\ m\ ; p_{c,min} = 5.8 \cdot 10^6 Pa; p_{atmospheric} = 1.0 \cdot 10^5 Pa;$$

$$0 + 9.81 \cdot -1060 \cdot 1.20 \cdot 10^3 + 5.8 \cdot 10^6 = 0 + 9.81 \cdot 1.20 \cdot 10^3 \cdot h_2 + 1.0 \cdot 10^5$$

$$h_2 = -573m$$

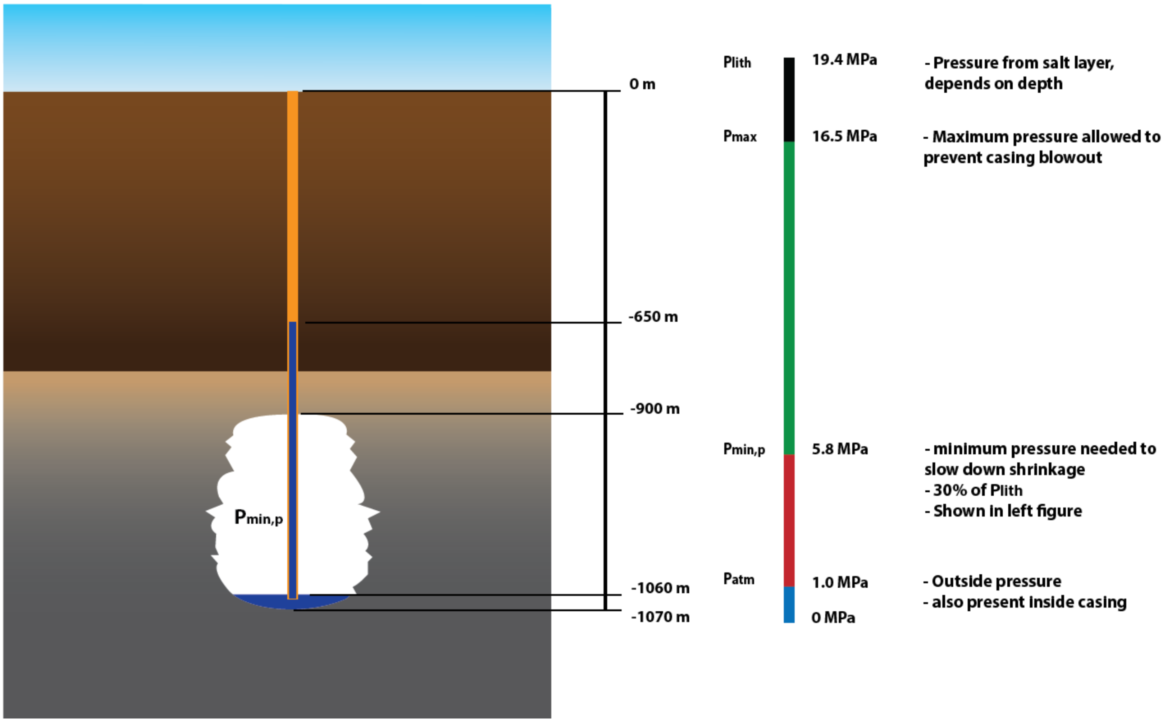


FIGURE 24 - SITUATION SKETCH OF SALT CAVERN AT MINIMUM PRESSURE

This means that at minimum pressure, the brine level inside the shaft is at -573 m. At this state, it is impossible to use the Pump turbine, which leads to the second restriction. In order for this to work, brine has to reach the Pump turbine itself. Therefore, additional pressure inside the cavern is needed to keep the brine level at least at Pump turbine-level. This pressure can be found with the formula of Bernoulli by comparing the situation inside the cavern (position 1) and inside the shaft (position 2).

$$\frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_e + p_{min} = \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + p_{atmospheric}$$

Where:

- $\rho_1, \rho_2 = the\ density\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively$ $[kg/m^3]$
- $v_1, v_2 = the\ velocity\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively$ $[m/s]$
- $h_e, h_2 = the\ elevation\ of\ the\ fluid\ compared\ to\ a\ reference\ plane\ at\ position\ 1\ and\ 2\ respectively$ $[m]$
- $p_{min}, p_{atmospheric} = the\ pressure\ at\ position\ 1\ and\ 2\ respectively$ $[Pa]$

The h_e depends on the chosen cavern and the chosen height of the cavern and leads to a height of -1060 meters, while h_2 is the level of the Pump turbine defined at 0 m. Because the water needs to reach the Pump turbine and not more, the pressure is atmospheric pressure. Solving this equation will lead to a pressure of 12.6 MPa inside the cavern.

However, the Pump turbine does not run efficiently for all head differences. The third and last restriction is therefore based on the working range of the Pump turbine. This crucial component performs with the highest efficiency at the pump height it was designed for. As a rule of thumb, the working range of the Pump turbine is defined as:

$$\frac{2}{3} H_{max} < H_{working\ range} < H_{max}$$

Where H_{max} is the design height of the Pump turbine and $H_{working\ range}$ *is* the head difference for which the Pump turbine runs efficiently, which will both be expressed in meters of water column. The calculations done for this restriction lead to a system of four formulas that define the relation between the different variables. An important formula used below is based on the ideal gas law, which states that the pressure multiplied with the volume of a gas is constant. This is shown below as the comparison between the volume at charged- and uncharged state.

$$\frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_{t,e} + p_{t,min} = \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + p_{well,min}$$

$$\frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_{t,f} + p_{max} = \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + p_{well,max}$$

$$V_{cs} = \frac{V_{us} \cdot P_{t,min}}{P_{max}} = \left(h_{top} - h_{t,f}\right) \cdot \frac{\pi}{4} \cdot \phi_{cavern}^2$$

$$P_{well,min} = \frac{2}{3} \cdot P_{well,max}$$

Where:

- $p_{t.min}$ = The minimum pressure in the cavern needed to keep the Pump turbine running efficiently [Pa]
- $p_{well,min}$ = The minimum pressure needed at the turbine to stay within the efficient range [Pa]

- $p_{well,max}$ = The maximum possible pressure at the turbine [Pa]
- V_{us}, V_{cs} = The volume of brine at uncharged(us)- and charged(cs) state $[m^3]$
- ϕ_{cavern} = The diameter of the cavern [m]

The calculations concerning this requirement have been done in the program Maple 17. They lead to a minimal required pressure of 15.3 MPa, which is much higher than the other requirements. This value is also relatively close to the maximum value, which makes the working space increasingly small. Because these pressures cannot be changed, the amount of water displaced between these values needs to be maximized. This would mean that as little water as possible needs to be inside the cavern at the uncharged state, because of the much larger compressibility of air. To see which variables can be varied to improve the working capacity of the cavern, a sensitivity analysis has been done. This analysis calculated the amount of cavern space needed for different situations. It shows that:

- The depth of the brine level at uncharged state is crucial, this will be explained below
- The cavern should be as deep as possible, with a diameter as large as possible
- Efficiency needs special attention, because of the significant effect

The sensitivity analysis has shown that the height of the cavern needs special attention. To be more precise, the depth of the brine level at uncharged state has a significant effect on the capacity of the cavern. For every cavern depth, there is a certain perfect height. This effect occurs because the capacity of the cavern depends on both the head difference and the displaced volume. At small heights of the cavern, a small increase in height will linearly affect the head difference, because the brine needs to be pushed up the shaft further. However, the displaced volume increases relatively significant, which results in a higher storage capacity. When the cavern height keeps increasing, the pump head reacts linearly, but the increase of displaced volume decreases. This leads to a maximum storage capacity at the point where the decrease due to loss of pump head is equal to the increase due to displaced volume increase. The head difference and displaced volume for different cavern heights can be seen in Figure 25. The change of displaced volume can be explained by looking at the volume at charged state. This reacts non-linear to height changes. While the volume at uncharged state reacts linear to a height increase or decrease, the volume at charged state increases more than linear when the height increases. This leads to a slowly decreasing increase of displaced volume when the cavern height increases.

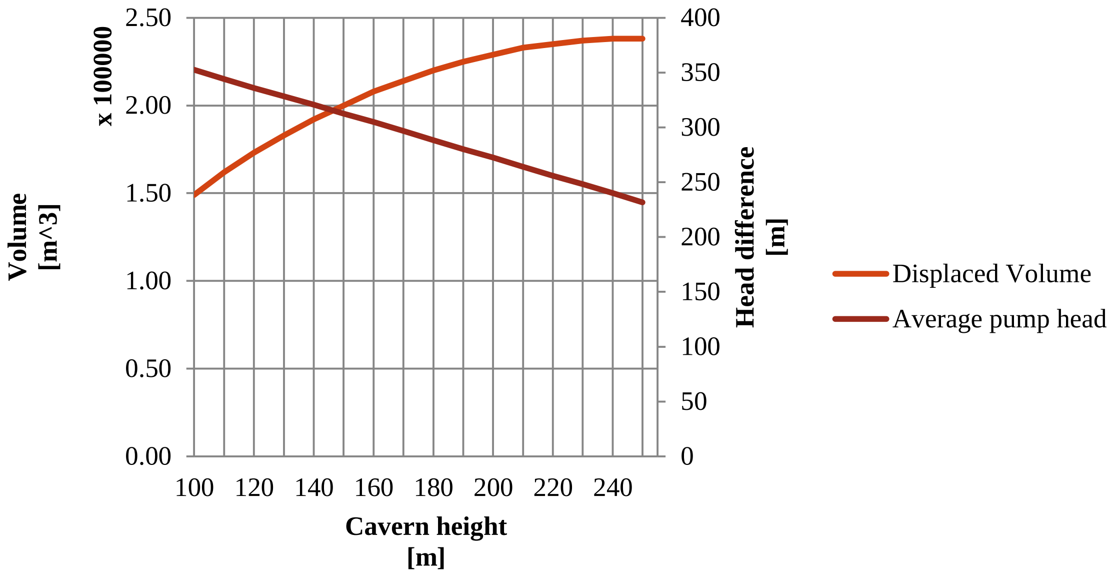


FIGURE 25 - CHANGE OF DISPLACED VOLUME AND AVERAGE PUMP HEAD FOR DIFFERENT CAVERN HEIGHTS

The cavern height projected above assumes a brine depth of 10 meters. Both the displaced volume and average pump head depend on the difference between the brine level and the top of the cavern rather than the cavern height. The optimal height difference is therefore 160 meters. Only the compressibility of air is considered in the current calculations. This means that a cavern of 170 meter with a 10 meter brine depth will lead to the same results as a 260 meter cavern with 100 meter brine depth. This may become convenient when abandoned salt cavern are projected for energy storage, because the perfect height difference can be simulated or created independent of the cavern height.

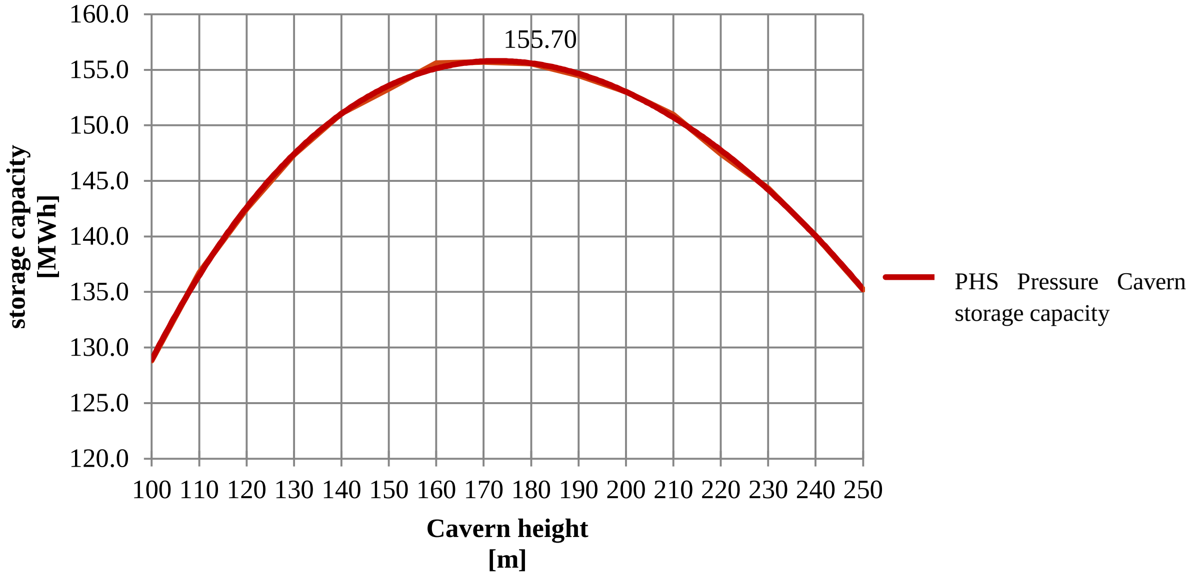


FIGURE 26 - CHANGE OF ENERGY STORAGE CAPACITY FOR DIFFERENT CAVERN HEIGHTS

Figure 26 shows the resulting energy storage capacities for different cavern heights. It is clear that there is one optimal cavern height, which mostly depends on the depth of the top of the cavern. Concluding, the following operation management scheme can be used:

TABLE 16 - BOUNDARIES OF THE PHS PRESSURE CAVERN- OPERATIONAL SYSTEM

State	Description
Uncharged State	Brine level as low as possible. Air pressure inside cavern at 79% of the geostatic pressure. Head over the Pump turbine is $\frac{2}{3}$ $of\ H_{max}$
Charged State	Air pressure as high as possible at 85% of geostatic pressure. Brine level follows from gas law. Head over Pump turbine is at H_{max}.

This operational design in based on a single cylindrical salt cavern. The use of another shape of cavern will change the operational system and its capacity. Usage of a nearby cavern to increase the operational system could also positively affect the profitability. As a first preliminary design, a single cylindrical cavern is assumed. It can be a challenge to find a salt cavern with these dimensions, as especially the diameter is not common, although not impossible as well. This has to be discussed with investing parties and salt producers in a later stage, but should be kept in mind in the meantime.

From this analysis is concluded that a cavern of 170 meters high, with a minimum brine layer of 10 meters is optimal. This will lead to a total amount of displaced brine of $V_{displaced} = 2.1 \cdot 10^5\ m^3$.

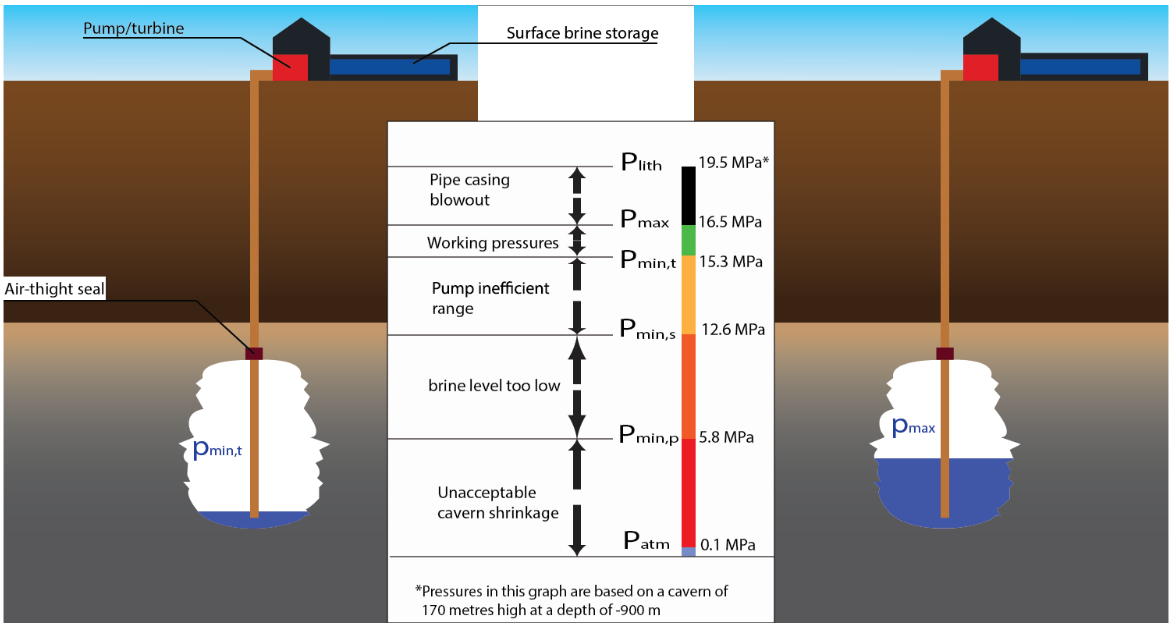


FIGURE 27 - SCHEMATIC OVERVIEW OF THE CAVERN AT UNCHARGED- AND CHARGED STATE

Storage capacity

The amount of energy that can be stored by using the cavern can be calculated by using the average head difference over the pump turbine and the amount of brine that can be moved between the cavern and the surface reservoir:

$$E_{storage} = \eta \cdot \rho_b \cdot g \cdot \Delta H_{avg} \cdot \mathrm{V_{displaced}}$$

Where:

- $E_{storage}$ is the total amount of energy that can be stored inside the cavern [MWh]
- η is the roundtrip efficiency [-]
- ρ_b is the density of the brine [kg/m^3]
- ΔH_{avg} is the average head difference over the pump [m]
- $\mathrm{V_{displaced}}$ is the volume of brine that can be moved between the reservoirs [m^3]

When the calculated values of $\Delta H_{avg} = 300m$, $\rho_b = 1200\,kg/m^3$, $\eta = 75\%$ and $V_{displaced} = 2.1 \cdot 10^5\,m^3$ are used, a total storage capacity of **156 MWh** is calculated.

Pump turbine capacity

This storage capacity has to be transported in and out of the cavern. The capacity of the Pump turbine is a very important variable when this transportation is concerned. If a Pump turbine with a high power output is chosen, more money can be earned at peak capacities. However, the salt cavern will be drained earlier. Longer duration will lead to a cheaper Pump turbine, but will lower the revenues as well. The optimal Pump turbine capacity should result from a thorough investigation on the market, its needs and what role the PHS Pressure Cavern can have inside this system.

For now, it will be assumed that the PHS Pressure Cavern should be able to run for three hours on full capacity. This way, the highest price peaks in the morning and afternoon will lead to considerable arbitrage revenues and the facility still has sufficient power output to become a significant player on the electricity market. The Pump turbine capacity will therefore be on average **52 MW**, which will vary slightly as the operation will start with a higher head difference and therefore a higher power output. This will affect the design of the Pump turbine itself, as it should be design on the highest power output.

4.5 Technical design

As has been mentioned before, the technical design will mainly focus on the structural elements of the system, because the operational scheme has already been optimized. The findings concerning these structural elements will only shortly be mentioned here. For more information, see **Appendix I**. The following elements will be worked out in more detail:

- The Pump turbine
- The shaft
- The reservoir
- The salt layer reaction

4.5.1 Pump turbine design

The heart of the system consists of the pump and the turbine capable of discharging brine in and out of the salt cavern. Besides this crucial task, the Pump turbine is also by far the most expensive element of the system. In order for it to work properly for the entire lifetime of the system, it has to cope with two problems. First of which is the pressure difference over the Pump turbine. In its design, it should be able to work with pressures comparable with 237 meters up to 356 meters of brine column. Secondly, the system needs to work with extremely salty water. Because Pump turbines are normally designed on head differences in fresh water column (instead of brine), the Pump turbine needs to be designed for a head difference between 285 meters and 427 meters.

When a system requires a pump and a turbine that can work with these head differences, a combined Pump turbine is the most common choice. The Pump turbine will work according to the Francis principle. A simple explanation of the flow through a Francis turbine can be seen in Figure 28.

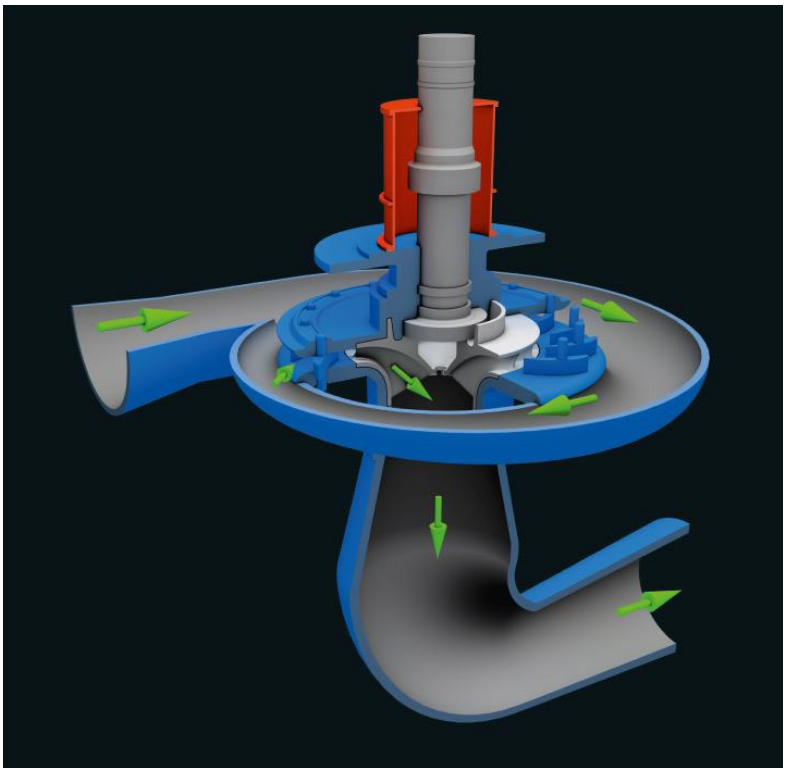


FIGURE 28 - CROSS-SECTION OF A STANDARD FRANCIS PUMP TURBINE. (SOURCE: WWW.KWM.CH)

The flow direction shown suggests the turbine-stage. Brine from the cavern enters the Pump turbine, from the left side in the figure above. From here, it enters the spiral case which spreads the brine and therefore the pressure around the runner, which is the heart of the pump turbine. The pressure from the cavern pushes the water in high speed through the spiral casing, from which it is pushed down runner into the draft tube beneath it, which ends in the reservoir. While going through the runner, the direction of the brine changes. The force exchange between the runner blades and the brine that makes this possible also turns the runner blades. The rotating runner blades are connected through a steel shaft with a generator, which is not shown in Figure 28.

By turning the shaft the other way, the runner can suck water into the pump turbine from the reservoir and pump it into the cavern. This component needs to be submerged at all times to be able to suck the brine into the runner. Another factor that has to be taken into account is the loss of pressure due to the suction. The turning runner creates a lower pressure in the brine below the runner. The brine can start to boil locally because the boiling point lowers with lower pressures, which causes small bubbles to form inside the brine. When the pressure increases again inside the Pump turbine itself, these bubbles implode causing a shockwave. This effect is called cavitation and is able to destroy the Pump turbine in a matter of days. How much this effect takes place depends on the characteristics of the Pump turbine.

It is clear that cavitation needs to be avoided. There is only one way to avoid cavitation, which is to increase the pressure of the brine at draft tube. This can be done by increasing the height difference between the Pump turbine inlet and the reservoir level. For Pump turbines this size, this difference can lead to a required height difference of several tens of meters. As the reservoir is hard to place this high above ground, the Pump turbine has to be placed below the surface. A first step is to place the Pump turbine vertically, with its highest point at the surface. This way, the draft tube will be located roughly 20-25 meters below the surface. These additional costs are included in the installation costs.

The Pump turbine needs to be designed for the top part of the head difference, as it can only handle little higher head differences and can easily handle lower head differences. Consulting a known Pump turbine manufacturer, a fixed-speed Pump turbine with design head of 420 meters is capable of handling a head of 320 meters without significant efficiency loss. With the use of a variable-speed runner, also lower heads are possible. Head differences as low as designed (285m) or even lower can be assumed to be possible without significant efficiency loss. Because the Pump turbine is designed for the top part of the head difference instead of the average head difference, the design power output is higher than the average power output. Therefore, the Pump turbine will be designed for a power output of 65 MW, while the average output will be 52 MW.

Rotation speed

An important characteristic of the Pump turbine is its rotation speed. The actual rotation speed is based on the desired specific rotation speed n_s, which has to be above roughly 30 rpm to optimize the efficiency. A specific rotation speed of 35 rpm is chosen to be on the safe side:

$$n_s = n \cdot Q^{\frac{1}{2}} \cdot H^{-\frac{3}{4}} = n \cdot 15^{\frac{1}{2}} \cdot 420^{-\frac{3}{4}} = 40\ rpm$$

$$n = 9.6 \cdot 10^2 \ \ rpm$$

This results in a design rotation speed of the runner of $9.6 \cdot 10^2\ rpm$. Because the Pump turbine is designed to have a variable rotation speed, this number can be scaled down to cope with lower head differences.

During operation, the Pump turbine will have to work with brine that has a salt concentration comparable to the Dead Sea. To avoid corrosion, a cathodic protection can be used, which means that a sacrificial metal is attached close to the runner. Another possibility is to use an electric current. Easier, but more expensive, could be to protect the components of the Pump turbine with the use of protective coating or to make these entirely out of stainless steel.

4.5.2 Shaft design

The shaft has a special place among the structural elements of the system. It connects the facility and the reservoir with the salt cavern. The required dimensions of the shaft could pose a problem, as it has to be able to transport large quantities of brine daily over a great depth underground. Calculations which are shown below can also be seen with more explanations in **Appendix I.1.**

The maximum velocity of brine inside the shaft is based on common velocities for water inside steel casings and is assumed to be 7 m/s. The needed diameter can be found with:

$$A_{req,borehole} = \frac{Q_{max}}{v_{max}} = 2.8m^2; \quad D_{pipe} = 2 \cdot \sqrt{\frac{A_{pipe}}{\pi}} = 1.9\,m$$

Where:

- $A_{req,borehole}$ is the required surface area for the design speed [m^2]
- Q_{max} is the maximum discharge through the shaft (20 m^3/s) [m/s]
- v_{max} is the maximum brine velocity through the shaft (7 m/s) [m/s]

A trade-off is necessary where a higher maximum velocity will increase the wear on the casing and the friction losses on one side and the shaft construction costs on the other side. For now, a relatively high velocity is chosen. The thickness of the casing is assumed with the use of the outside pressure. From earlier calculations this pressure at the position of the casing shoe was found leading for the design of the casing. The casing can be modelled as a horizontal ring. When one half of this ring is considered, the internal compressive forces of the steel needs to compensate the outside pressure. This is shown in Figure 29.

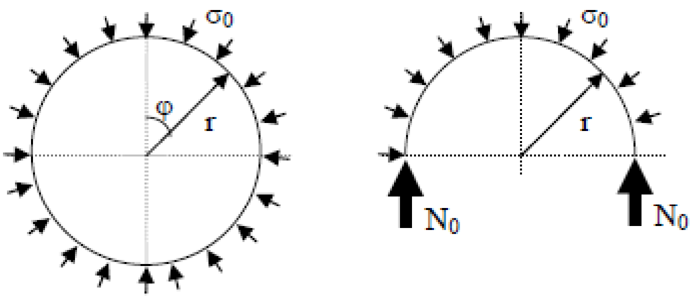


FIGURE 29 - MODEL OF THE PRESSURE FROM THE GEOSTATIC PRESSURE ON THE CASING, SOURCE: (BLOM, 2009)

For more extensive calculations and explanation on the model, **Appendix G.2.1** can be consulted. From these calculations, the thickness of the steel can be found:

$$N_0 = \sigma_0 \cdot r = 16.5 \cdot 10^6 \cdot 0.95 = 15.7 \cdot 10^6 N = 15.7 \cdot 10^3 kN$$

$$Steel\ (\sigma_y = 235\ N/mm^2): \qquad t_{steel} = 67\ mm$$

Where:

- N_0 is the internal force needed to counter the outside forces [N]
- σ_0 is the outside geostatic pressure at 900 meters depth [N/m^2]
- r, h are the radius and the modelled height (1m) of the shaft [m]
- σ_y is the yield stress of steel [N/mm^2]
- t_{steel} is the required thickness of steel [mm]

This results in the following shaft dimensions:

TABLE 17 - MAIN DIMENSIONS OF SHAFT CASING

Description	Value	Unit
Width shaft	2.00	m
Diameter casing	1.90	m
Thickness casing	0.07	m

Construction phase

These dimensions can be problematic, as the main diameter is too large for conventional bores, but relatively small for mining. There are two possible ways of constructing the shaft, which are both explained in more detail in **Appendix I.1**. The most common and best suited solution is Micro tunnelling, which uses the principles of Shield Tunnelling on a smaller scale.

The technique involves a drill head that has the right dimensions right away. On top of it, the first part of the casing is placed, which is about 10 meters long. The drill head drills a certain depth into the ground, after which a second part of the casing is placed on top. To avoid the unnecessary decoupling and re-attaching of cables every casing piece, the casing parts are divided up into two parts, which are placed around the cables and bolted together. This is repeated until the salt cavern is reached. At this point, the casing is already 900 meters into the ground and it would be impossible or uneconomical at least to retract the entire casing in order to retrieve the drill head.

To handle this problem, a retractable drill head will be used. When the drilling is done, which is when the salt cavern is reached, the drill head is able to decrease its diameter. The smaller drill head will then be pulled up to the surface through the casing. The casing will be pushed further into the salt cavern until the required depth is reached.

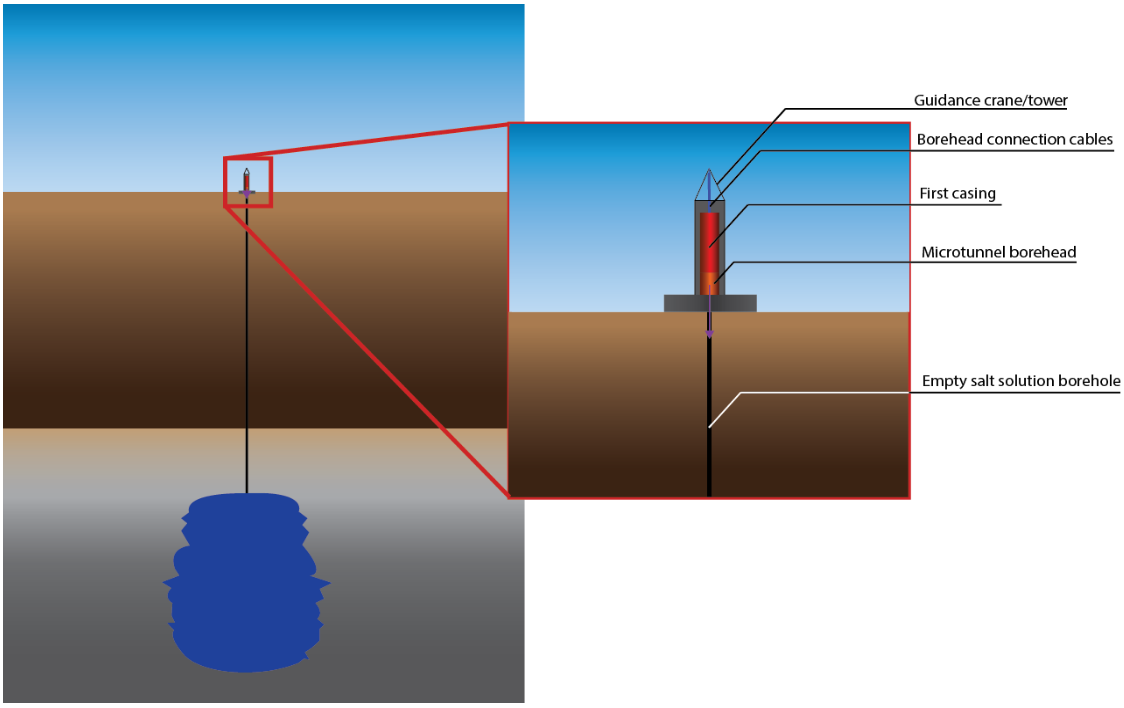


FIGURE 30 - STARTING POSITION OF THE DRILL HEAD AND THE FIRST CASING

When this form of drilling is used, the friction between the wall and the casing needs special attention. When the drill head approaches the salt cavern, roughly $5.4 \cdot 10^4\ kN$ of force is needed to push or pull the casing down. This and other calculations concerning the friction can be found in **Appendix I.1**. The required force can be lowered by using a bentonite layer between the wall and the casing.

To keep the casing lubricated along the entire height, grease fitting might have to be used on several places along the 900 meter route down. This will spray bentonite through the casing into the soil on the outside. Before completion, these grease fittings need to be removed to ensure a casing with as little friction as possible during the operational stage.

A possible opportunity to lower the costs is to use a different drilling method. Instead of shield tunnelling, also Vertical Direction Drilling or VDD can be used. This method is usually used for horizontal purposes (HDD), but can also be used vertically. It involves a gradually wider diameter cutting head, which has to be pushed down the shaft that has been made before.

When the wanted diameter shaft is constructed, the casing can be lowered down. This method is easier, faster and cheaper. However, it is significantly more risky, which makes it unacceptable to use in this phase of the project when another method like Shield Tunnelling is available.

Additional research is required to investigate the effects of construction and operation on the casing inside the cavern, where a height of almost 300 meters needs to be bridged without soil to keep it in place. Another important property of the shaft is the friction loss of the casing. The kinematic viscosity is assumed to be $\nu = 1.25 \cdot 10^{-6}\ m^2/s$, which leads to a Reynolds number of $Re = 1.15 \cdot 10^6$. When the k_s-value of steel (0.15 mm) is inserted into the Moody-diagram, the total loss of the shaft friction can be calculated:

$$\Delta H_{loss} = \left(\lambda \frac{L}{D} + \Sigma \xi_i\right) \frac{U^2}{2g} = \left(0.013 \cdot \frac{1060}{1.9} + 0\right) \cdot \frac{7^2}{2 \cdot 9.81} = 18\ m$$

This will decrease the pressure difference on the pump turbine, which will slightly decrease the power output. When compared with the head difference, this will decrease the efficiency with 4.0%. Further calculations can be found in **Appendix I.1.1**.

4.5.3 Reservoir design

The largest impact on the surroundings will result from the reservoir. The size of the reservoir depends on the capacity of the salt cavern. With the chosen values from earlier chapters are applied, more than 210,000 cubic meters of brine needs to be stored. As a shape for the reservoir, a semi-submerged round shape is used, of which the average diameter will be roughly 230 meters. The inside of the reservoir is protected with watertight geotextile, which is held in place with stone ballast. A layer of brine is present inside the reservoir to minimize the chance of contamination and to protect the geotextile, even when the maximum amount of brine is pumped out of the reservoir.

A crucial requirement of the reservoir is its ability to be watertight. The brine used in the facility has a salt concentration of 25%, which will have a catastrophic effect on nearby farmland. It is necessary for the geotextile to give a sufficient security for the entire lifetime of the facility. If this is not possible for the geotextile, another option would be to replace the upper layer below the geotextile with a sand-bentonite mixture (Oosterom, 1990). When a mixture of about 5% bentonite is used, this will act as a watertight back-up, which has already been proven as a protective layer around landfills. In the proposed design, a dike of 3.5 meters high is used and a total of $160{,}000\ m^3$ of soil has to be displaced to form the reservoir. The total surface impact will therefore consist of a circular dike with an outer diameter of 300 meters. These dimensions were chosen to provide a first estimate. A first impression of the dimensions can be seen in Figure 31. More information can be found in **Appendix I.2.1**.

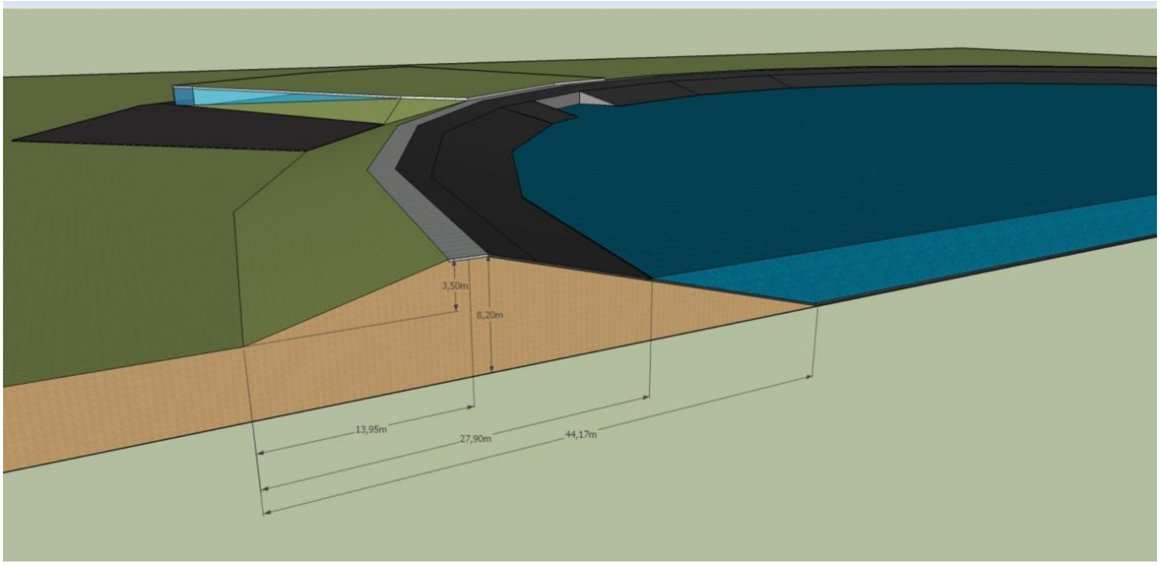


FIGURE 31 - OVERVIEW OF A PART OF THE DIKE WITH MAIN DIMENSIONS

4.5.4 Salt layer reaction

During the conceptual phase, the possible bottlenecks of the two remaining alternatives were highlighted. For the Pressure Cavern, which has shown a lot of potential, only a few smaller possible problems remained. The unknown factor which needed additional attention the most urgently was the reaction of the salt layer. Although the compressed salt is known for its homogeneous structure and its watertight property, a wrong assumption concerning its capability to perform under high pressure could instantly change the profitability of the entire project.

A new problem emerges here, as the soil reaction can only be estimated accurately with the use of geotechnical surveys. However, the homogeneous property of the salt layer allows for reasonable assumptions to be made based on experience. Companies like AkzoNobel have investigated and used the salt layer beneath the Netherlands for several times. Although the detailed design is always based on actual geotechnical surveys, the preliminary design uses assumptions based on experience.[10] All findings can be found in **Appendix I.3**. A small summary is stated below:

- The salt layer can be considered fully impermeable for all pressures below the geostatic pressure. Losses due to the salt layer reaction can therefore be neglected.
- Pressure is measured at the casing shoe, where an overpressure could become problematic when the geostatic pressure is reached. As a safe margin, the pressure is kept below 85% of the geostatic pressure.
- Any pressure below geostatic pressure will lead to creep. Shrinkage can be countered easily by inserting non-saturated brine.

These conclusions positively influence the projected profitability. Large deviations from these conclusions are not expected, as the Dutch salt layers have been investigated extensively throughout the years. Although nothing is certain until geotechnical investigations have been done, these assumptions suffice for the current phase of the project.

[10] These first estimates, as used by AkzoNobel, are based on an interview with Dr. R. Groenenberg from AkzoNobel Industrial Chemicals B.V. on July 30th 2014.

4.6 Risk analysis

The feasibility of the energy storage facility relies on the willingness of companies to invest in this innovative project. This willingness is influenced by a number of factors, among which is the risk of the concept. The risk of a facility like the PHS Pressure Cavern can be divided between internal risk, which is the risk of the facility not performing like it was designed, and external risk, which is the risk of the involved companies and governments not reacting like expected. As the internal risk can be projected and controlled for a large extent, a risk analysis can be a powerful tool to show and prove that this innovative project will not be more risky than other comparable investment opportunities.

With the use of the system map, a fault tree analysis can be made for the total system. The top event which should be avoided is named 'Failure to produce'. This is meant as a calculation of Ultimate Limit State (ULS), which means that the component in question is actually broken or altered beyond quick repair. This is chosen as opposed to the Serviceability Limit State (SLS), which accounts for smaller, temporary problems. SLS is not assumed here, because of the daily idle time of the facility, in which small repairs or replacements can easily be done. The consequence of failure has not been taken into account here. The consequences cannot be estimated with the same range of certainty as the change of failure itself. The consequences of the events with the highest chance of failure are estimated qualitatively in this subchapter. The total fault tree can be found in **Appendix I.4**. The first layer of possible events is shown below in Figure 32.

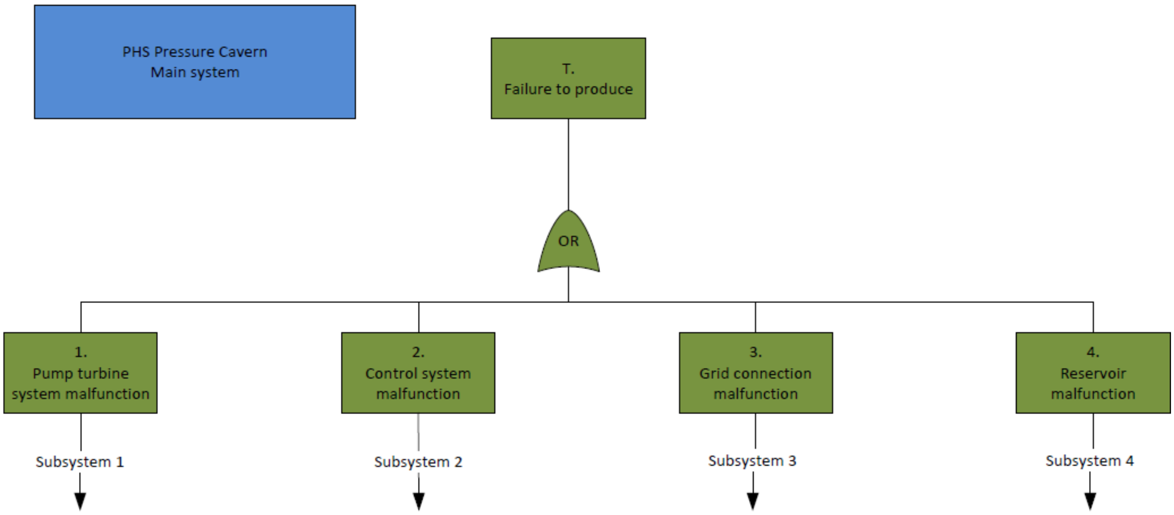


FIGURE 32 - MAIN SYSTEM OF PHS PRESSURE CAVERN FAULT TREE ANALYSIS

This first layer of the fault tree divides the risks between the four major parts of the system as shown in the system map. The possible errors are worked out in more detail in the four subsystems. This can be used to have a clear view on the weak spots of the system and where additional attention to risk reduction would be the most effective.

In the fault tree analysis, which can be found in full in the already mentioned Appendix, the risks have also been quantified. By quantifying the events up to two levels below the top event, a first estimate of the total risk is possible. This resulted in a projected risk of failure to produce of 0.0075/year, which shows that the chance of failure is rather small. Effects of wear and years of operation have not been taken into account. Figure 33 shows the division of risk between the four main components.

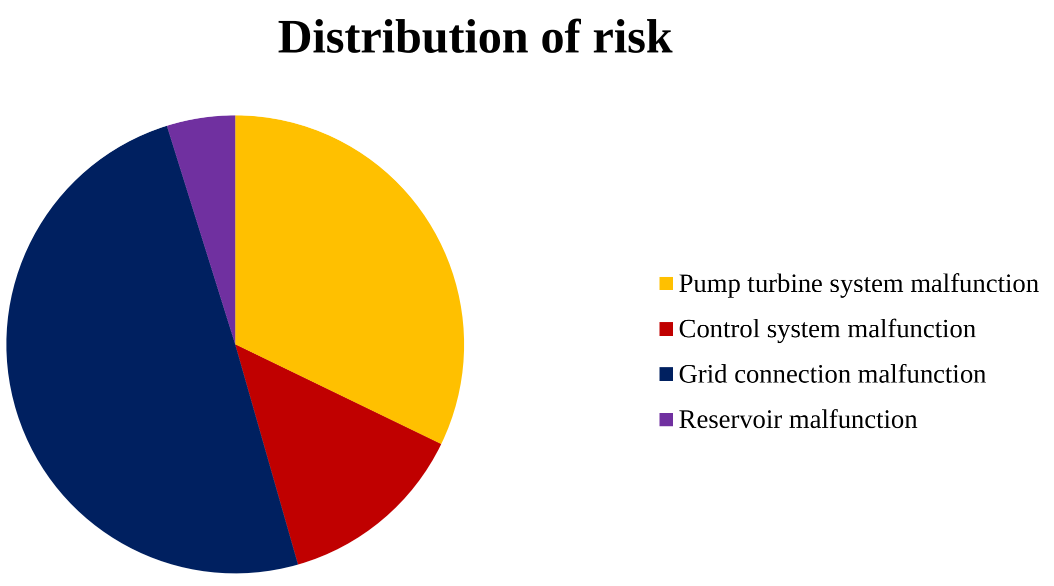


FIGURE 33 - DISTRIBUTION OF RISK BETWEEN THE DIFFERENT SUBSYSTEMS AS A PART OF THE TOTAL RISK

Figure 33 clearly shows the dependence on the Pump turbine and the grid connection. This can be dedicated to the use of a single transformer and a single Pump turbine. This can also be concluded when the three most risky events are considered. Table 18 shows these three risks and possible control measures

TABLE 18 - LARGEST RISKS OF THE PHS PRESSURE CAVERN-SYSTEM

Risk	Failure chance per year	Control measures
Transformer malfunction	$3 \cdot 10^{-3}$	Additional transformer when needed
Obstruction of pump turbine	$2 \cdot 10^{-3}$	If necessary double pump turbines or extra maintenance
Control panel connection malfunction	$8 \cdot 10^{-4}$	Additional wires for most risky connections

Whether these control measures are worth it to execute, depends on their additional costs and their ability to lower the risk. From the fault tree analysis can be concluded that the risks of a facility malfunction are low, because of the low amount of system components and the easy-to-implement additional redundancy. When the risk turns out to be too significant, it is possible to lower the risk further by focussing on a small amount of events. The current risk for severe failure (ULS) has been estimated at 0.0075 per year. When compared with the average availability of the Dutch grid, which was available for 99.9955% of the time[11], it is clear that these low failure rates are not uncommon when the electricity grid is concerned.

[11] From: Betrouwbaarheid van elektriciteitsnetten in Nederland, resultaten 2013 (Netbeheer Nederland)

4.7 Economic analysis

The new insights mentioned earlier in the preliminary design can be used to update the economic view on this project. First of all, it can be used to improve the cost-benefit analysis. The more detailed view on the system and the most important components of it will lead to a better estimate for the total costs. Another important aspect of the economic analysis is the investment incentive, which has already been mentioned briefly earlier. Whether the project will become reality, depends greatly on the question who can benefit the most from its construction and who has a company-wide incentive to build and operate such a facility.

4.7.1 Preliminary Cost-Benefit analysis

Now the dimensions and the construction methods are mostly clear, the costs and revenues of the PHS Pressure Cavern-concept can be estimated in order to get a better view on the profitability of the project. Table 19 shows the cost distribution of the facility between the five components. Of these five components, the first three are the actual construction. The fourth is the preparation, which refers to design and ground acquisition. The fifth component consists of the additional costs, which cover the unforeseen, indirect and the 'to-be-designed' costs. Further explanation can be found in **Appendix I.5**.

TABLE 19 - PRELIMINARY COST ESTIMATE FOR TOTAL PHS PRESSURE CAVERN-FACILITY

Component	Component costs [euros]	Total costs [euros]
PTC-Station	21.9 million	
Shaft	5.2 million	
Surface reservoir	2.6 million	
Preparation	6.3 million	
Subtotal costs		36.0 million
Additional costs		12.2 million
Total costs		**48.2 million**

The table shows that the Pump Turbine- and Control-Station is by far the most costly component of the total system. This is due to the construction- and placement costs of the Pump turbine itself. Another important component is the cost of the shaft. The construction method needs special care because of the unusual diameter, which requires Micro Tunnelling instead of conventional cheap drilling.

In total the costs add up to **48.2 million euros.** Whether this amount is problematic can only be concluded after reviewing the potential revenues of the facility.

The benefits can be received in the form of four revenues, two of which have not been taken into account during the conceptual phase. The possible revenues are explained further in **Appendix I.5.2**. In short, the revenues are:

- Arbitrage, the difference between off-peak and peak prices
- Fuel costs, using cheap coal or renewables instead of expensive gas
- Production deferral, less production capacity needed as peaks are lower
- Secondary services, where the facility is paid to help maintain the stability of the grid

The first and most direct form of revenue is arbitrage. After a closer look to the peak and off-peak prices for electricity in the Netherlands, a price difference of €30 per MWh is assumed to be realistic at the moment of first revenue. This is based on the average differences on the daily market and slightly increased because some of the electricity will be used at the Unbalance Market, which uses higher prices. The development of this difference over the years is still uncertain. While the appearance of energy storage could have a stabilizing effect, the planned increase in renewable energy will most likely increase the price difference. It is therefore assumed that the difference between peak and off-peak prices will grow to €45 per MWh at the end of the facility lifetime after 50 years. When the cavern is assumed to be used 95% of the days, a total of 54.1 GWh will be stored every year. This will lead to potential revenue in the first year of $54.1 \cdot 10^3 \cdot 30 = 1.6$ million euros.

The fuel costs have not been taken into account earlier, but can still lead to a significant increase in yearly revenues. It is based on the change from expensive gas powered electricity to the cheaper coal or even renewables. Predictions from (ECN, 2013) assume that this will change the costs of energy from €30.0/MWh to €12.5/MWh. A problem concerning the revenues may rise when both the production- and energy storage facilities are linked to the national grid. This will lead to unclear situations about which part of the production is stored in the cavern. Coal- and gas prices are assumed to converge over time, which will decrease the profit.

The third form of revenue is the production capacity deferral. By using the PHS Pressure Cavern-facility for peak shaving, less peak capacity is needed. This form of revenue has also been considered on reference projects, which assume a much larger decline in needed peak capacity.[12] Therefore, the assumed deferred production capacity, which was estimated to be 60% in the conceptual phase, is increased to 80% of the energy storage capacity. This is well below the percentage used in reference projects, but is assumed to be more realistic when the commitment of the producing companies is taken into account as well.

The last form of revenue is the most important addition, as it adds an entire function to the energy storage facility. The fast reaction time of the Pump turbine allows for secondary services to be provided. These services include the regulating capabilities, which can increase the stability and the quality of the grid in the form of frequency control. The stabilising services are uncommon in Dutch production facilities, as the reaction time of gas- or coal facilities is much longer. The amount of revenues is based on the same reference projects and is projected to be €190 per kW of power output used for quality control. This figure results from the reference project OPAC of Royal Haskoning, which will be further explained in Appendix I. The amounts of revenues at the beginning and at the end of the project lifetime are summarized in Table 20.

TABLE 20 - YEARLY REVENUES FOR THE POSSIBLE FORMS OF PROVIDING BENEFITS FOR THE PHS PRESSURE CAVERN

Revenue	Year 0 [euros]	Year 50 [euros]
Yearly arbitrage revenues	1.6 million	2.4 million
Yearly fuel revenues	0.9 million	0.5 million
Yearly production deferral revenues	1.4 million	1.6 million
Yearly secondary services revenues	2.9 million	2.9 million

An important assumption to note is the usage rate. These revenues assume that the total capacity of the cavern is used once every day for 95% of the days in a year. These revenues do consider some change over time, but mostly do not incorporate inflation in order to keep on the conservative side. When it is possible to benefit from all these revenues, it would be possible to generate a total of €6.8 million euros the first years of operation up to €7.4 million euros towards the end of the lifetime. Caution is needed

[12] Ondergrondse Pomp Accumulatie Centrale (OPAC). Royal Haskoning, 2006.

when addressing these revenues, as it might not be possible to benefit fully from all these forms of revenue. This will be covered later in the next subchapter.

Net Present Value

By using the costs and the revenues stated above, it is possible to update the calculation for the Net Present Value of the project. This approach is a commonly used tool to predict the profitability of the total facility. The entire calculation and other used assumption can be found in **Appendix I.5.3**.

The costs and the benefits are discounted over the years according to the principle that the value of money decreases over time. This decrease is assumed to be 8% per year, which is much higher than the inflation rate. This can be explained by incorporating the additional risk of the project. Figure 34 shows the total amount of discounted costs and benefits over the years. The benefits used in this figure assume that all forms of benefits can be used.

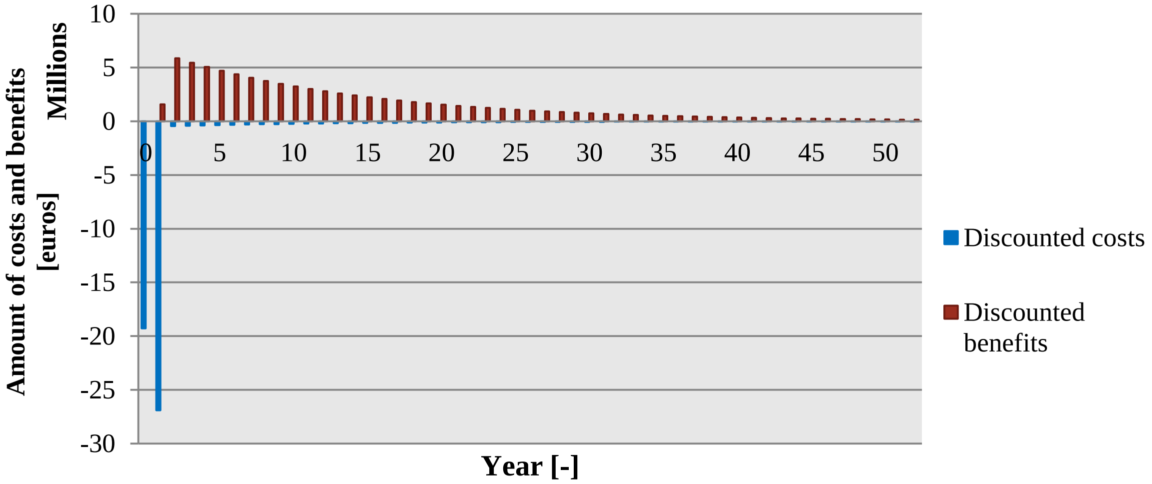


FIGURE 34 - YEARLY DISCOUNTED COSTS AND BENEFITS FOR THE PHS PRESSURE CAVERN-FACILITY

When these numbers are added, the change of profit over the years can be seen. The next figure shows the profitability of the project at full potential. However, as mentioned earlier, the possibility of missing out on one or two of the revenue sources can occur. This is also shown in Figure 35.

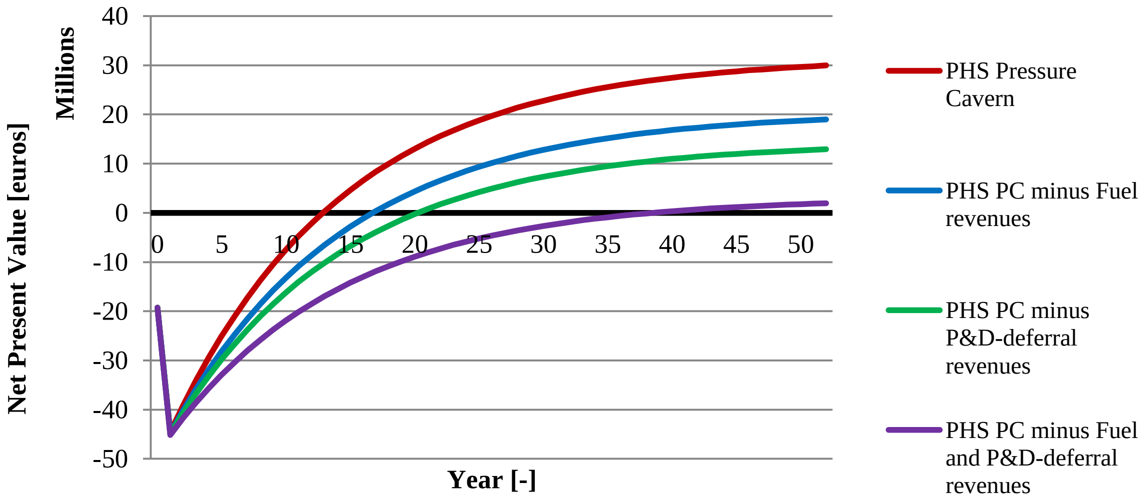


FIGURE 35 - NET PRESENT VALUE CALCULATION FOR DIFFERENT SCENARIOS OF POSSIBLE REVENUE FOR PHS PRESSURE CAVERN-FACILITY

As expected, the loss of revenue influences the profitability negatively. On the other hand, the loss of one of the revenue sources would still lead to a desirable project. The Net Present Value and the Payback Periods of these scenarios can be seen in Table 21.

TABLE 21 - NET PRESENT VALUES AND PAYBACK PERIODS FOR DIFFERENT REVENUE SCENARIOS

Scenario	Net Present Value [euros]	Payback Period
All revenues	30 million	7 years
All minus fuel revenues	19 million	8 years
All minus P&D-deferral revenues	13 million	10 years
Only arbitrage and secondary services revenues	2 million	12 years

The figures and the table show that the Net Present Value can add up to €30 million, with a payback period of 7 years. It also shows that even the loss of one of the revenue sources will lead to a positive NPV.

Concluding, the project is technically and economically feasible, given that the right revenues can be generated. This shifts the main focus of the feasibility study from the technical challenges towards the right investment planning. With the preliminary design above, it has been proven that it should be possible to build a 65 MW, 156 MWh energy storage facility with a price tag of 48 million euros, which means that it is able to generate profits. The remaining problem is to find investing companies with the right incentives and the ability to benefit from the possible revenue sources.

4.7.2 Investing opportunities

From the technical preliminary design and the cost-benefit analysis done above, it can be concluded that the energy storage facility is technically feasible and is able to generate benefits that exceed the costs of the facility. However, market parties need financial incentive in order to invest in energy storage. Until now, no storage technology was competitive enough to be able to join the actual Dutch electricity market. No energy storage is implemented on Dutch soil, as the only storage capacity is imported from Norway. A possible energy storage facility needs an extensive investment plan that clearly defines its place and role inside the many markets that supply the electricity to the Dutch consumer. First, a short overview of the electricity market is needed.

In 2004, the Dutch electricity market was liberalized as ordered by the European Union. The entire market was set free to private companies except for TenneT, the coordinating institution. TenneT supplied the high-voltage transmission and controlled the entire system. This meant that all activities (production, regional grid operation, electricity trading, linking supply and demand) had to be done by private companies. To ensure the stability and security of the grid, the following scheme is constructed:[13]

[13] Based on conversation with ir. O. Tessensohn (TenneT) on 16-09-2014

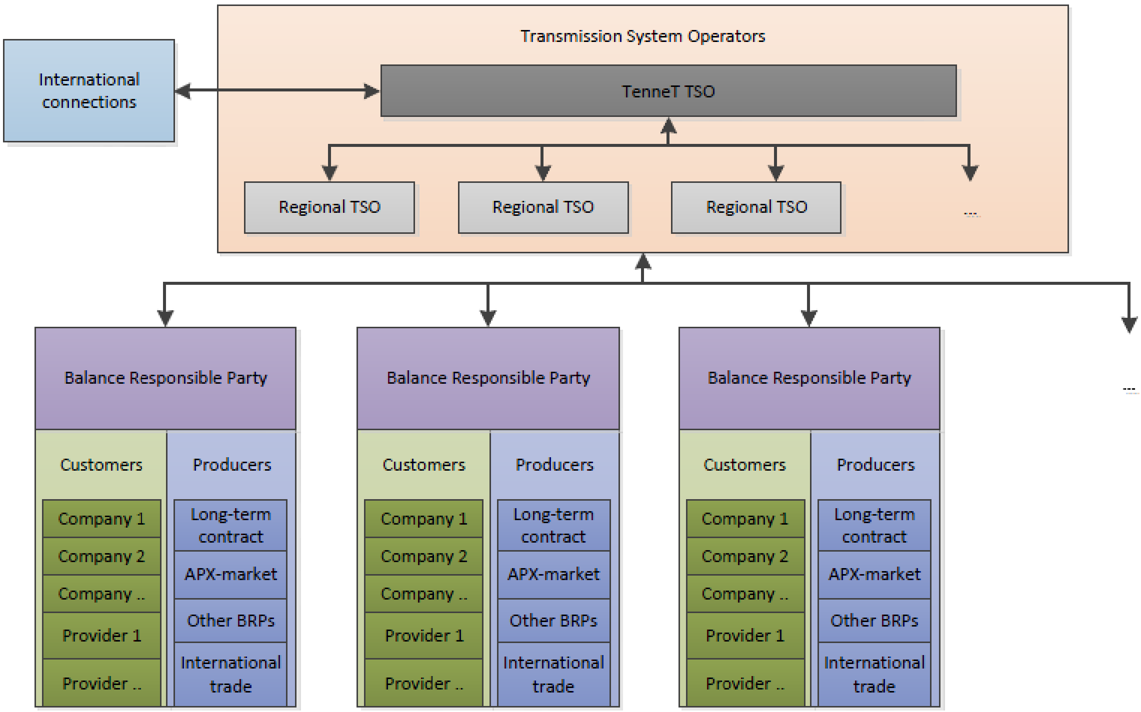


FIGURE 36 - SIMPLIFIED OVERVIEW OF THE RESPONSIBILITIES IN THE DUTCH ELECTRICITY MARKET

The Dutch electricity market

An important place is reserved for the so-called Balance Responsible Parties or BRPs. These parties can be independent, but are often part of bigger energy-related organizations, and have the responsibility to provide electricity for all customers connected to them. They have a list of companies and households (through electricity providers) connected to them which require electricity. It is their task to find sufficient electricity to fill these needs. They can provide this service by having long-term contracts with production companies, buying on the daily market (APX-market) or buying from other BRPs. Every day they have to provide a list to TenneT with the amount of electricity that will be produced and consumed for every period of fifteen minutes of the day.

During the day, both production and consumption are uncertain and will deviate from the predicted amounts. This deviation should be sorted out by the BRP itself in the first place. When this is not enough, TenneT stabilizes the grid. This is done through regulation capacity.

There are three kinds of regulation capacity. The primary regulation capacity is the fastest and the smallest part. This is meant to handle the small constant changes in a matter of seconds. To keep the grid stabilized on this scale, only small regulation capacity is needed (± 30 MW).

The secondary regulation capacity is by far the largest form. When TenneT identifies an instability that cannot be coped with by using primary regulation capacity, they turn to the Unbalance Market. Everybody with short-term available production capacity can signal TenneT and join the Unbalance Market, where they give a certain price for a particular amount. TenneT enters the amount of electricity needed, contracts the cheapest suppliers and fixes the unbalance. Prices at the Unbalance Market can vary greatly and can rise far higher than the APX-market or the long-term contracts.

The third and last form of regulation capacity is the emergency capacity. Everyone with a certain amount of production capacity can signal TenneT that they can supply whenever needed. This is capacity that is not used in normal situations. TenneT estimates the amount of capacity it might need in extreme situations and contracts several of these emergency producers. This emergency capacity has to be available at all times and is paid for this availability. Also this market is much smaller than the APX- or Unbalance Market.

European market

The most important reason for the European Union to demand liberalization was the wish for one connected European electricity market. Over the years many connections between countries emerged, starting with the collaboration between France, Belgium and the Netherlands. Ten years after the Dutch market liberalization almost the whole of Western- and Northern-Europe is connected to each other. This opens the opportunity to trade electricity from across the border, which equalizes the international electricity prizes. Every day the national Transmission System Operators (TSOs), which is represented in the Netherlands by TenneT, supply a list of expected electricity demand and possible supply, together with the associated price ranges. A central agency calculates the amount of production that should be done in which country and how the international transmission lines should be used in order to maximise the price equality in the connected countries.

This has had its impact already. Price differences between countries decreased significantly and the political decisions of separate countries affected international electricity markets. Because of three recent trends, this has negatively affected the Dutch electricity market. First of all, the price of gas has risen over the recent years. Dutch electricity became more expensive, because this market mostly depends on gas. Secondly, coal became cheaper because of the recent decline in coal facilities. Thirdly, the environmental fee on more polluting systems like coal is not high enough to discourage coal production. These three effects resulted in a much lower electricity price in coal-dependent countries like Germany than gas-dependent countries like the Netherlands. As a result, newly built gas facilities in the Netherlands are kept unused, because they cannot compete with the prices of German coal or Norwegian hydropower. Although the Netherlands has a large overcapacity of electricity production, it has still imported more electricity than exported over the last years.

Energy storage opportunities

The challenge for energy storage is to find a suitable place for energy storage in the large dynamic market of Dutch and European electricity. The Dutch market currently has no energy storage whatsoever and is constructed in such a way that storage of electricity is not needed at this moment. The complicated system of BRPs, producers and TenneT is necessary because of the inability of the grid to react to changes.

In a perfect system, such a large amount of energy storage would be available that the entire production could be spread across the day independent of the time of production or consumption. The primary regulation capacity would be unnecessary, as hydro power can react in seconds. The Unbalance Market would not be required as well, as unbalances can be handled with the use of storage. Monitoring and checking of BRPs would not be required anymore, as they do not threaten the stability of the grid. Only general monitoring of the grid and several emergency production facilities would be needed in the new, simple, but effective system.

However, the market currently has no energy storage at all and is built up in such a way that it can work without. The PHS Pressure Cavern is not able by far to supply enough storage for load levelling of the entire Dutch grid, which makes it impossible to propose a transition of the Dutch electricity market towards a more logical storage-integrated system. This means that the PHS Pressure Cavern will have to work inside the current market. For the storage facility to become profitable and to find investors, the economic strategy needs to focus on the strong points of using energy storage.

The most important service that energy storage has to offer is flexibility. It is the only form of energy production that has no losses when an amount of energy is suddenly needed earlier or later than predicted. It can solve inconsistencies caused by wrong predictions of the supply or demand of electricity. This ability can be strong incentive for BRPs or even TenneT to use energy storage. BRPs can use energy storage to keep their unbalance low and thus avoiding fines from TenneT. TenneT can use it as a way to decrease the need for the Unbalance Market.

Another advantage of energy storage is the low price. The running price of the facility is negligible. Thus the price of electricity from the energy storage facility is equal to the price of the electricity it buys, which is off-peak energy. It is possible to make contracts with wind farms and solar panels to make it able to sell all energy from renewable energy sources at peak moments. This will have a positive effect on the conventional base load facilities that do not have to worry about competing against wind farms at off-peak moments. Also, a much higher average price can be expected for renewable energy sources because only peak energy is sold. The low price will also assure its competitive place in the Unbalance Market, if it chooses to enter.

Next to the obvious role of producing electricity when required, other tasks can be done as well for small revenue. The first additional task it can do is to provide emergency capacity. In order to do this, a part of the storage capacity has to be unused until required, for which the facility gets paid. The second possible additional revenue is by providing blackout-recovery services. Because the facility can run independent of the grid, it can be used to return the first needed amounts of electricity when the country faces a blackout.

In short, the following possible roles are possible for energy storage facilities:

- As pure off-peak consumer and peak producer
- As additional flexibility for the BRPs
- As line of defence against instabilities for TenneT
- As producer on the Unbalance Market
- As provider of emergency capacity
- As provider of blackout-recovery services

All these markets use the energy storage capacity in a slightly different manner. Finding the right division between the roles energy storage can play inside the current Dutch electricity market is essential for its profitability. A clear understanding of the (development of) prices on the different markets is required, as the storage capacity is limited. The best strategy for the storage facility to use would vary on a daily basis, depending on the amount of renewable energy, the difference between peak and off-peak prices and the amount of unbalances on the grid.

To estimate its profitability in the current market, it can be compared to other innovative technologies. One of the more commercial ones, which already has conquered a small part in the market, is AES Energy Storage, which uses batteries. As stated on its website,[14] it can reach an (advertised) cost per kW-ratio of €1000 per kW power output and €250 per kWh storage capacity. When this is compared to the numbers from the cost-benefit analysis of the PHS Pressure Cavern, the potential of the PHS Pressure Cavern becomes clear. When all benefits can be expressed in revenues, the ratio will be as low as €740 per kW output and €300 per kWh storage capacity.

It is complicated and misleading to compare different technologies purely based on these figures, because the comparison leaves out the many factors that lead to the choice of the best storage facility for that location. It should also include factors like lifetime, purpose, development phase, additional requirements, efficiency and risk. This comparison, although in need of further context, shows the

[14] AES Energy Storage, www.aesenergystorage.com/ , accessed on 17-09-2014

potential of the PHS Pressure Cavern in the current market. A shortlist of current storage facilities that are comparable in size can be seen in Table 22 below.

TABLE 22 - COSTS OF PHS PRESSURE CAVERN COMPARED TO OTHER ENERGY STORAGE TECHNOLOGIES

Description	Project costs [euros]	Storage capacity (Power output) MWh (MW)	Costs per kilowatt €/kW	Costs per kilowatt-hour €/kWh
PHS Pressure Cavern	48 million	156 (65)	740	300
Duke Energy Batteries	44 million	24 (36)	1220	1830
AES Kilroot Batteries	50 million	-(50)	1000	250
Achorage Batteries	30 million	14 (25)	1200	2140
Nevada Solar One Thermal Storage	210 million	36 (72)	2920	5830
Manchasol 2 Thermal Storage	300 million	375 (50)	6000	800
Advanced Rail Energy Storage Nevada	46 million	12.5 (50)	920	3680

Another alternative, CAES, has been left out of the comparison because of its special position and requirements. As described in **Appendix A**, CAES is no pure energy storage facility due to the need for natural gas. Cost-, efficiency- and capacity calculations can therefore change depending on which part of production is viewed. Although the amount of storable energy can be enormous[15], the lower efficiency and necessary use of expensive natural gas decrease the incentive to use CAES down to a level where only two operating plants are built in 40 years of development. New innovations can improve the technology significantly, but rely on relatively uncommon and risky methods, while the PHS Pressure Cavern is solely based on known technologies and methods.

If the potential market implementations are compared to the named benefits, it can be seen that there are some differences in the approach towards revenues. Therefore, the final profitability will not be a clear cut addition of three or four revenue sources. However, the benefits named can provide a good indication of the worth of the services delivered and will therefore act as such. Further market analysis should point out the market potential more detailed. For now, the investment potential can be estimated:

- Most probable scenario: Net present value of 15 to 20 million, payback period of 8-9 years
- Best case scenario: Net present value of 25 to 30 million, payback period of 7 years
- Worst case scenario: Net present value of 0 to 5 million, payback period of 12-14 years

Beat the market

An important remark is the presence of the market principle that is decisive in every way. When energy storage wants a place in the electricity market, it has to beat the competitors on that market. If the storage facility supplies to the APX-market, it has to beat the coal- and gas plants that are also

[15] As example, recent project collaboration is planning to enter the design of a 1.5 billion dollar, 2.1 GW, 60GWh CAES-facility in 2015 in Wyoming, USA. More information on: powermag.com/massive-wind-caes-project-proposed-to-power-southern-california/. Accessed on 06-10-2014

registered for the APX-market. When it wants to produce on the Unbalance Market, it has to be cheaper than the current regulating producers. This makes comparison to other energy storage possibilities useless, as these facilities are not the ones the PHS Pressure Cavern needs to beat in price.

The same applies for international transmission lines. A common question asked when assessing energy storage is: “why not construct a second cable to Norway, where hydropower storage is abundant?” In short, the NorNed-cable is not a competing market player. The NorNed-cable increases the maximum interchangeable production capacity, which decreases or increases the demand of TenneT on its Unbalance Market. This is an investment done by TenneT to improve the overall electrical circuit. It actually lowers the profit made by TenneT, but improves the equality of international electricity prices. Energy storage on the other hand is a player on these markets and therefore acts on a different level. Whether it will be profitable depends on the ability to beat the prices from existing production plants.

At the moment the special abilities of energy storage, which is that it can transfer off-peak production to peak moments, is not required in the current Dutch electricity market. Because of the developments of the last years, a lot of over-capacity is present in the Netherlands. Unused gas facilities can be used to handle the large peaks. Flexibility is not required yet, because the capacity of the Dutch production is far larger than necessary. This keeps the peak prices low. Also the fines for causing instability are limited, as it can always be solved easily.

When looking a decade ahead, when price differences will probably have moved in favour of gas production due to pollution taxes, the scenarios may look different. Peak demand can cause problems, as the Dutch production may not be able to handle it so easily. They will also occur more often, because of the large implementation of wind power. Price differences will most probably rise, which will influence the profitability of a possible energy storage facility. In short, there are strong signals that the PHS Pressure Cavern can find its profitable spot in the current market. The signs of the future developments show an even more optimistic chance for implementation in the Dutch electricity market of the 2020’s, which is filled with unpredictable renewable energy and potentially filled with energy storage.

A cavern-filled country

This report has shown and explained a new alternative for energy storage that is not only technically possible, but also economically feasible and is able to provide several much-needed services on the current market. It is therefore interesting to see how far the technology can stretch when found applicable. At the moment, the salt layer beneath the Netherlands stretches across three provinces. The shape and size makes the vicinity of a salt dome a necessity, as the layered salt deposits beneath Hengelo are too thin. In the salt dome, currently tens of caverns are constructed. The size of the salt dome is large enough to provide space for another large number of caverns. However, because the construction of the salt caverns themselves need to be profitable for the salt producers, a market potential of hundreds of caverns is assumed to be unrealistic. Therefore a market potential of tens of salt caverns useable for the construction of a PHS Pressure Cavern-facility is assumed in the foreseeable future. This may not be enough to structurally change the electricity market, but can most certainly have a stabilizing effect and affect the way we view the potential of energy storage.

4.8 Visualisation

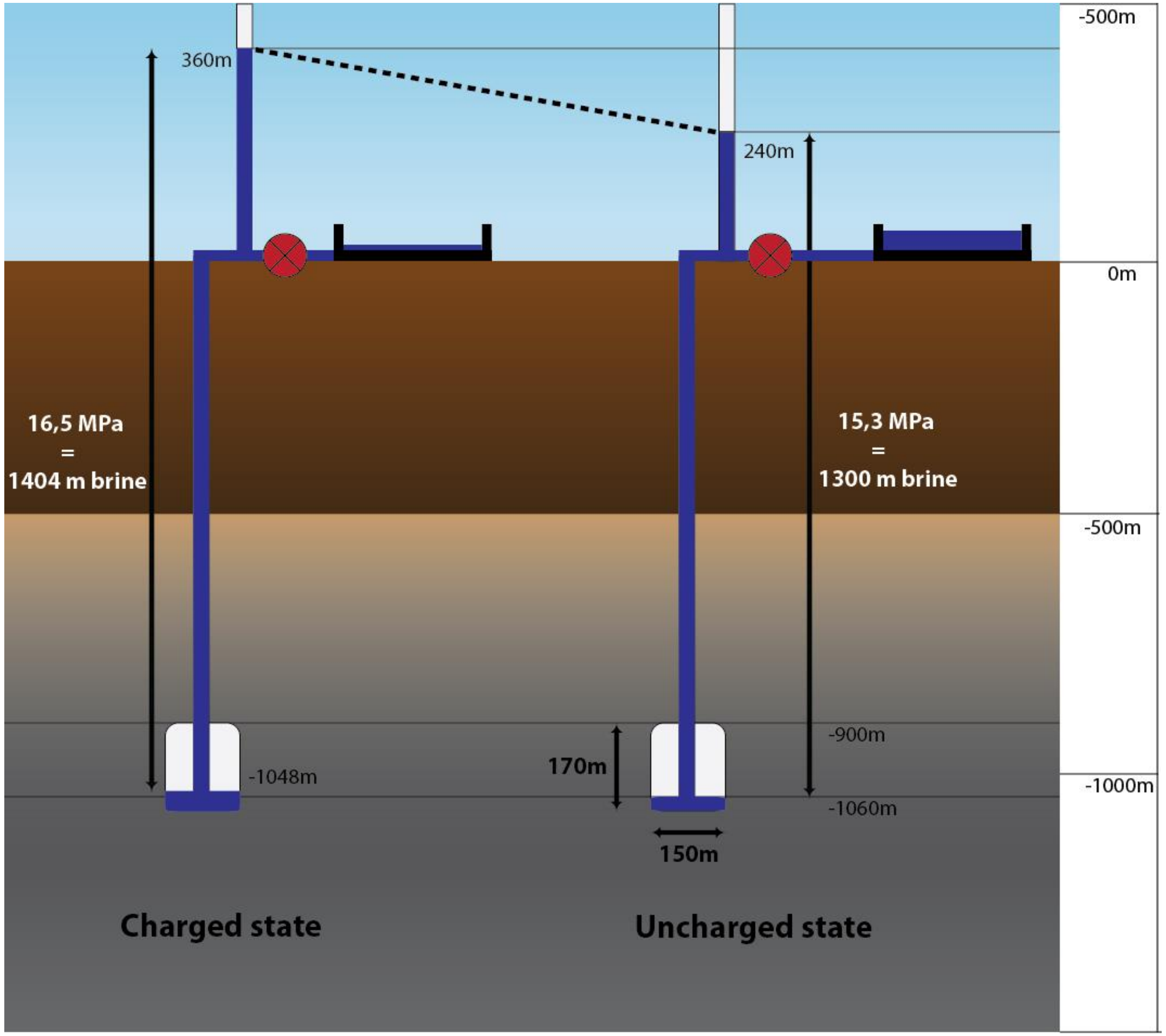


FIGURE 37 - SCHEMATISATION OF BRINE HEIGHTS AND PRESSURES AT BOTH STATES

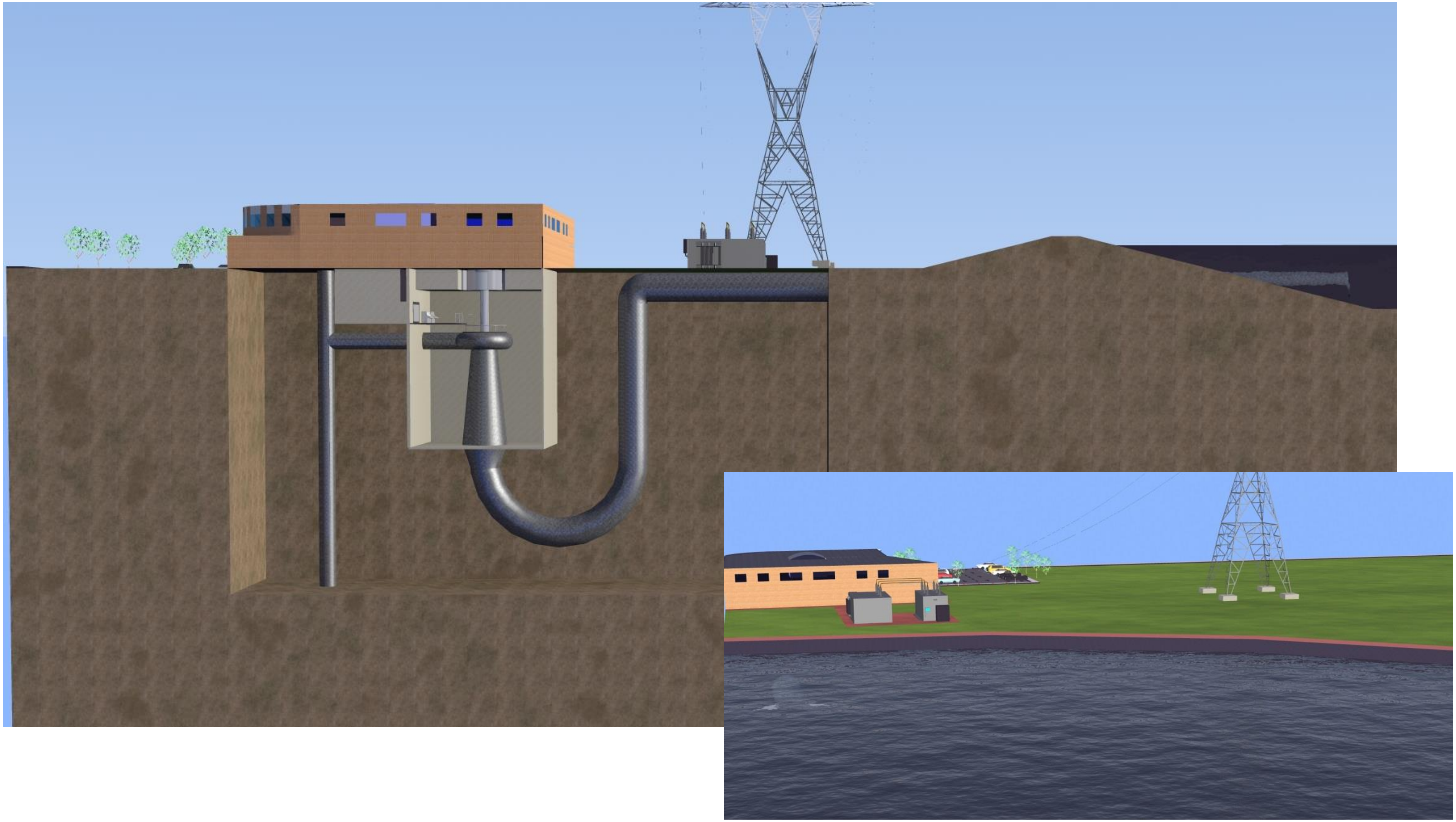


FIGURE 38 - VISUALISATION OF (SUB)SURFACE CONSTRUCTION PARTS

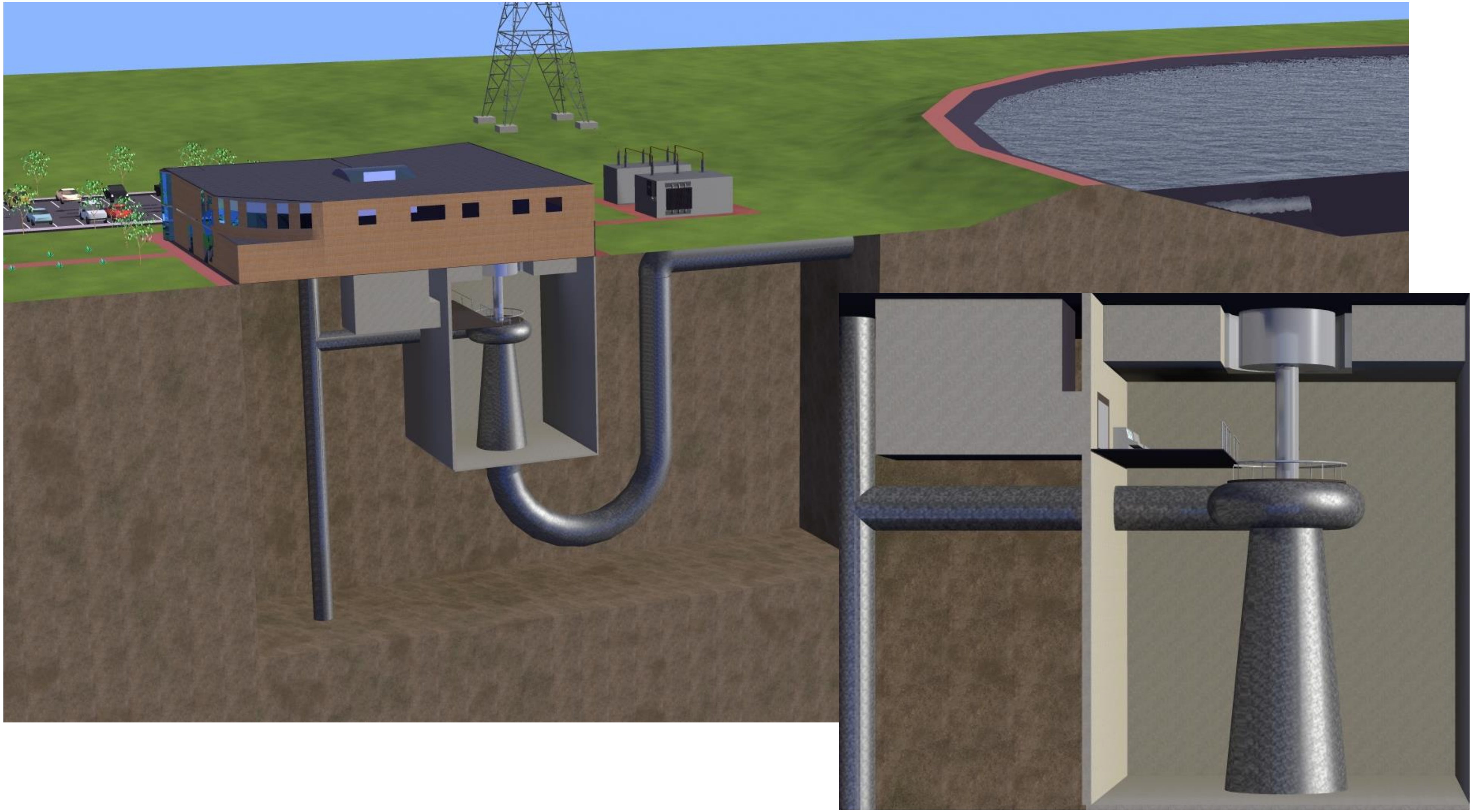


FIGURE 39 - ***VISUALISATION OF MAIN OVERVIEW***

Conclusions

This feasibility study has shown that there is most certainly potential in the idea of using salt cavern in the search for energy storage capacity. The process has been explained from the first concept up to the preliminary design. Although still several components need further investigation, the following statements can be concluded:

1. *The current worldwide energy storage capacity is dominated by* ***Pumped Hydro Storage****. Its need for large height differences and large environmental impact will make the use of Pumped Hydro Storage impossible in low-lying countries like the Netherlands. No alternative can currently compete with the profitability of Pumped Hydro Storage. Other than these alternatives, the new Pressure Cavern-concept is based on the main components of conventional Pumped Hydro Storage.*

2. *Salt caverns can be used as underground storage for different substances. The use of a salt cavern requires a minimum pressure to be present inside the cavern at all times, which makes the possibility of using conventional Pumped Hydro Storage impossible. With the use of the principle of the* ***Pressure Cavern****, it is possible to increase the pressure inside the cavern up to the point where it can be used as a reservoir with a higher energy level than a surface reservoir.*

3. *The Pumped Hydro Storage: Pressure Cavern uses a closed off cavern with a small amount of brine present inside the cavern and the rest of the cavern filled with air under pressure. At an uncharged state, the air pressure and the pressure inside the brine is able to push the brine in the bore shaft up to the surface and beyond up to a point where a Pump turbine, placed at the surface, can operate efficiently. Energy can be stored in the cavern by pumping brine from a surface reservoir into the salt cavern, which will increase the air pressure and brine pressure. At a charged state, at maximum pressure, the pressure at the Pump turbine is at its highest. The system can store* ***156 MWh*** *of energy with the use of* ***a 65 MW Pump turbine****.*

4. *The concept of the Pressure Cavern results in a* ***low risk*** *solution, as the* ***proven technology*** *of the Pumped Hydro Storage is used in an* ***innovating way****. Only a surface reservoir, Pump turbine-station and bore shaft are required next to the salt cavern itself as structural components. The main risks of further commitment to the concept are mainly based on uncertainties concerning the construction of the bore shaft and the availability of salt caverns with an appropriate diameter.*

5. *It is economically feasible to store energy in a salt cavern with the principle of the Pressure Cavern. The costs associated with the construction are estimated to be* ***48 million euros****. Based on possible benefits and their potential on the current Dutch electricity market, a yearly revenue of* ***5-6 million euros*** *is estimated, which results in a Net Present Value in the range of* ***15-20 million euros.***

Below, the conclusions stated above are explained further:

1. This conclusion is based on data provided by internationally renowned institutions. More than 99% of the current market consists of height-based conventional Pumped Hydro Storage. CAES has been found profitable. However, it does not provide pure energy storage, as it uses natural gas as well. Batteries can also be profitable, but has large environmental and safety issues. Also, it is not yet implemented on large scale. These reasons keep these alternatives from being able to compete with Pumped Hydro Storage. The concept of the Pressure Cavern is based on the idea of using the proven technology of the Pumped Hydro Storage in an innovative manner.

2. This conclusion is based on measurements on- and experience with the surrounding salt layer. The salt will act as a fluid when under high pressure. This means that the cavern will shrink when the pressure falls below the geostatic pressure.

3. All characteristic pressures inside the cavern that are necessary for complete understanding of the system are stated in Table 23. During operational stage, the pressure inside the cavern varies between the charged- and uncharged state.

TABLE 23 - CHARACTERISTIC PRESSURE OF PHS PRESSURE CAVERN SYSTEM

Description	assumption	Pressure in example cavern
Geostatic pressure	21.6 kPa/m depth	19.5 MPa
Charged state (maximum pressure)	85% of lith. Pressure	16.5 MPa
Uncharged state	2/3 of maximum head difference at the surface	15.3 MPa
Minimum pressure cavern stability	30% of lith. Pressure	5.8 MPa

4. The main characteristics of the energy storage facility can be found in Table 24. This concept is based on several structural components, which are all common technology:

- A single-stage, variable speed Francis Pump turbine with a design head difference of 420m and a design power output of 65 MW.
- A steel-lined shaft with a diameter of 1.9 m and a thickness of 0.07m, constructed with the use of Micro-tunnelling, a retractable drill head and a divisible casing.
- A surface reservoir, capable of storing the brine separated from the ground water with the use of geotextile and a sand/bentonite layer.

TABLE 24 - MAIN CHARACTERISTICS OF THE PHS PRESSURE CAVERN

Property	Value	[unit]
Cavern		
Depth	900	m
Dimensions(Diameter · h)	150 · 170	m
Diameter shaft	2.0	m
Pump Turbine		
Discharge	19.8	m^3/s
Design Power output	65	MW
Design head	420	m
Energy storage facility		
Storage Capacity	156	MWh
Running time	3	Hours
Efficiency	74	%

5. This conclusion is based on an analysis on the potential forms of revenue, their potential on the current Dutch electricity market and a comparison to some of the already implemented storage facilities around the world. When the diversity of the Dutch electricity market and their connection to the potential benefits described in the Cost/Benefit-Analysis is considered, a yearly revenue of **5-6 million** and a resulting Net Present Value of **15-20 million euros** is considered probable.

Recommendations

This feasibility study covers several steps of design and offers a closer look towards the implementation side of the story. However, many parts of the project still need more detailed designing in order to make investment decisions. The current steps have been based on common assumptions and general calculations. This is enough to see the possible potential of the facility, but may not be sufficient proof for investors that the concept will be profitable when executed in the form of a pilot plant. Therefore, several small but necessary researches need to be carried out before investors can be approached.

Recommended additional research:

- *Salt layer characteristics*; although homogeneous, the actual characteristics of the salt layer itself is not known for certain until geotechnical research is done.
- *Micro Tunnelling construction*; with better information about the soil it is possible to accurately describe the construction of the shaft, which is a crucial part of the facility.
- *Surface plant construction*; although it will not be a decisive part of the system, a design of the surface building itself and the many links between the components within can clarify the size and the connectivity of the facility as a whole.
- *Location*; a big step towards an actual energy storage facility is to find a suitable location. The location needs to accommodate the entire reservoir and should be placed above a salt cavern or the salt layer.
- *Suitable salt cavern*; calculations have shown that every depth has a perfect cavern height. On the proposed location, the salt cavern needs to be able to develop into the proposed size.
- *Grid connection*; the cavern needs to be connected to the national grid, which limits possibilities if additional costs want to be avoided.
- *Salt cavern shape*; the research conducted in this report assumes a cylindrical shaped salt cavern, which is chosen as the best shape based on qualitative arguments. Additional quantitative research might show different opportunities when using a different shape. Another interesting case might be to use multiple caverns, where one is used storage of the brine and the other(s) are solely used for air-storage.

Market-related recommendations:

- *Optimal market implementation*; the current research has named the benefits of the project and sketched the possible places that energy storage can have inside the current market. Which algorithm of possible uses is the best for high revenues, is still to be calculated.
- *Market development study*; the facility will probably not be implemented in the coming years, which means that more knowledge is needed on the developments and chances in the future.

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Programs used

- *Maple 17 (**Maplesoft**)- www.maplesoft.com*
- *Adobe Illustrator CC 2014 (**Adobe**) – www.adobe.com*
- *Sketchup 2014 (**Trimble Navigation Limited) –** www.sketchup.nl*
- *Artlantis Studio 5 (**Abvent R&D**) – www.artlantis.com*

Models used

- Office Building (Sketchup, 2014) – filip13
- Substation Transformer (Sketchup, 2014) – Martin Lelle

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NOVEMBER 2014
DELFT UNIVERSITY OF TECHNOLOGY

PUMPED HYDRO STORAGE: PRESSURE CAVERN

Appendices

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Royal HaskoningDHV

AkzoNobel

Challenge the future

A. Energy storage technologies

Below, some of the more promising and developed electricity storage technologies will be further introduced to give a clear view on the current market for electricity storage. Due to the great importance of Pumped Hydropower Storage for this research and the current market, this technology will be explained and discussed in more detail in the main report.

A.1. Compressed Air Energy Storage (CAES)

This technology uses pressure to store energy in a closed space. Practically, underground spaces have been used because these places are easy to seal. Also, abandoned mining activities have left numerous open spaces in hard soil, ideal for storage of air.

TABLE 25 - MAIN PROPERTIES OF CAES-TECHNOLOGY

BASED ON : (BEAUDIN ET AL., 2010) AND (CHEN ET AL., 2009)

Power output	5-300 MW
Efficiency	50 – 60%
Discharge at capacity	1-24+ hours
Response time	Seconds-minutes

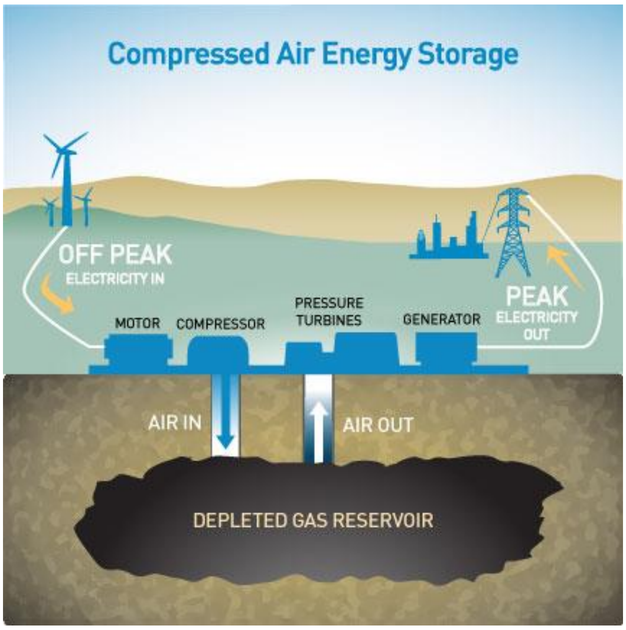

FIGURE 40 - GRAPHICAL EXPLANATION OF CAES SOURCE: PG&E COMPANY, WWW.PGE.COM

The most used function of CAES is time shifting, which can be seen in Figure 40. Off-peak electricity is used to power a compressor, pumping air into an old underground reservoir. When needed, the air is released through a series of conventional gas-turbines, which in turn power a generator to produce an additional amount of electricity during peak periods. This means that a CAES plant cannot operate on its own as a renewable energy production plant, but significantly decreases the fuel consumption of a gas-powered plant. In a new planned project in Iowa, the Iowa Stored Energy Park, this decrease in fuel consumption is estimated to be 60% compared to a system that does not use CAES through energy management (Beaudin et al., 2010).

The large possible storage capacity makes it the only large energy storage technology besides PHS. Only two plants have been constructed, built at least twenty years ago. There are several reasons that keep companies from building more storage plants, mainly concerning uncertainties, but also efficiency. Nowadays, the main concern is based on the fact that the CAES, combined with the gas-plant, does not result in totally renewable energy production and storage.

Advantages:

- Large scale energy storage capacity
- Fast response time
- Low investment costs

Disadvantages:

- Requires special location (depleted rock mines, gas fields, etc.)
- Only two completed projects
- Only possible as part of gas-fuelled plant

A.2. Flywheel

The flywheel uses kinetic energy in the form of a large spinning mass to store energy. This mechanism uses energy from the grid during charging to spin up the flywheel. This is done by an electrical motor, which also acts as a generator during discharge.

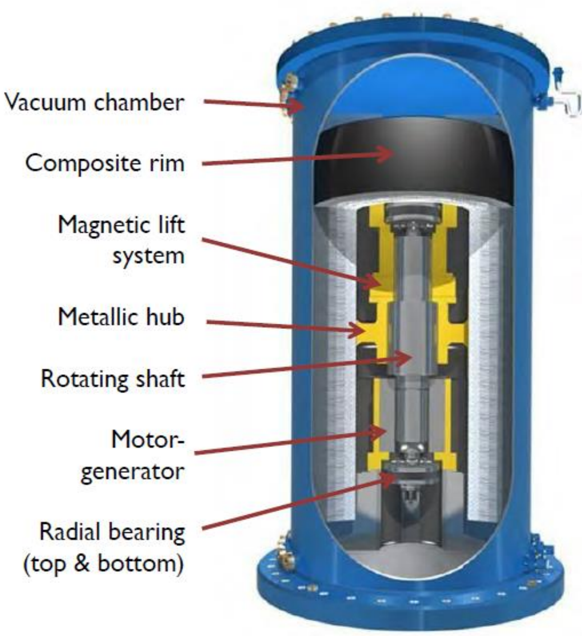

TABLE 26 - MAIN PROPERTIES OF FLYWHEEL TECHNOLOGY

BASED ON: (BEAUDIN ET AL., 2010) AND (CHEN ET AL., 2009)

Power output	Up to 250 kW
Efficiency	90-95%
Discharge at capacity	1-15 minutes
Response time	< seconds

FIGURE 41 - GRAPHICAL EXPLANATION OF FLYWHEEL TECHNOLOGY. DIFFERENT COMPONENTS ARE EXPLAINED. AN ECONOMICALLY FEASIBLE PLANT HAS MULTIPLE UNITS. (SOURCE: BEACON POWER LLC, BEACONPOWER.COM)

Due to the fast response time and the high efficiency, the flywheel is often used as a power quality measure or to bridge the gaps between changes in energy source. The low capacity and the relatively high standby losses (the loss of stored energy over time) make the flywheel unsuitable for energy management or load levelling. Flywheels are already widely used for small scale applications and may provide a solution on specialized challenges, like standardizing the energy from individual wind turbines(Abedini, Mandic, & Nasiri, 2008), but need additional research for large scale applications.

Advantages:

- Fast response time
- High efficiency
- Long lifetime

***Disadvantage*s:**

- Very small duration
- Small storage capacity
- Relatively high standby losses

A.3. Batteries

Batteries use chemical reversible reaction to store energy. This can be done on a variety of ways with different materials. Common properties include a very fast response time, slow standby losses and a relatively simple design.

TABLE 27 - MAIN PROPERTIES OF BATTERY TECHNOLOGY

BASED ON: (BEAUDIN ET AL., 2010) AND (CHEN ET AL., 2009)

Power output	Up to 40 MW
Efficiency	60-90%
Discharge at capacity	Seconds-hours
Response time	Milliseconds

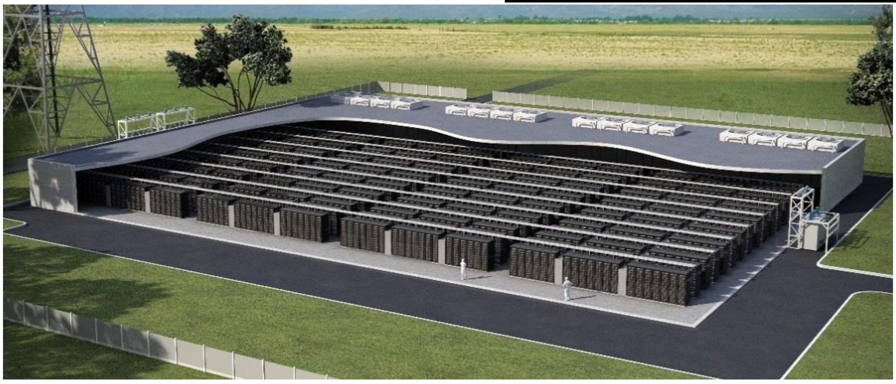

FIGURE 42 - LARGE SCALE BATTERY ENERGY STORAGE (SOURCE: A123 ENERGY SOLUTIONS, A123ENERGY.COM)

Batteries can be categorized as simple, heavy and big energy storage plants. In order to have a multiple MW facility, an entire hall is needed. The most common type of battery is the lead-acid battery, which also is the oldest. It is used for its simplicity and efficiency, but has a short lifetime and is relatively heavy. Its lifetime is mostly dependent on the amount and depth of the discharges, where full discharges can limit its lifetime significantly (Parfomak, 2012). Other possibilities include the Nickel-cadmium batteries, which has a longer lifetime, but uses the more toxic material cadmium and has a memory effect, which means that it has to be completely discharged before being recharged. A third option is the Lithium-ion batteries, which also increase to properties, but for a higher price.

A fourth common battery variation is the Sodium-Sulphur (NaS) battery. This battery has a much longer lifetime than most batteries and can handle full discharges well. The downside includes a required surrounding temperature of more than $300°C$. In order to maintain this temperature, its own energy is used, pulling down the efficiency. A second drawback is the danger for accidents, which can occur more easily in the heated environment. When the two components might mix, fire or explosions could occur.

Advantages:

- Easy to use and maintain
- Very fast response time
- Adaptable to various situations

Disadvantages:

- Short lifetime
- Heavy components
- Each alternative has significant drawbacks

A.4. Hydrogen fuel cell

The use of hydrogen fuel cell to store energy means that electricity and water is used to make hydrogen and oxygen. The hydrogen is stored and when electricity is needed, it is guided back into the fuel cell in order to produce water and electricity.

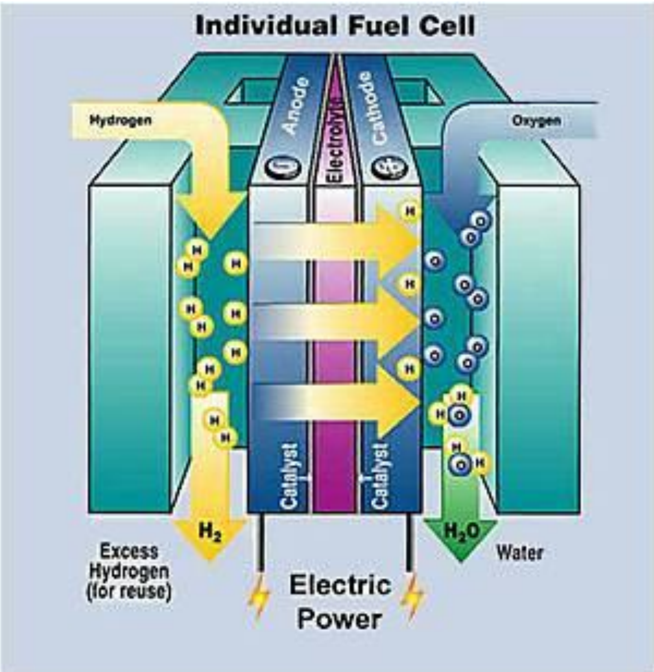

FIGURE 43 - INDIVIDUAL FUEL CELL. PROCESS IS EXPLAINED IN THE FIGURE. HYDROGEN AND OXYGEN ARE CHEMICALLY CONVERTED IN WATER SOURCE: WIKI.UIOWA.EDU.COM

TABLE 28 - MAIN PROPERTIES OF HYDROGEN FUEL CELL. BASED ON: (BEAUDIN ET AL., 2010; CHEN ET AL., 2009

Power output	Up to 50 MW
Efficiency	20-50%
Discharge at capacity	Up to 24+ hours
Response time	Up to seconds

This form of energy storage is still in development phase and therefore hardly used for large scale energy storage. Various technical challenges appear before a competing large scale plant is possible. The largest problem is the efficiency, but also the explosive nature of the hydrogen and the expensive construction are problems. However, the technology is still considered promising, because of the high energy density, which means that small components can store large amounts of energy and the diversity of the fuel cells. These can be placed, transported, split and reconfigured as modular components. Small scale use, for cars or other appliances are more likely to take off first, but hydrogen fuel cells also have energy storage potential.

Advantages:

- High energy density. This will mean that less space is needed to store large amounts of energy.
- Non-toxic components and waste lead to clean way of energy storage. The storage works in the form of water and produces water alternatively water and oxygen. Both these elements have no negative environmental impact.
- Large scale energy storage possible

Disadvantages:

- Low efficiency
- High costs
- Explosive storage material

A.5. Superconducting magnetic energy storage (SMES)

The SMES-technology keeps the electrical current stored in its electrical form. It is stored as a current on a superconducting coil. In order to do this, the coil needs to be held at very low temperatures.

TABLE 29 - MAIN PROPERTIES OF SMES-TECHNOLOGY BASED ON: (BEAUDIN ET AL., 2010; CHEN ET AL., 2009)

Power output	1-10 MW
Efficiency	97%
Discharge at capacity	seconds
Response time	milliseconds

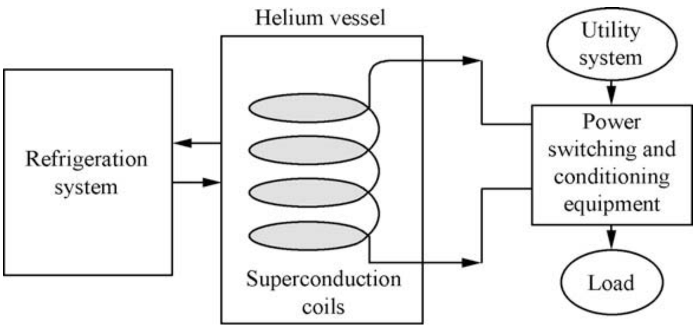

FIGURE 44 - SCHEMATIC OVERVIEW OF SMES-TECHNOLOGY (SOURCE: (CHEN ET AL., 2009))

To construct a SMES-facility, three major components are needed: a superconducting unit, a cryogenic refrigerator and a power conversion system. The cryogenic refrigerator is needed to keep the temperature at a few Kelvin, or around $-270°C$. This temperature is needed to use the coil as a superconducting coil, which eliminates the electrical resistance, resulting in a very high efficiency. Even though it has a very long lifetime, the costs are also high and the effects of strong magnetic fields are still not totally known.

Advantages:

- High efficiency
- Very fast response time
- Long lifetime

Disadvantages:

- Short duration
- High costs for construction and maintenance
- Standby storage needs considerable cooling energy

B. PHS-based alternatives

This chapter focusses on the current developments in use of hydropower to produce electricity. Several feasibility studies and technical analyses have been done. The following will shortly be described here:

- Underground Pumped Hydro-electric Storage
- Energy island
- Hydraulic Hydro Storage

B.1. Underground Pumped Hydro-electric Storage

This study tries to evade the mountains by realising the height difference in another way: by going underground. By digging new cavities and spaces underground or using existing mines, a lower reservoir could be constructed underground. It would minimise the environmental effect, because the top reservoir would be a lake on normal ground level and most of the equipment and buildings will be placed underground. A schematised view on this technology can be seen in

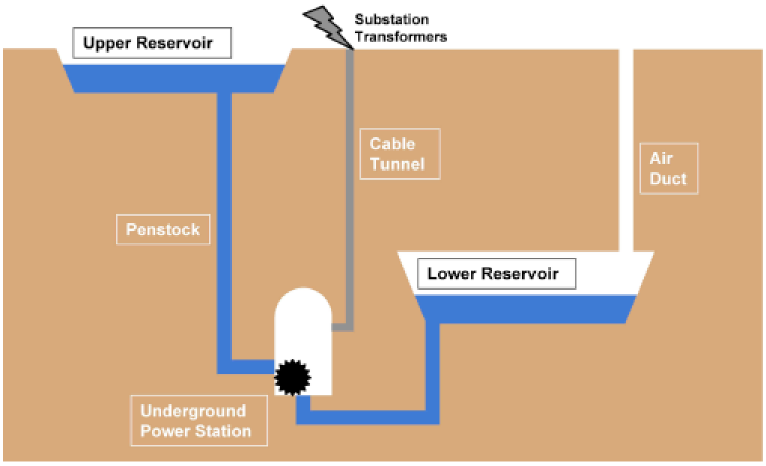

FIGURE 45 - SCHEMATISED VERSION OF UNDERGROUND PUMPED HYDRO-ELECTRIC STORAGE. SOURCE:(MARTIN, 2007)

Of all the PHS-variations, the underground station is the most popular research topic. Like conventional PHS, it grew in popularity in the 70's and 80's during the rise of nuclear power. However, no actual facilities were built, for which several reasons rose in literature (Pickard, 2012):

- Competent rock, in order to provide structural support, is crucial for the economic feasibility
- Environmental impact: aside from the necessary surface structures and environmental impact of the construction phase, the excavated ground needs to be disposed of and there will be environmental issues with the heat caused by the turbine losses.
- Economic analyses in the past have shown long payback periods, which could scare investors from providing capital. Especially in a market that is developing and changing as rapid as the energy market, strengthened by the uncertainty of government policies and price levels.
- Budget-bound governments are reluctant to invest greatly in long term projects, providing benefits mostly for a future generation, while the elections are never more than a few years away.

What can also be seen from these downsides is the lack of decisive technical restraints. The technology is possible and the main task into making this reality is to make the project economically feasible, by providing short-term profits, limiting investment needs and dealing cunningly with the environmental issues.

B.2. Hydro Storage Islands

Another way of dealing with the formula is focussing on the flow Q. This is the main point for countries where a height difference in the form of mountains is not available. The answer is a low head pumped hydropower storage facility, which normally leads to pump-back PHS plants in rivers. However, also these sites are rare, because of the requirement of a river and the use of mostly inhabited river-shores. A variation, which is still in research phase, was developed in 2007 by (Boer, 2007). It described the construction of a large ring dike in the North Sea, off the Dutch coast, called ‘Energy Island’. Here a very small head difference (<40 m) is compensated by the enormous area ($40\ km^2$) and a large volumetric flow Q. To make the island more attractive other functions are included, like recreation, wind power production and a harbour. The plan didn’t continue to be executed.

FIGURE 46 - EXAMPLES OF HYDRO STORAGE ISLANDS: 'ENERGY ISLAND' (UP-LEFT), 'GREEN POWER ISLAND KATTEGAT' (UP-RIGHT) AND 'THE ELEVENTH PROVINCE' (BELOW)

Abandoned by the Dutch government, other similar projects are emerging. Currently, Danish designers have teamed up with the developers of Energy Island and concept designs have been made for Green Power Islands in Florida, Bahrain, India, China and two in Denmark. The only short term project however, is currently being designed in Belgium, called ‘The Eleventh Province’, and is planned to start construction in 2017.[16] Some impressions of these islands are shown above in Figure 46.[17].

The concept of energy islands is to accommodate energy production and energy productions at the same place. The big advantage of the islands is the location. The sea is uninhabited for humans, which means that no nuisance will occur from constructing or operating the structure. The downside is also the location, where a very large, strong structure is needed in order to create a non-eroding island. In order to make this project profitable, it has to be linked to other functions. Across the various projects, there have been plans to combine energy production and storage with transportation, recreation, shipping, housing and industry.

An interesting side note when considering the hydro storage islands is the inverse use of pumped hydro storage. Even though the part surrounded by the dike could have a higher water level than the sea, it mainly acts as the ‘lower basin’, which will be pumped empty when electricity is sufficient and filled when electricity is needed.

[16] Based on: ‘Onze elfde, federale provincie komt eraan’ (Our eleventh, federal province is coming) http://newsmonkey.be/article/365. Accessed on 26-03-2014

[17] Pictures from: Lievense.com (Energy Island); Greenpowerisland.dk (Green Power Island Kattegat); Standaard.be (Eleventh Province); Accessed on 26-03-2014

B.3. Hydraulic Hydro Storage

This original research idea (Heindl, 2013) is one of the more extreme kinds. It tackles the problem of height difference by going back to the formula, where the output power P is not just dependent on the physical vertical distance between the two reservoirs, but also directly linked to the difference in water pressure at both sides of the turbine. In a normal case, this would be the result of a different water surface height in the open air. Another way to produce this difference is a change in pressure on top of the water.

Prof. Dr. Heindl proposed in his paper to drill a large circle in the ground, creating a piston made of the rock inside of the circle. A small protected cavity underneath leaves room to be filled with water. This open underground space should be connected to surface water through a small bored tunnel. During a period of electricity surplus, cheap electricity will be used to pump water into the cavity, lifting the rock above and creating an artificial pressure head difference between the underground water and the surface water. When needed, the pressurized water could be led through a turbine back to the surface water, using the potential energy of the rock piston to produce hydro-powered electricity. The original paper implies the production of pistons with a radius up to 500m, which would be able to store 1600 GWh, approximately the daily use of entire Germany.

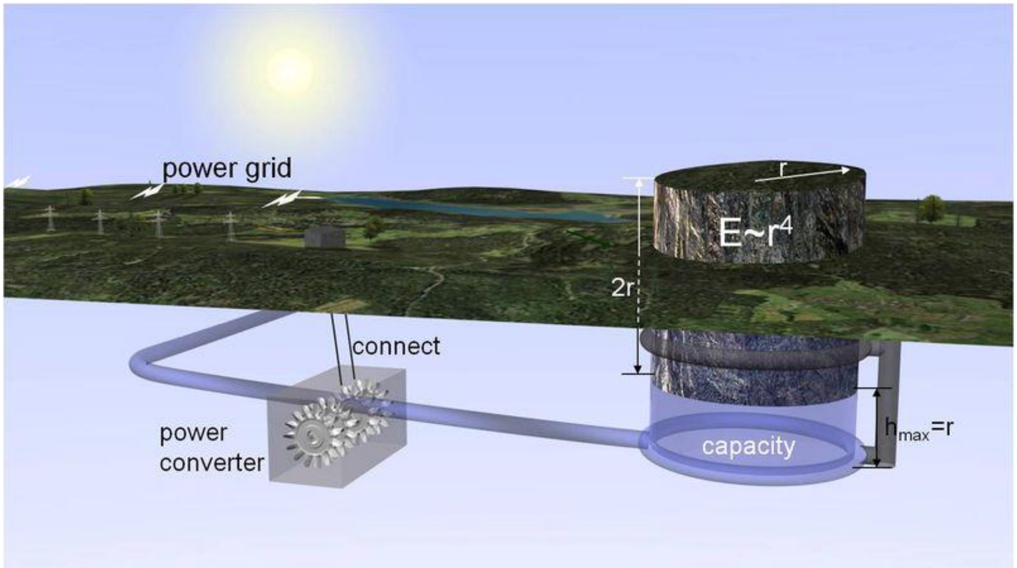

FIGURE 47 - CONCEPTUAL OVERVIEW OF THE HYDRAULIC HYDRO STORAGE PLANT SOURCE: HEINDL-ENERGY.COM

This idea uses the interesting concept of pushing over pressurized water through a turbine, instead of transporting the water itself up a mountain. In a more recently done study (Tarigheh, 2014), the so called Gravity Power Module was designed to store energy in the form of potential energy of a large solid construction. Although large amounts of energy were able to be stored, especially the costs of the material itself and the detailing of the connection between the piston and the surrounding structure were considered to be challenging. This challenge may also become problematic when the Hydraulic Hydro Storage is concerned. The moving part of the construction is built up from natural material, which increases the uncertainties in the radius. Loss of pressure through leaks and exceeded tolerances can greatly decrease its efficiency.

B.4. Subhydro: Sea Bottom HPS

Another innovative idea is the concept of Sea Bottom Hydro Power Storage. As proposed by the Norwegian company Subhydro AS[18], the concept of Sea Bottom HPS turns the idea of Pumped Hydro Storage around.

The main construction of the system relies on large concrete spheres on the sea bottom floor. The high pressures on this depth mean that a lot of electricity can be generated by opening the door. The pressure will push the water through a turbine generating energy. When the spheres are full, a pump can be used to push the water back out. To keep the pressure inside the spheres at atmospheric pressure, a ventilation shaft is needed.

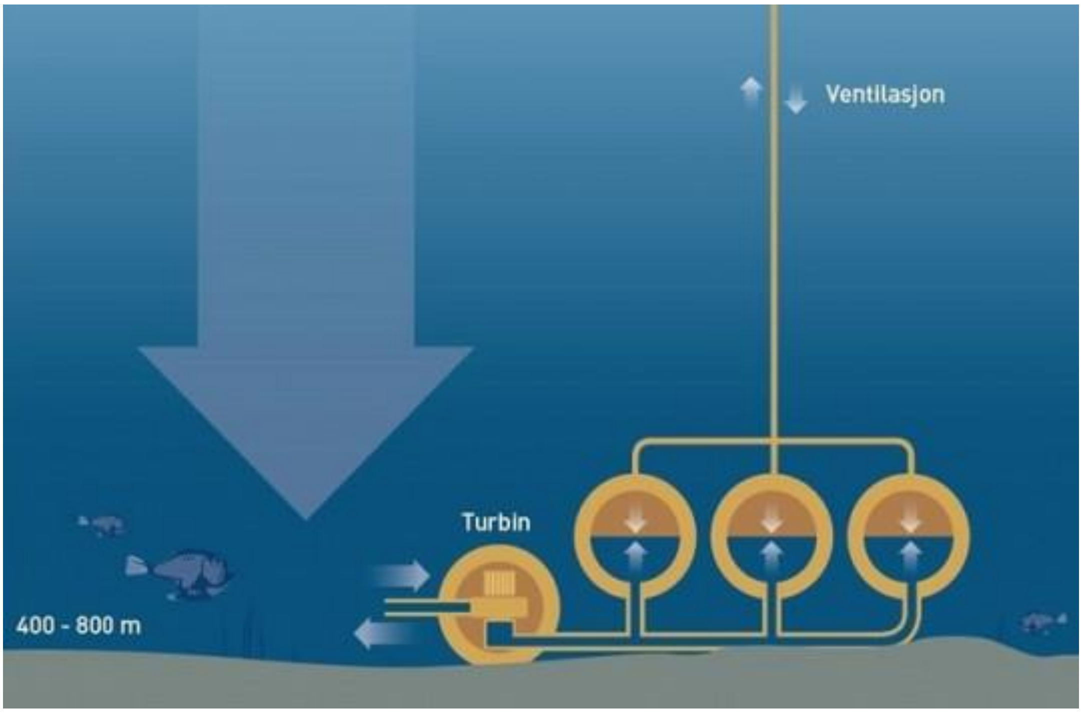

FIGURE 48 - OVERVIEW OF THE SUBHYDRO SEA BOTTOM HPS

Other than conventional PHS, this technology relies on pressure rather than height. This means that the entire facility can be constructed on one location. It also turns the functions of the two water reservoirs (inside and outside of the spheres) around. Instead of the artificial reservoir being the top reservoir, like is the case with conventional PHS, it is now virtually the lower reservoir. After all, power is generated when the water enters the spheres.

This technology has a large potential, but suffers from one big drawback which is the size of the spheres. A very thick layer of concrete is needed in order to handle the large pressures at the bottom of the sea. The currently projected concrete needs an unworkable thickness in terms of costs and construction. New innovations on high strength concrete are needed to turn this opportunity into reality.

[18] Information on http://subhydro.com/ and www.sciencedaily.com/releases/2013/05/130515085343.htm

Accessed on 02-09-2014

C. Energy Storage economics

This Appendix will further elaborate on the economic opportunities of the use of energy storage. This is a crucial part of assessing the feasibility. Whether the project will be implemented in the future will largely depend on the economic incentive to start such a project. Below, the three main economic incentives are listed. Through Time shift revenues, Fuel revenues and Electricity production- and distribution deferral enough revenues should be made to offset the costs and the risks.

C.1. Time shift Revenues

The first argument uses the most obvious and oldest form of trading by using the principle of supply and demand: “Buy low, sell high”. The price fluctuates over the course of a day because of the change in demand. During the night, demand is low. Instead of closing part of their operations down, base load plants choose to sell their electricity for lower prices. This will cost them less loss of profit than having to turn down their production, lowering their efficiency. The price may rise when demand is high, especially when the demand is growing rapidly, because the supply can’t easily react and the suppliers will sell their product even if it is more expensive. Another reason is the necessary use of more expensive to use peak power plants. The relation between the market demand for electricity and the market price can be seen in Figure 49

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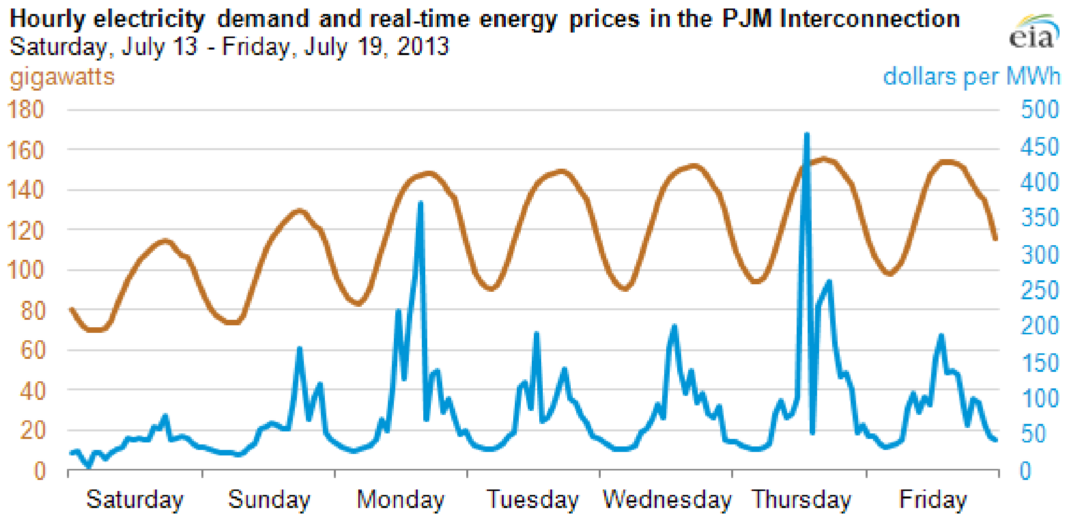

FIGURE 49 - VARIATION OF ELECTRICITY DEMAND AND ENERGY PRICES OVER THE COURSE OF A WEEK
SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION BASED ON PJM DATA[19]

As can be seen from Figure 49, the price of electricity can vary with a factor up to 15 within day and night. The difference that the market is willing to pay for the same commodity on different times of the day results in ‘price arbitrage’, which is an economical concept of market malfunction, leading to risk-free profit. In this case, this definition doesn’t apply completely, because the peak price is unknown by the time the electricity is stored and the time difference between the buying and the selling. However, the daily rise of the electricity price is close to certain. Using energy storage will therefore almost certainly result in profit, as long as the price difference times the supplied energy is enough to offset the expenses of the EES-plant. The profits made from price arbitrage can be formulated as(Rahul Walawalkar, 2006):

[19] Source: http://www.eia.gov/todayinenergy/detail.cfm?id=12711. Accessed on 27-3-2014

$$\Sigma R_{energy}(t) = \sum_{t=T_{DS}}^{T_{DS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)] - \frac{1}{\eta} \sum_{T_{CS}}^{T_{CS+N(energy)}} [P_{Energy}(t) * Q_{Energy}(t)]$$

Where:

- $R_{Energy}(t)$ is the revenue made at time t
- T_{DS} is the starting hour of discharge
- T_{CS} is the starting hour of charging period
- $P_{Energy}(t)$ is the price of energy at time t
- $Q_{Energy}(t)$ is the amount of energy delivered at time t
- N is the duration of charge/discharge

This formula shows a few interesting things:

- The efficiency η is very important, a difference between 80% and 60% efficiency can increase the necessary energy costs by 33%. This can be seen in the formula above by looking at the $\frac{1}{\eta}$ factor, which will strongly increase the costs of pumping with decreasing efficiency.
- The continuous changing price level results in a changing optimal duration N per day. When the price is expected to rise fast, a shorter duration is advised. This effect is also affected by the efficiency.

There is a downside if one would rely on this profit for its business model. A famous attribute of arbitrage is the instability of it. In its most well-known form, where one stock on two markets is rated at different prices, one might earn risk-free profits by buying the cheaper stock and selling it at the other market for a higher price. However, the change in supply and demand for both stocks will change the prices of the stocks until the difference doesn't exist anymore. This did not happen on the energy market yet because of the time difference between on-peak and off-peak moments. No organisation on the electricity market is able to bridge this time gap with such amounts that the actual supply and demand of electricity is affected significantly. When the market for EES would really take off however, the price level would be affected by the stored energy. The prices would be less fluctuating and the profits would shrink. Until this moment of significant energy storage interference of the electricity market, this form of arbitrage is possible and profitable.

C.2. Electricity production and distribution deferral

The second benefit focuses on what is not built. By using energy storage, the stability of the grid and production facilities will be better. In production, peaks will be lower and troughs will be higher. Because the peak capacity should no longer be produced and distributed on the same time as the peak demand, there will be less need for peak plants and the distribution grid can be used more efficiently. Building storage will therefore lead to lesser production plants needed and less overcapacity for the grid needed, at least for the near future. Upgrades to the production capacity and the grid will need longer intervals. Although this does not provide direct profits, this does provide benefits to the government and grid operators. An indication for the amount of value the production and distribution deferral can produce is given by the Boston Consultancy Group in (BCG, 2011): "We believe that once the share of wind and PV has increased to around 20 percent or more of actual electricity generation, compensation power in the range of 30 to 40 percent of the average vertical grid load will be required to balance RE fluctuations".

The benefit of lower costs or delay of costs can be easily described with the use of Net Present Value (NPV). This economic method recalculates all costs made over time to the comparable costs at one time, usually the present, to give a clear view on profits. An important concept for this is the discount rate, which is the rate the value of an investment decreases over time. This value decreases due to inflation and opportunity costs[20]. The main formula for NPV is:

$$P_0 = \frac{P_n}{(1+d)^n}$$

Where:

- P_0 is the present value of an investment [€]
- P_n is the value of an investment done at time step n [€]
- n is the amount of time steps done, usually years [-]
- d is the discount rate per time step [-]

The NPV can subsequently be calculated by adding all values of all investments and revenues associated with the project:

$$NPV = \sum_{t=0}^{n} \frac{P_n}{(1+d)^n}$$

This leads to the following conclusions:

- The discount rate is very important. A difference of a 6% and 10% discount rate will decrease the Net Present Value by 50%, when considering a time span of 20 years.
- Early revenues and costs are relatively important. This means that investment costs should be limited and revenues should start as early as possible.

C.3. Fuel revenues

A third form of collecting benefits the revenue from fuel substitution. Energy storage will have a stabilising effect on the market of production. It will increase demand at off-peak moments and increase supply at peak moments. Because the demand for electrical energy is not affected by the use of energy storage, this will influence the amount of other production capacity needed.

During off-peak moments, more capacity is needed, which will be supplied by cheap coal plants. The opposite happens during peak moments, where less capacity is needed. Expensive gas plants will run less, saving this relatively expensive fuel. The potential revenues from this change can add up to:

$$R_{fuel} = \left(P_{gas,MWh} - P_{coal,MWh}\right) * Q_{energy,MWh}$$

Where:

- R_{fuel} is the potential revenue from fuel substitution [€]
- $P_{gas,MWh}$ is the price of producing with use of gas per MWh [€/MWh]
- $P_{coal,MWh}$ is the price of producing with use of coal per MWh [€/MWh]
- $Q_{energy,MWh}$ is the amount of energy stored [MWh]

[20] Opportunity costs refer to the value of other things that you could have done with your money. Officially: 'the loss of potential gain from other alternatives when one alternative is chosen' (New Oxford Dictionary). When you have a positive NPV for a project that is discounted for opportunity costs, it will make more profit than a comparable alternative with the same risk.

Trying to calculate the revenues from fuel could lead to some problems. This is mainly caused because of the interference of the grid. The national grid is built up by a number of production facilities connected with the foreign countries, the demand side and the potential energy storage facility through power lines. Because the presence of energy storage capacity affects the entire grid, all production capacity will benefit equally, including production capacity not owned by potential investors.

It will be hard to quantify the amount of production capacity of a certain gas plant used less because of the energy storage plant without directly connecting production plants to the energy storage facility.

D. Salt Solution Mining

The type of cavern described in the main report is called the Single Completion Cavern (SCC) to signify that the cavern has only one well. The shape of the cavern is mostly dependent on the thickness of the salt layer. A common form for caverns is the flat cavern, with a width of around 100 meters and a height in the order of 10-30 meters. The form of these caverns is due to the layered form of the rock salt. The best quality and most stable form are found in the deeper part of the rock salt, which limits the maximum height of the cavern. These caverns are found in the east of the Netherlands, around Hengelo. Around 200 caverns are in use or used in the past in this area.[21]

Another well-known form is the cigar-shape. The width is around 100 meters, but the height can easily be as much as 300-400 meters, leaving a cavern of up to 2 million cubic meters. The larger volumes make these caverns more suitable and profitable for secondary usage after depletion of the cavern. These caverns can be found in the thick rock salt domes in the north of the Netherlands.

Before the Single Completion Cavern, the salt was mined with three separate wells: Multiple Completion Caverns (MCC). The functions are the same as with a SCC-well, but this form isn’t used anymore. The usage of MCCs would result in a much more flat-shaped cavern with a limited height to ensure stability. The use of a MCC can be recognized by the three closely located small salt houses, signalling the location of the three wells.

D.1. Current usage of old salt caverns

When a salt cavern is depleted, all that’s left is a large space deep underground filled with brine. Over the years, several technologies have made good use of this space. After all, using a cavern has many advantages. Most of these technologies have resulted in the storage of fossil fuels or aided in the more efficient use of fossil fuels. The salt caverns have been preferred and chosen for the following reasons:

- Closed-off space without storage structures and with sufficient safety
- Minimal surface constructions needed because of underground storage
- No mining activity needed by storage company, because cavern is product of other mining activities by salt producing companies

Summarizing, it is possible to store energy cheaply, out of sight, with minimal structures and a relatively low risk in a cavity that was already there. The technology of solution mining could also be altered easily in order to store other substances instead of brine and by cooperating with the salt solution mining company, it was possible to steer the wanted shape of the salt cavern while it was used by the salt production company. Over the past years, several substances and gasses have been stored in abandoned salt caverns, like:

- Natural gas
- Crude oil
- Liquefied Petroleum Gas (LPG)
- Nitrogen
- Compressed Air

For different reasons, the storage of these substances is profitable. The different methods will be elaborated on shortly. Compressed Air Energy Storage has already been clarified in Paragraph A.1.

[21] Estimates are based on interview with Dr. R. Groenenberg from AkzoNobel Industrial Chemicals B.V. on the 26th of March 2014

D.2. Cavern storage methods

When considering the storage of substances in a depleted salt cavern, an important distinction can be made between liquid and gas storage. All of the methods keep the interaction with the creeping salt layer, instead of creating a border between the substance and the salt layer.

The difference between gas and liquid storage is the need for brine when storing liquids. To keep the pressure at all times, liquids like oil need a replacement. Gasses on the other hand can be easily stored with different amounts of pressure. It is stored up until the higher limit of the possible pressure and emptied until the lower limit of the possible pressure.

D.2.1. Gas storage

The most common type of cavern storage is that of gas. The amount of gas stored is in a space like a cavern is mostly dependent on the pressure which the storage space can sustain. When the salt solution mining is closed down, the cavern is left filled with brine. The necessary surface tools and structures are transformed from solution mining to gas storage. When this is done, the brine is pushed out by pumping large volumes of gas into the cavern. This puts a large pressure on the walls and especially the casing of the well. There is a maximum pressure which can be put on the casing, which is usually made out of steel with concrete around it to cement it in place, before a crack will occur between the concrete and the salt. When storing gas, there are two minimum limits to the amount of gas. First of which is the minimum pressure needed to slow the decline of the cavern down to an acceptable level. The second minimum requirement is the so-called ‘cushion pressure’ or base pressure, which is needed to provide an adequate deliverability rate for the amount of pressure that is allowed to vary in the cavern, called the working pressure.

To give an indication on the pressure and the volume, two salt caverns projects in the Netherlands and Germany will operate with a working gas capacity between 90 and 180 bar and between 40 and 210 bar respectively. In both these projects, natural gas is stored (Breuning;, 2006; Noordoven, 2009).

When the choice is made for underground gas storage, several options are available (Partners, 2010). One could choose for a depleted reservoir, which initially was filled with oil, gas or both. In order for a depleted reservoir to be suitable, extensive research should be done to assure sufficient porosity and permeability. These requirements should be met in order for the reservoir to accommodate sufficient amounts of natural gas and assure a sufficiently high flow through the reservoir. Natural gas storage in depleted reservoir is the cheapest to develop, operate and maintain.

The second option is to store natural gas in an aquifer. This option is mostly chosen when no other is available. An underground permeable rock formation can be used as a storage area for natural gas. Because of the permeability, these aquifers are mostly filled with water, which has to be pushed out with gas pressure. The aquifer needs to be investigated thoroughly before usage to discover the suitability for gas storage and the possible gas storage capacity. Together with the long duration of filling and emptying, this makes the aquifer the most expensive as well.

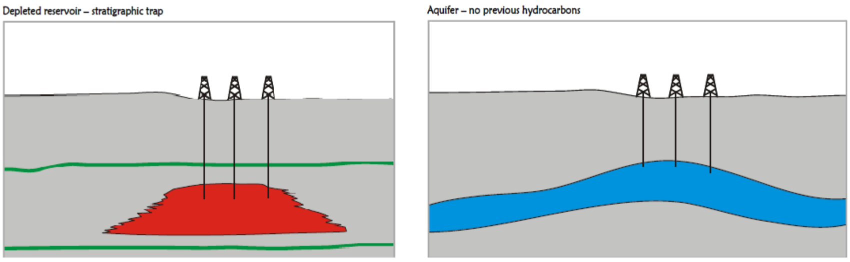

FIGURE 50 - SCHEMATIC VIEW ON TWO ALTERNATIVE UNDERGROUND GAS STORAGE TECHNOLOGIES: (LEFT) A DEPLETED RESERVOIR AND (RIGHT) AN AQUIFER. SOURCE: NISKA PARTNERS, 2010

The third and final commonly used underground gas storage technology is the salt cavern. Because of their relatively small capacity in comparison to the depleted reservoir, they cannot be used for base load storage requirements. In the other hand salt cavern have a high rate of injection and withdrawal relative to the amount of working gas capacity and a high deliverability. This makes them well suited for quick reactions on changes in the demand or supply and gives them the opportunity to be used several times every year. The impermeable salt surrounding the cavern makes the salt cavern a suitable place for natural gas storage. The constant pressure from the brine or gas will lead to a very slow moving salt cavern wall. The slow geological movement will therefore not cause earthquakes or other unwanted situation.

As different other gasses are also suitable for storage in salt caverns, the use of natural gas should be considered the largest competition for PHS in salt caverns. It is already an proven technology with gas-filled caverns all over the world (Partners, 2010).

D.2.2. Liquid Storage

The storage of liquids in abandoned salt caverns is not as easy as gas storage. Pressures cannot be regulated as easy and the liquid is too valuable to keep large quantities stored permanently in order for the pressure to be at the minimum level. To make liquid storage possible, another trick is used. In another reservoir on the surface, brine is kept standby in which can be pumped back into the cavern when the stored substance is needed, in literature named as the ‘brine compensation-method’. Known stored substances to be stored in a liquid form include crude oil and Liquefied Petroleum Gas (LPG). Both benefit greatly from the impermeable nature of the surrounding salt, which provides a cost benefit. When using other storage options, a lot of safety has to be included to divide the oil from the water sources in the ground or nearby rivers. The salt cavern is protected naturally by the homogeneous impermeable salt.

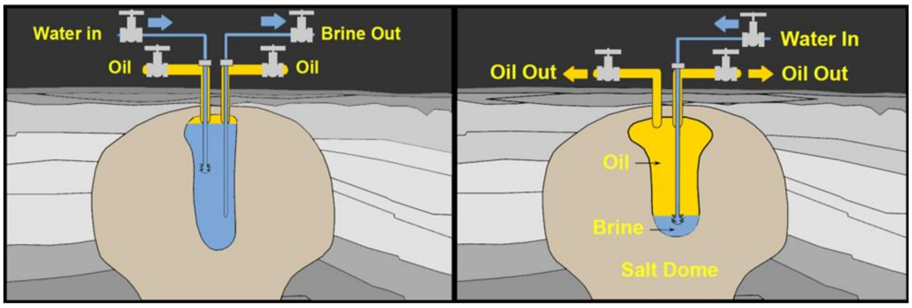

FIGURE 51 - SCHEMATIC VIEW ON LIQUID STORAGE WITH THE BRINE COMPENSATION-METHOD[22]

[22]Source: oilchangeproject.nationalsecurityzone.org/strategic-petroleum-reserve-is-buffer-against-shortages/ Accessed on: 07-04-2014

Use of salt caverns for the storage of crude oil has been done on a large scale for decades. Because oil fields are concentrated around a few spots on the earth, the entire planet is dependent on the production, prices and demands of a few producing countries when it comes to unrefined oil. Also, the largest oil-fields are located in the recently unstable region of the Middle-East, resulting in large price deviations and occasional oil-shortages. To counter this dependence, other countries have developed crude oil storages. Especially the United States, the largest importer of crude oil in the world, have seen the need for the so-called Strategic Petroleum Reserve. Divided between four fields of used salt caverns, around $110 \cdot 10^6\ m^3$ of crude oil is stored underground, which is equal to around 700 million barrels.[23]

The main reasons to use salt caverns are the low costs, low environmental risks and low oil-losses of the salt caverns. Another advantage of the use of salt caverns is the natural temperature difference between the top and the bottom of the cavern, resulting in a naturally induced circulation of the oil. This helps keeping the oil at constant quality. Although the needed strategic oil reserves are hopefully less needed in the future, they will form a popular alternative use for salt domes and salt caverns for the coming decades.

[23] Information from *oilchangeproject.nationalsecurityzone.org/* (accessed on 07-04-2014) and *www.spr.doe.gov/dir/dir.html* (inventory figures from 28th of March; accessed on 07-04-2014)

E. PHS in Salt Cavern challenges

To be able to use Pumped Hydro Storage in a salt cavern, a few challenges rise. Whether these challenges will cause the technology to be unusable or eliminates the chance for this technology to be economically undesirable will be clarified further in this research. Below, the various challenges are listed with their possible impact on the project.

E.1. Minimum pressure

This problem has already been described earlier in Paragraph 3.1.2. It explained the large pressures at the large depths where the salt caverns can be found. When the brine would be pumped out of the cavern, leaving a large cavity with atmospheric pressure, the salt cavern would start to shrink. Extensive research has been done throughout the years by Dr. Benoît Brouard and Dr. Pierre Berest on the topic of salt caverns and their behaviour under (the lack of) pressure (Berest, 2001; Brouard, 2007).

This poses a problem when someone would want to use Pumped Hydro Storage for energy storage. This technology relies on storing energy in the form of potential energy of a liquid. This is different than everything done with salt caverns before, because:

- Compressed Air Energy Storage also uses potential energy to store energy, but does this in the form of pressure and in the gas phase. This will keep the pressure uniform in the entire cavern, while PHS will result in atmospheric pressure at the places where water is no longer present. Pressuring this arisen cavity, for example with air, will cost energy and will decrease the efficiency of the storage facility.
- Crude oil and other liquid storage used until now are not storing potential energy but chemical energy. For this, the 'brine compensation-method' is used, which pumps the high energy-containing substance to the surface by letting the low energy-containing brine fall down into the cavern. Pumping oil into the caverns will actually cost potential energy, because the brine pumped up is heavier than the oil which is let down. Using two fluids with different specific weights is possible, but would probably be very inefficient and low profitability.

In both these cases, the shrinkage is not stopped completely. The total geostatic pressure is not totally compensated by the static pressure from the liquid or the gas pressure. The salt cavern shrinkage will only be slowed down in such an extent that it will be economically usable for engineering purposes. The difference is that leaving the cavern empty will increase the shrinkage significantly up to the level that it will be closed before it can be used as a profitable project. As a precondition for further research and plans the precondition is noted that atmospheric pressure in the salt cavern is not an option.

Atmospheric pressure can be avoided in multiple ways. First of all, the minimal acceptable pressure should be formulated. This is important to be able to quantify and name the measures that should at least be taken. However, this is not easy to determine, as the minimal pressure is related to the desired economic lifetime of the project. An unnecessary large amount of pressure is needed to stop the cavern shrinkage completely, what practically means that the shrinkage will be there in every realistic scenario. A slow shrinkage is desired, but a project with a relatively low pressure with an even shorter payback period[24] could also result in the best option. This dependence is mostly important when one tries to keep the pressure intact with the use of gas.

[24] payback period refers to the amount of time needed to fund all project investments

Resisting the outer pressure from the salt cavern wall

When considering the options of resisting the outward pressure, the first choice to make is whether the reacting pressure should be carried by the stored substance or not. In all other applications of the salt cavern in the form of storage, this has been chosen. The main reason for this is because the salt cavern and the deep position of the salt cavern already ensures impermeability and division between the chemical components and the vulnerable environment. Refilling the oil-storage salt cavern with brine is apparently economically more attractive than applying a protective layer.

This introduces the other option, providing a separation between the salt cavern wall and the stored substance. This separation would function as a shell which redirects or receives the outer pressure from the salt cavern wall. Inside this protective shell, atmospheric pressure could be possible and no other chemical- or pressure-related restrictions apply. Off course this presents the new challenge of providing the shell at such a depth for such a large capacity, randomly-shaped salt cavern, while the only point of access is a borehole with a diameter in the order of half a meter. On the other side, it should be technically possible with present technology. The question remains whether this is possible without too much additional risk for an acceptable price.

The other option is to let the substance itself take and execute the wanted pressure. Also this can be done on different ways. When first considering the liquids, not a lot of options are present. Because liquid does not distribute itself equally over the entire space, this directly means that the cavern should be filled with a liquid completely at all times. When exchanging liquid is needed, this can for example be done with the already mentioned brine compensation-method. This makes the use of Pumped Hydro Storage a lot harder and almost useless. The acquired electricity from the turbine is almost entirely needed for the pumping of the liquid already in the cavern. Because the volume cannot be varied anymore, the profit has to come from the variation in density. After all, running a heavy liquid through a turbine produces more power than a light liquid. Energy storage would mean that the heavy liquid is stored at the surface and the pressure is assured by a lighter liquid in the salt cavern.

Three problems appear. Firstly, the light liquid has a lower resistance against the pressure from the cavern. This could lead to a very short economical lifetime for the storage use of the cavern, while simultaneously improving the possibility of unwanted subsidence on the surface. Secondly, the heavy liquid usually has a higher viscosity, making it harder to work with. Demanding a low viscosity will limit the amount of possible liquids. Thirdly, the density difference between the heavy and light liquid are very small. As a light possible liquid, light oil could be used, provided that this would not limit the economic lifetime too much. The heavy liquid could be heavy oil, if this is possible within the wanted range of viscosity. Else, brine will provide a tested liquid. Light oil is possible with a density of $830\ kg/m^3$, while brine is usually stated as $1030\ kg/m^3$. This $200\ kg/m^3$difference can be used, but has a very small chance of being profitable. A small advantage rises when considering that the lighter liquid would naturally be pushed out of the cavern, limiting the amount of pumping needed. However, the efficiency of this system would probably be very low and the stability of the cavern under the light pressure needs additional research.

Keeping the pressure with the use of gas is easier. An economically optimal minimum pressure can be calculated and kept as lower boundary. To use this in combination with Pumped Hydro Storage, interaction between the water, which most probably be brine to prevent enlarging of the cavern, and the gas is probable. A mechanical or chemical system should ensure the amount of pressure in the cavern. This should also apply when the cavern is being drained in case of an energy surplus. To keep the pressure at a sufficiently high pressure, additional gas should be added into the cavern or the space on which the gas is acting should be made smaller.

Both these measures will cost additional energy. Pumping gas into the cavern will cost energy to run the pump. Using a gravity-based system inside the casing will cost energy put into the potential energy of the weight. Keeping the minimum pressure will artificially lift the head level of the lower reservoir, which means that the head difference is less and the Power output will be lower.

Concluding, it is strongly desired to find a cheap and low-risk shell in order to relieve the stored water from the task of providing pressure. When this is not (economically) possible, gas pressure is the best alternative to develop further.

E.2. Salinity

When working with water and salt, the salinity is an important notion. When the salt cavern is being developed, fresh water is pumped down the well and brine is pumped up. This water needs some special processing afterwards and can only be led back to the surface water system after extensive and energy-consuming processes. This has great consequences for the type of PHS-system to work with. When someone would choose for an open-loop system, the water before storage and after storage needs to be fresh water. Because of the reason mentioned above, this is nearly impossible when the interaction between the water and the salt cavern is kept intact. Also, leading fresh water into the cave would lead to additional growth of the cave. This could lead to stability problems of the cavern.

Another option is to use salt water (brine) in the first place. This is possible when adding salt to the fresh water or using brine stored at the surface. This last option is by definition a closed-loop system. The advantage of a closed-loop system is that it does not matter what kind of liquid is used in the process. On the other side, the demand for a surface reservoir with a comparable capacity to the salt cavern forms an important disadvantage.

Still, the only realistic options with the use of current technology are to protect the water from the salt wall or to use brine in a closed-loop environment. The first option would mean that a protective shell is needed. The second option would lead to a large reservoir on the surface.

E.3. Underground station

The third project risk consists of the requirement to have the turbine and pump placed at the bottom end of the PHS-system. Normally, this is an advantage, because it is easier to build this accommodation at ground level compared to a construction at the top of the mountain. In this case however, the accommodation for the Pump turbine is needed at salt cavern level. Even more problematic, the system needs to be accessible for repair and maintenance. In other words, this space needs to be connected to the surface, safe for personnel to travel to and well ventilated.

Again, different options are possible. The most obvious solution would be to dig another borehole next to the salt cavern, going down to the level of the cavern and connect the newly acquired space with the cavern and the surface. This simple but probably expensive solution will provide for a separate space without other restrictions. Ventilation, surface connection and abundance of space for equipment can be added without complications. The biggest problem would be to dig the needed space without adding costs and to get the Pump turbine in place and working.

The second possibility would be to store the Pump turbine in a closed space in the cavern itself. In this case, this Pump turbine should be able to be moved back up to the surface for repair or should be able to be accessed underground. The bottom of the cavern will consist of sunk salt, on which a closed off space can be constructed. An advantage for this option will be that the well itself can be used as transportation shaft. This would probably mean that this borehole needs to be enlarged. First, some research is needed to ensure the stability of the underground salt layer. Possibly, measures are needed in the form of a concrete layer. Subsequently, the closed-off section should be constructed. Depending on the measures of earlier problems, this needs to be done underwater or in a dry environment. If this construction is done in-situ, the placement of the Pump turbine would be the biggest problem. When prefabricated elements are used where the closed-off space is placed together with the Pump turbine, the lowering and placement of these elements will prove to be the biggest challenge.

A third option to the problem of the underground station would be to integrate the pump(s) and turbine(s) in the pipe itself. The pipe diameter would have to be increased significantly and a lot of time and effort should be invested in the optimal design of the pipe. No construction at depth of the cavern is needed and a system could be constructed to bring the Pump turbine back to the surface for maintenance. Another option would be to accommodate human transfer to the system down into the pipe, which would also increase the pipe diameter further. Additional costs are avoided by using the space of the pipe and the cavern, which makes the construction of an underground workspace unnecessary.

E.4. Surface reservoir

The last complication anticipates on the possibility that a closed-loop system is used, as stated in **Appendix E.2**. In this case, a second reservoir has to be built on the surface. The reservoir should be able to accommodate the amounts of water that can be compared with the amounts of water in the salt cavern. When considering a salt cavern with a capacity of $1 \cdot 10^6 m^3$ and an average reservoir depth of three meters, a reservoir with an area of $333 \cdot 10^3 m^2$ is needed.[25] This would be a large environmental burden on the surface and would therefore eliminate one of the largest advantages of the use of underground storage. Also, the water can hardly be used for other purposes as the water is extremely salt.

Another possibility would be to use a second salt cavern. To achieve this kind of transport and make it profitable, a salt cavern close to the original cavern is needed. Also, to keep the head as large as possible, a cavern close to the surface is needed, which will still decrease the head difference significantly.

Concluding, a solution without the use of a closed-loop system is preferred. When necessary, a surface reservoir will probably provide the best solution. However, this should be clear by the time the salt cavern is starting to be exploited, because of the large surface requirements. Salt caverns close to residential areas or close to nature-appointed areas are not suitable.

E.5. Conclusion

It is clear that the technology of using a salt cavern in combination with Pumped Hydro Storage for energy storage still has some complications to overcome. Especially the need for a minimum pressure and the extremely salt environment will make conventional Pumped Hydro Storage impossible.

However, the potential of the large, safe, impermeable underground space is large enough to continue searching for potential solutions. Changes to the main principles of Pumped Hydro Storage might be necessary, which would increase the amount of innovation in the project and therefore the projected project risk.

[25] Approximately 50 football fields

F. Multi-Criteria Analysis

The main idea of a Multi-Criteria Analysis (MCA) is to approach the decision objectively by comparing the alternatives on a wide scale of criteria. This clearly shows the strong and weak points of an alternative and the differences between the alternatives. To differentiate between importances of criteria, these criteria are first compared to each other before the final score is assigned. For this MCA, a scale of five levels is chosen:

TABLE 30 - SCORES AND DESCRIPTIONS USED IN THE MULTI-CRITERIA ANALYSIS

Score level	Description
1	Major disadvantage/ very negative
2	Disadvantage/ negative
3	Neutral/ average
4	Advantage/ positive
5	Major advantage/ very positive

The goal of the criteria is to show the similarities and differences between the proposed solutions. The criteria below, listed in alphabetic order, are used:

- Constructability
- Implementation period
- Durability
- Environmental impact & surface interference
- Large scale applicability
- Lifetime costs
- Risk & Safety
- Roundtrip efficiency
- Storage capacity
- Technology stage & blind spots

F.1. MCA Criteria

The Multi-Criteria Analysis will be done with the criteria below. Every criterion is named, with a small description on the exact definition of the criterion. Subsequently, arguments will be given how to distinguish the possibilities. Lastly, the scores will be added and weighed to make the final decision.

F.1.1. Constructability

The ability to actually build the plant is a very important requirement when choosing one alternative over another. Especially in this case, where most construction has to take place on an incredibly large depth, the constructability can be decisive.

Most construction underground needs specialized equipment. This equipment has to be designed and built separately. Limiting the amount of work done in the salt cavern itself will therefore increase the constructability, as most surface construction can be done by personnel on site with familiar equipment. For this category, the PHS Concrete Bubble definitely has a disadvantage. Almost all construction needed is at a salt cavern depth. Also, the construction of the bubble stabilisers and the Concrete Bubble itself can cause major construction problems. PHS Pressure Cavern is fairly easy to construct, as the only underground component is the air-tight cap and the extended well. Other components, like the reservoir, are common and standard practice. PHS Pressure Barrels will also be tough to construct. The stability of the borehole and the cavern needs to be ensured, even with the enlarged borehole, which basically will be a shaft. The construction can be problematic, where the modules have to be placed in an orderly way and the connections have to be made in the salt cavern. The prefab elements however result in an easier and better controllable construction than the Concrete Bubble. The PHS Abandoned Mine-alternative depends largely on the mine itself. On one hand, every adjustment needed has to be done underground in the mine. On the other hand, these underground spaces are accessible for humans and larger equipment. Therefore, no special equipment is needed.

With the stated considerations, the scores add up to:

TABLE 31 - ALTERNATIVES AND GIVEN SCORES FOR CONSTRUCTABILITY

Alternative	Score
PHS Concrete Bubble	1
PHS Pressure Cavern	4
PHS Pressure Barrels	2
PHS Abandoned Mine	2

F.1.2. Implementation Period

There always is a certain period between the first ideas of the possibility and the actual point of operation. The lack of energy storage is present-day problem which needs a solution as fast as possible. Sticking to known technology and avoiding important permits will result in a short testing period and faster implementation.

The worst off when it comes to needed developments are PHS Concrete Bubble and PHS Pressure Barrels. However, both PHS Pressure Cavern and PHS Pressure Barrels will need additional permits in order to be able to use the salt cavern for energy storage. PHS Pressure Cavern requires long testing to find the effects of long-lasting high pressure on the salt cavern and the surrounding underground environment. Special permits will be needed to use the caverns and put them under high pressure. The second reservoir on the surface will also need additional permits, because extremely salt water will be stored in a large basin. Even though this basin will not have to need as much capacity as the salt cavern itself, it will still require a substantially large basin. Because this water will be able to mix and pollute nearby surface water, strict safety requirements will restrict this project. PHS Pressure Barrels will have to cope with the same problem concerning the surface reservoir. Besides that, special attention is needed when placing (possibly corrosive) material underground. This could lead to other complaints and needed permissions. Thirdly, the possible size of the cavity can draw extra attention from regulating offices. PHS Abandoned Mine does not use equipment which still needs designing and testing, but will have to put time and effort into ensuring the safety of the working crew. Also the effect on the groundwater will have to be investigated and proven sufficiently small. Concluding, all options will need different amounts of time in the preparation phase. PHS Pressure Barrels and PHS Pressure Cavern will most likely take the longest time before actual implementation, because of a combination of newly needed designs and permissions. The following scores are given:

TABLE 32 - ALTERNATIVES AND GIVEN SCORES FOR IMPLEMENTATION PERIOD

Alternative	Score
PHS Concrete Bubble	3
PHS Pressure Cavern	2
PHS Pressure Barrels	2
PHS Abandoned Mine	4

F.1.3. Durability

The ability to endure is an important property. The energy storage system should be designed to resist the internal and external influences of the system for its entire lifetime. This includes the influence from the geological movements, storage operations, maintenance, surface- and subsurface events and human errors. Strong and easy accessible constructions will benefit this ability.

When looking at the durability of the system, the many fragile parts of the PHS Concrete Bubble and PHS Pressure Barrels stand out. The Concrete Bubble will have to be held in place by stabilising units, which are anchored inside the salt cavern walls. Although strong and durable stabilizers can possibly be designed and used, this is not clear at this stage of the design process and the stabilizers will at the moment be seen as a liability. Also, two rooms in the salt dome (the concrete bubble and the Pump turbine-station) will have to be connected through a water-tight pipeline, which can also be seen as a weak point. Repairs can only be done on large depths and repairs inside the salt cavern cannot be done by hand at all. Fragile and expensive equipment is needed here. PHS Pressure Barrels relies on the use of a collection of storage modules, which can be interconnected or only connected to a Pump turbine module. The many different (connected) parts and connections will make the alternative more fragile and less durable. The alternative of PHS Pressure Cavern can be an example of durability. Because of the lack of underground construction parts, almost everything is easy accessible and maintainable. The well-cap may have to be replaced once every few years. One side-note here is the uncertainty of the salt caverns response to the height and changing pressures in the salt cavern. It may well be that the changing pressure and the occurrence of high pressures will have an increasingly negative effect on the permeability of the salt cavern and will therefore decrease the efficiency until the point that the energy storage facility cannot be used anymore. At the moment, this effect is not known yet, but it is clear from recent research that more is happening and changing inside and around salt cavern than originally thought.

The durability of using PHS inside an abandoned mine is mainly dependent on the original mine and the kind of mine it was. The PHS construction itself will be reasonably safe, as all the elements will be safely accessible by humans and testing and maintenance can be done on-site instead of through remote robots. In conclusion, the following scores are given for the four alternatives:

TABLE 33 - ALTERNATIVES AND GIVEN SCORES FOR DURABILITY

Alternative	Score
PHS Concrete Bubble	2
PHS Pressure Cavern	4
PHS Pressure Barrels	2
PHS Abandoned Mine	2

F.1.4. Environmental impact & surface interference

An increasingly important criterion is the impact on the environment. The producers and users of energy are slowly starting to realise the effects of the human production of energy and electricity and the usage of natural resources. Also, the construction of a large and polluting plant will most likely lead to complaints from the surroundings. Complaints and concerns will also negatively affect the chance and needed time for permits.

Minimising the impact on the surface surrounding and environment can be seen as an important advantage. The PHS Concrete Bubble will have that advantage entirely. Because all of the constructions are done inside the salt cavern and the only surface disturbance will be the second borehole, almost no changing environment can be noticed. However, the effect of the steel and concrete on the salt layer and the surrounding geological layers is still unknown and the uncertainty of the effect of these materials can be seen as an environmental risk. Still, these problems will most likely be marginal compared to the surface and environment impact of the PHS Pressure Cavern and the PHS Pressure Barrels. These will have to be accompanied with a large surface reservoir, filled with brine. A small accident in the storage facility here will have significant environmental influences on the surrounding nature and agriculture. The PHS Pressure Barrels also transports several possibly polluting materials to the salt cavern depth. The abandoned mine is a special case, where the original mine will most likely have cleared the direct surroundings from people unwilling to live near a mineshaft. As the mine may not be totally cut off the surrounding ground water, construction in the mine may also have some effects on the ground water level.

TABLE 34 - ALTERNATIVES AND GIVEN SCORES FOR ENVIRONMENTAL IMPACT AND SURFACE INTERFERENCE

Alternative	Score
PHS Concrete Bubble	5
PHS Pressure Cavern	2
PHS Pressure Barrels	2
PHS Abandoned Mine	3

F.1.5. Large scale applicability

Energy storage is troubled with several problems. First of all, the developing technologies cannot produce large capacities and the large-capacity technologies like conventional PHS cannot be applied on a large scale. Therefore, an actual solution to this problem should be a large-capacity plant which can be used on a variety of locations.

To find the solution that is most applicable on large scale, the alternative has to be found that states the least amount of demands on the salt cavern and the project area itself. The worst alternative will be the PHS Pressure Cavern and PHS Pressure Barrels, which both demand a large amount of open space on the surface on which the second reservoir can be built. The PHS Pressure Cavern-alternative also states maximum amounts of permeability, as leakage during the high-pressure state will decrease the efficiency of the system. PHS Pressure Barrels does not make great demands to the salt caverns, as the module-based construction is applicable in all kinds of caverns.

PHS Concrete Bubble will need an additional shaft to be dug next to the salt cavern, which will be increasingly expensive when tougher ground properties are present. Therefore, the alternative will not have direct demands, but strong geological layers on top of the salt dome will eventually lead to a negative Net Present Value of a project. When constructing a PHS plant in an abandoned mine, strong restrictions on the permeability of the surrounding soil are present. Also, the remaining lifetime in terms of safety has to be enough to house the PHS during its entire project lifetime. On the other hand, there are far more conventional mines in the world than salt caverns, which will lead to comparable or a larger amount of possible project sites, even if the percentage of usable mines is much smaller.

TABLE 35 - ALTERNATIVES AND GIVEN SCORES FOR LARGE SCALE APPLICABILITY

Alternative	Score
PHS Concrete Bubble	4
PHS Pressure Cavern	2
PHS Pressure Barrels	4
PHS Abandoned Mine	3

F.1.6. Lifetime costs[26]

The price of the project will be one of the deciding criteria. If the project will not lead to profit, it will not be executed on large scale. Maximum capacity and efficiency with the minimal amount of complicated equipment and needed investments are crucial. Lifetime costs are based on Net Present Value, which means that initial investments will weigh relatively heavy and a quick start and long lifetime will have positive effect.

All the possibilities have a few points that could lead to an increase in costs, with an almost certain negative NPV as a result. The most promising when it comes to costs is PHS Pressure Cavern. It mainly relies on two uncertainties: the cavern wall-losses and the capacity. At this stage in design however, they seem relatively easy to improve or endure. This is not the case with PHS Concrete Bubble. Because of the many underground works, the initial investments will be relatively large. At no moment, a human can enter the salt cavern, while a lot of construction has to be done here. Designing and using remote controlled robots to do this will cost large amounts of money. Besides, the second borehole and the construction of the entire Pump turbine-station will cost significant amounts of money. On top of this, there are a few uncertainties about the construction and needed strength of the concrete bubble itself and the stabilizers, which could turn out to be expensive. On the other hand, income from energy storage will be the highest, as both the capacity and the roundtrip efficiency will be the highest of all alternatives.

The PHS Pressure Barrels also contains several possibly costly uncertainties. First of all, an enlarged borehole is needed. The stability will have to be ensured, which will result in additional costs and time in both the design and construction phase. A second cost factor can be the placement and connection of the storage modules and the Pump turbine module. The Pressure Barrels-alternative will therefore most likely lead to higher costs than the PHS Pressure Cavern, as is the case for PHS Concrete Bubble. However, less excavation is needed than is the case with the Concrete Bubble-alternative and the storage capacity can be extended to beyond the capacity of the PHS Pressure Caverns limits.

The PHS Abandoned Mine is again mostly dependent on the state of the old mine. When a low-permeable geological layer is used in combination with a strong and reliable mine, only a limited amount of adjustments is needed. Projects with a too high amount of needed investments will be terminated and the actual question for PHS Abandoned Mine is whether there are enough mines that make actual NPV profits.

TABLE 36 - ALTERNATIVES AND GIVEN SCORES FOR LIFETIME COSTS

Alternative	Score
PHS Concrete Bubble	2
PHS Pressure Cavern	5
PHS Pressure Barrels	3
PHS Abandoned Mine	4

[26] Although costs can be quantified in most projects and play such an important role, they are usually left out of the Multi Criteria Analysis. However, because of the large amount of uncertainties and blind spots, only a qualitative comparison can be made and the costs will be included in the MCA.

F.1.7. Risk & Safety

Using a salt cavern for Pump Hydro Storage will attract a lot of attention. With the recent activities of gas-extraction and the resulting earthquakes in the northern part of the Netherlands, special care and attention is needed to name and counter the risks of the project site and its environment, as well as the safety of everybody involved. Besides, what can be learned from the other energy storage technologies, the risk in comparison to the investment is a critical concept to consider.

Both these terms have been named before, where the risks will increase estimated costs and the durability and the safety is linked to the constructability and the implementation period. However, risk and safety are more than that. Risk is directly linked to the discount factor of the projects NPV-calculation, making it a very important statistic. In this stage, risk and safety can show the real differences between the alternatives. The highest project risk is estimated to be at the PHS Concrete Bubble-alternative, where a lot could go wrong. The cavern will not collapse and on the surface, no changes can be noticed, besides the total loss of energy storage.

PHS Pressure Cavern has the disadvantage of working under high pressure. When the well-cap breaks or the brine pipe is malfunctioning, a blowout at the surface can occur while all the stored energy is released at once. The risks at construction are relatively small however, as no human has to enter the subsoil and only little construction is needed for this alternative to work. The project risks are mostly present in the behaviour of the salt layer, which can lead to large efficiency drops. However, this has almost no effect on the safety of the people involved. PHS Pressure Barrels also has risks to consider. These are mostly concentrated around the stability of the soil, because of the use of a much larger borehole. The roof of a cavern which was not designed to have a larger shaft could become unstable and fall down the cavern. This could lead to damage to the Pump turbine- and storage-modules and could lead to surface subsidence. Another risk is the large amount of possible corrosive material inside the brine-filled cavern, which could eventually damage the system and the surroundings on the long term.

The last alternative, which uses PHS in an abandoned mine, mainly has risks that are unique for the chosen mine, which makes it hard to compare to the other alternatives. The use of old abandoned mines brings a variety of unknown factors along that all increase the risk of collapse or human casualties. All mineshafts involved with the exploitation of the PHS-station should be checked and secured appropriately. The spaces with will serve as the reservoirs should not only be checked on possible stability problems, but also on weak spots in the surrounding soil when it comes to porosity, permeability and pollution. Al these factors could increase the risk of the project not being as profitable as calculated during the design phase or could lower the safety of the humans involved. But all together, the risks of using an abandoned mine can be estimated and incorporated into the design much easier than the risks of using a salt cavern. The surrounding layers have been examined and used before and testing is much easier and cheaper to do.

TABLE 37 - ALTERNATIVES AND GIVEN SCORES FOR RISK AND SAFETY

Alternative	Score
PHS Concrete Bubble	2
PHS Pressure Cavern	3
PHS Pressure Barrels	3
PHS Abandoned Mine	3

F.1.8. Roundtrip efficiency

As already has been mentioned in the first Chapter, the efficiency is a crucial parameter when it comes to the profitability of the project. Efficiency affects the amount of water that needs to be pumped in comparison to the amount of water that can be used for the production of electricity. This has been one of the strong points of conventional PHS. The main task of the alternatives is to keep these advantages when transferring the system of PHS to the salt caverns.

PHS Concrete Bubble has the advantage here that the main principle of Pumped Hydro Storage is kept intact. By using fresh water in atmospheric pressure, all the major parts that make up the PHS-system are the same as for the conventional case. This also makes the efficiency of the system much more reliable than other alternatives. PHS Pressure Barrels also tries to copy the main principles of the conventional case, but more losses can occur because of the many storage modules and connection pipes. PHS Abandoned Mine can be modified to have the same kind of efficiency as the Concrete Bubble, but this would need strict requirements to the surrounding ground layers or would need a lot of adjustments.

The worst alternative is most likely the PHS Pressure Cavern-alternative, which will have some losses when converting the electricity from the grid into potential energy in the form of pressure and converting this back into electricity. During the storage of high pressurized air and water, the losses through the salt cavern walls will increase and could possibly be a factor when calculating the efficiency.

TABLE 38 - ALTERNATIVES AND GIVEN SCORES FOR ROUNDTRIP EFFICIENCY

Alternative	Score
PHS Concrete Bubble	5
PHS Pressure Cavern	2
PHS Pressure Barrels	3
PHS Abandoned Mine	4

F.1.9. Storage capacity

The profitability is based on multiple factors of which the storage capacity is one of the most obvious ones. The main task of the system is to store energy and the ability to store more energy is considered as an advantages. Not only can more energy be sold at times of need, but also more functions can be fulfilled when the energy is stored on a larger scale.

The amount of energy that can be stored is limited by the size of the cavern and the maximum pressure that the cavern and the used construction can take. The PHS Concrete Bubble however is most likely limited first by the maximum size of the concrete shell itself. As the needed thickness of the shell is more than linearly linked to the diameter of the shell, which means that the most economic thickness and size is reached much earlier and may well be much smaller than the size of the cavern. The PHS Pressure Cavern is definitely benefitted with a larger cavern, but is limited mostly by the minimum and maximum pressure that can be used in the cavern. Because the amount of water used and pumped around is only a portion of the cavern, this will have a lower capacity than the Concrete Bubble-alternative.

PHS Pressure Barrels is limited by the amount of storage modules that can fit inside the cavern. Because of the many connections and the needed additional space for the brine, these will not make up the entire cavern. The many small storage modules will therefore limit the total storage capacity and the profitability more than proportionally with the size of cavern. For example, the difference between Pressure Barrels and Concrete Bubble will be relatively small when using a small cavern with a small capacity, but this difference will increase when a larger cavern is used.

As has been mentioned in other criteria, the profitability of using an abandoned mine is mostly dependent to the mine which is used. It will be challenging to find a usable mine with the size comparable to a salt cavern. Another option is to use multiple spaces in one system, which will also have an effect on the total efficiency.

TABLE 39 - ALTERNATIVES AND GIVEN SCORES FOR STORAGE CAPACITY

Alternative	Score
PHS Concrete Bubble	4
PHS Pressure Cavern	2
PHS Pressure Barrels	3
PHS Abandoned Mine	3

F.1.10. Technology stage & blind spots

The last criterion is linked to the amount of unknowns which are still linked to the alternative. Many considerations and conclusions have been made in MCA above which are linked to estimates rather than calculated results. The main reason for this is the technological stage of most of the alternatives. Both the current stage of the technology and the appearance of further blind spots can be seen as a risk and should be counted as such.

The PHS Concrete Bubble-alternative has several blind spots which are mostly linked to the construction and the construction stage. The technology itself is mostly proven and well developed, but the concrete shell and construction stage inside of the cavern could lead to several, possibly expensive, adjustments. PHS Pressure Cavern not only has a lot of blind spots, but is also a technology which is at a very early stage. A lot of additional research is needed to learn more about the reaction of the salt layer and the cavern to the changing and increased pressures. Also the possible overall efficiency is unknown and forms an important blind spot.

PHS Pressure Barrels uses a lot of known technologies and only a few additional researches and considerations are needed to make this alternative work. As is the case with the Concrete Bubble-alternative, these additional considerations are mostly needed in the construction phase. When expensive solutions are needed for the construction of for example the connections between modules, this could severely damage the profitability of the project.

The PHS Abandoned Mine has one important blind spot, which is the project site. A lot of additional research is needed for every single project site to find the strong points and weak spots of the underground working site. The blueprint of the mine will be different for every single mine, which will mean that a specially made solution will have to be developed for every case, with its own challenges and blind spots. The technology itself, with protecting the mine chambers-walls and connecting these with pipes and a Pump turbine-station, is mostly proven technology and will show no disadvantages to the technology used in PHS Concrete Bubble or the already functioning conventional Pumped Hydro Storage.

TABLE 40 - ALTERNATIVES AND GIVEN SCORES FOR TECHNOLOGY STAGE AND BLIND SPOTS

Alternative	Score
PHS Concrete Bubble	4
PHS Pressure Cavern	2
PHS Pressure Barrels	2
PHS Abandoned Mine	3

F.2. MCA Criteria weight factors

Not every criterion is considered to be equally important. Therefore it would be unfair to count the scores evenly. To differentiate between the importance of different criteria, a weight factor can be used which will give important criteria higher scores than relatively insignificant criteria. The weight factors will be given with the use of a weight matrix, which compares every criterion with every other criterion.

The following matrix will show which criterion is more important. If, for example, the criterion ‘Lifetime costs’ is compared to ‘Implementation period’, the lifetime costs are considered more important. Then the criterion ‘Lifetime costs’ gets a score of 1 and the criterion ‘Implementation period’ gets a score of 0. When considered equally important, a simultaneous score of 1 is possible. When all criteria are compared, the scores are added (‘subtotal’-column) and divided by the total (‘weight factor’-column).

TABLE 41 - WEIGHT MATRIX

Criterion	Constructability	Implementation period	Durability	EI & SI	Large scale applicability	Lifetime costs	Risk & safety	Roundtrip efficiency	Storage capacity	Technology stage & blind spots	Subtotal	Weight factor
Constructability		1	1	1	1	0	0	1	0	0	5	10%
Implementation period	0		1	0	0	0	0	0	0	1	2	4%
Durability	0	1		1	0	0	0	0	1	0	3	6%
EI & SI	0	1	0		1	0	0	1	0	0	3	6%
Large scale applicability	0	1	1	0		0	0	0	0	0	2	4%
Lifetime costs	1	1	1	1	1		1	1	1	1	9	18%
Risk & safety	1	1	1	1	1	0		1	1	1	8	16%
Roundtrip efficiency	0	1	1	1	1	0	0		0	1	5	10%
Storage capacity	1	1	0	1	1	0	1	1		1	7	14%
Technology stage & blind spots	1	1	1	1	1	0	0	0	0		5	10%
Total											49	100%

The weight matrix above shows the relative importance of the Lifetime costs and the Risk & safety compared to the Implementation period and the large scale applicability. The total score of an alternative is dependent on both the score and the weight factor. These requirements are added below.

In the following table, the individual scores of the options are listed per criterion. The weight factor, which was the result from Table 41, is listed in the grey column. To the right of this, the individual scores of the options per criterion are multiplied to the weight factor. The total score can be seen at the bottom of the columns. To give an indication of the height of the score, the maximum score is listed in dark grey in the last column.

TABLE 42 - WEIGHTED SCORES AND COMPARISON OF THE ALTERNATIVES

Criterion	PHS Concrete Bubble	PHS Pressure Cavern	PHS Pressure Barrels	PHS Abandoned Mine	Weight factor	PHS Concrete Bubble	PHS Pressure Cavern	PHS Pressure Barrels	PHS Abandoned Mine	Maximum
Constructability	1	4	2	2	10%	0,10	0,41	0,20	0,20	0,51
Implementation period	3	2	2	4	4%	0,12	0,08	0,08	0,16	0,20
Durability	2	4	2	2	6%	0,12	0,24	0,12	0,12	0,31
EI & SI	5	2	2	3	6%	0,31	0,12	0,12	0,18	0,31
Large scale applicability	4	2	4	3	4%	0,16	0,08	0,16	0,12	0,20
Lifetime costs	2	5	3	4	18%	0,37	0,92	0,55	0,73	0,92
Risk & safety	2	3	3	3	16%	0,33	0,49	0,49	0,49	0,82
Roundtrip efficiency	5	2	3	4	10%	0,51	0,20	0,31	0,41	0,51
Storage capacity	4	2	3	3	14%	0,57	0,29	0,43	0,43	0,71
Technology stage & blind spots	4	2	2	3	10%	0,41	0,20	0,20	0,31	0,51
Total					100%	3,00	3,04	2,67	3,16	5,00

The scores shown above do not mean anything on themselves. However, relative to each other, they show how promising the alternative can be. A few conclusions can be drawn from the scores:

- The highest score is the PHS Abandoned Mine

This can be explained with use of the considerations of the individual criteria. Because of the relative human-friendly environment of the mine in comparison to a salt cavern, the low-tech adjustments needed and the large availability of used mines across the world, this technology seems promising. Another side note can be that the main disadvantage of the PHS Abandoned Mine is not captured within the frame of these criteria. The disadvantage is the large number of unknowns that will stay with every project. For every individual mine, a lot of initial investment is needed to examine whether the mine is suitable for PHS. The costs of a second project will not be much lower than the costs of the first project. This is not the case with PHS in salt caverns. The blind spots with the other alternatives are connected to the technology, not the project site. When known, the solution can be copied almost entirely for different salt caverns. Because of the relative small amount of projects that are expected and the many unknown of both the technologies and the project sites of both the mines and salt caverns, the result of this difference is not clear.

- The lowest score is the PHS Pressure Barrels

This alternative has significant drawbacks in comparison to the other salt cavern-based alternatives, but has no real advantages to counter this. The main advantage of the PHS Pressure Barrels is the large adjustability of the system. The small elements will make it easy to adjust the system to other shapes and sizes of the cavern. However, one of the main advantages of a salt cavern is the property that most salt caverns have similar shapes. Also, it is possible to discuss with salt cavern manufacturers to get a certain shape. Both properties decrease the significance of the PHS Pressure Barrels advantage. On the other side, the alternative scores low on most options because of many connections and the unknowns connected to this.

- PHS Concrete Bubble and PHS Pressure Cavern have similar scores

Although there is a small difference, the scores of both alternatives can be considered equal. To find an explanation to this equality, a look at the individual criteria is necessary. Both possibilities have their own main advantage. PHS Concrete Bubble has the advantage of copying the conventional PHS and thereby copying the advantages of this known technology. PHS Pressure Cavern has the advantage of a very simple and surface-based solution.

Both promising solutions are held back however by a large number of unknown, which leads to the difference with the PHS Abandoned Mine. The construction of the concrete shell and the connections with the other components will severely impact the risks and costs of the PHS Concrete Bubble-approach. The operation phase of the cavern and the resulting efficiency and needed storage will possibly have a large effect on the profitability of the PHS Pressure Cavern-approach.

F.3. Conclusion

In this first study to the use of Pumped Hydro Storage in Salt Caverns, a general description is made of the related components. First of all, the storage of energy is a promising and crucial solution to a rising problem. It is needed more and more every year we progress into an age of renewable but unpredictable power sources. The best and practically only used technology to store energy, which is the Pumped Hydro Storage with mountains, is slowly running out of useable sites and alternatives are needed.

One of these alternatives is to run the Pumped Hydro storage underground. The MCA shown above will tell that in this stage of the design, the PHS Abandoned Mine is the most promising. This alternative uses abandoned but accessible mines by closing off chamber and connecting these with use of pipelines and a Pump turbine. However, every mine would need its own solution and it is not known at the moment how many mines can be used profitably with this technology.

Another option would be to use salt caverns. Much less is known about these caverns and their behaviour and the alternatives to use these spaces are much more complicated. However, additional research to the caverns and technologies will apply for almost every cavern and if a solution can be found, this can be used and copied on a much larger scale.

At this point of the project, two salt cavern possibilities look promising:

- PHS Concrete Bubble, which looks to copy the conventional mountain-based storage by using a closed concrete shell and fresh water connected to the main water system.
- PHS Pressure Cavern, which uses not only potential energy in the form of height, but also potential energy in the form of pressure to push water past a turbine without the need of underground constructions.

The best option would be to continue further with both these alternatives by concentrating on the largest and most influential unknowns in order to get a clearer view on the profitability of these options and whether they can compete with other energy storage alternatives inside or outside the scope of Pumped Hydro Storage.

G. Conceptual Design: PHS Concrete Bubble

Here the background information can be found, used for the conceptual design of the PHS Concrete Bubble-alternative.

G.1. Boundary Conditions

TABLE 43 - BOUNDARY CONDITIONS PHS CONCRETE BUBBLE CONCEPTUAL DESIGN

Boundary Condition	Description	Value	Importance
BC.1	The underground condition at large depth results in high pressures on every construction	$p_{lith} = 21{,}6\ kPa/m\ depth$	Natural restriction
BC.2	Above the salt dome, a thick layer of sand is assumed	$h_{top,salt} = -700\ m + NAP$	Natural restriction
BC.3	Fresh water inside the salt cavern will react with the cavern wall, expanding it. Equilibrium exists by using brine.	$S_{brine} = 25\%$ $S_{fresh} = 0\%$	Natural restriction
BC.4	Stability and environmental reasons lead to restriction to the size of the cavern. This varies lightly per situation. For conceptual design, these values are assumed.	(these values are realistic assumptions) $\phi_{cavern} = 80m$ $h_{cavern} = 200m$ $C_{cavern} = 1 \cdot 10^6 m^3$	Natural restrictions (assumed)
BC.5	Pressure inside the cavern exists at the pressure where the increase in pressure due to cavern shrinkage is equal to the decrease in pressure due to brine loss through the salt cavern wall	$p_{eq} = 13\ kPa/m\ depth$ (assumption based on reference project)	Natural restriction
BC.6	The salt cavern walls are impermeable for engineering purposes. Only high-pressure situations need to be accounted for.		Natural restriction
BC.7	The salt cavern shrinks due to geostatic pressure.		Natural restriction
BC.8	The borehole has a maximum diameter. When a larger borehole is needed, shaft sinking is necessary.	$\phi_{max} = 0.5\ m$	Engineering requirement
BC.9	No human presence should be required inside the salt cavern at any time		Engineering requirement

Boundary Condition	Description	Value	Importance
BC.10	Fresh water should be used. Water from the cavern should be reusable in the surface water system with minimal adjustments.		Project requirement
BC.11	The Pump turbine-station should be accessible for maintenance		Project requirement
BC.12	The concrete bubble should be constantly stabilized inside the cavern to avoid unwanted movements		Project requirements
BC.13	The concrete bubble, Pump turbine-station and surface water source should be connected air-tight		Project requirement
BC.14	The materials used inside the salt dome should have minimal environmental impact		Wish
BC.15	As much work as possible should be done at the surface.		Wish
BC.16	As much work as possible should be done with use of known technology		Wish
BC.17	As much underground work as possible should be done through the original borehole		Wish
BC.18	The storage capacity should be as large as possible		Wish

G.2. Structural design

By using these requirements and boundary conditions, a first conceptual structural design can be made. This design will first focus on the individual structural elements of the system and will different alternatives to construct these elements. The feasibility will be checked by adding dimensions. The implementation of PHS in a salt cavern with the use of PHS Concrete bubble consists of the following elements:

- Cavern storage space, the cavern needs to be adjusted to be able to accommodate fresh water without the loss of pressure
- Pump turbine-station
- Pipelines connections between surface water system and salt cavern through the Pump turbine-station
- Surface facility, where the pipeline is connected to the surface system through possible purification systems. Also the well and Pump turbine-station should be accessible for maintenance at this facility.

G.2.1. Cavern storage space

The first and most important component of the PHS Concrete Bubble-alternative is the Cavern storage space-adjustments. This part of the system should ensure the possibility of using fresh water under atmospheric pressure. This is made particularly complicated because of the requirement that all construction should be done through a borehole, which has a limited diameter and requirement that the salt cavern is prohibited for humans.

There are different ways to tackle this problem:

- Concrete spray: apply sprayed concrete directly onto the salt cavern walls.

This way, the forces can be led around the salt cavern. This way of constructing would probably mean that the cavern has to be emptied with pressurized air to prevent an underwater environment for the spraying of the concrete. After this, a robotized concrete sprayer has to be lowered into the salt cavern to lock the salt cavern into place, resisting all forces from the surrounding salt and separating the fresh water from the salt.

Advantages*: Uses simple, known techniques. Does probably not require larger boreholes. Uses entire cavern, resulting in maximum capacity*

Disadvantages***:*** *A lot of concrete needed. Spraying is hard because of the varying surface of the cavern walls.*

- Concrete fill: Instead of applying the concrete on the wall by spraying, it can also be filled around a large balloon.

When the concrete is filled in the cavern instead of sprayed, the concrete will automatically fill all holes and gaps in the cavern wall. The filling process is also easier than spraying. A problem rises with the space inside the concrete, needed as reservoir. This space can be formed by filling the concrete around a large pressurized balloon. This balloon would need to be very large, which can be a problem for transportation through the borehole. A larger shaft might be needed and a special design for the balloon should be made for it to fit inside the shaft and have the appropriate size as well.

Advantages: *certainty of concrete filling all gaps of the wall, smooth inside storage wall, easy filling process*

Disadvantages: *necessary balloon needs to be transported into the salt cavern, possibly bigger shaft needed. Leaves balloon material inside cavern after use.*

- Concrete bubble: This option uses a balloon, enforced with sprayed concrete as reservoir, with brine on the outside between the concrete and the salt cavern walls.

The other extreme would be to construct the reservoir separated from the salt cavern walls entirely. Brine will remain in the cavern to keep the salt cavern pressurized. Inside this brine, a balloon will be inflated to form the outer side of the fresh water reservoir. Inside this balloon, a concrete layer will be applied for strength. This can be done by spraying concrete or by filling between the balloon and a second balloon. This option avoids the unpredictable salt cavern wall, makes it possible to construct the reservoir in the optimal shape and needs to resist far less outside force. After all, it needs to withstand the equilibrium brine stress (±13 MPa) instead of the geostatic pressure (±20 MPa).

This does increase the amount of underground constructions however, as it is not only necessary to transport the balloon(s) into the salt cavern, but also a system that has to hold the concrete bubble in place. Thus, this option relies on innovative, but risky technology and will most likely only be more profitable when the amount of concrete needed for the other options is too high and puts too great restrictions on the storage capacity.

Advantages: *No interaction between the concrete and the unpredictable salt cavern walls. Bubble can be formed and constructed to have the optimal shape to withstand outside pressure. Far less pressure needs to be resisted.*

Disadvantages: *Sophisticated system needed construct the concrete bubble and sophisticated system needed to stabilize the concrete bubble. Possibly bigger shaft needed.*

The three considered options are shown below.

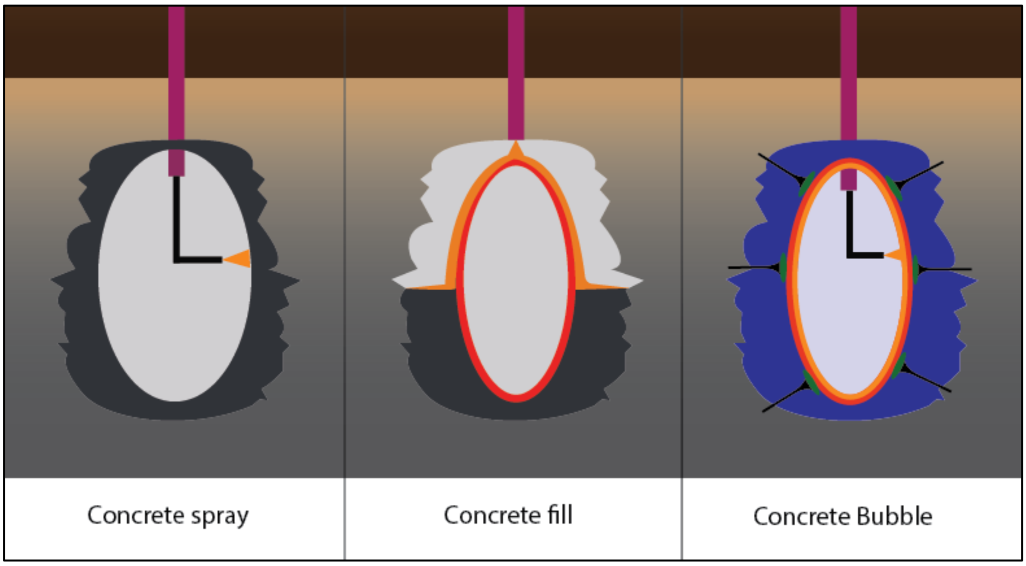

FIGURE 52 - THREE POSSIBLE OPTIONS FOR ADJUSTING THE CAVERN

G.2.1.1. Cavern storage space technical analysis

Which choice should be made depends on a variety of variables. The most important one however is the amount of concrete needed. Because of the large size of the cavern, a thick layer of concrete will be needed. In the first two alternatives, the concrete will at its weakest point span over 80 metres. When the concrete bubble is used, this can be adjusted to the most economical size.

For the conceptual design, this configuration can be modelled by a ring with diameter 80 metres. Although the salt cavern is not completely round in a horizontal plane, the shape will be enforced by the sprayed concrete. The conceptual system has the following characteristics:

- Depth top cavern: -900 meters
- Diameter D = 80 m
- Uniform outside stress $\sigma_0 = 21600 \cdot 850 = 18.4 \cdot 10^6 N/m^2$

The used pressure is the result of the geostatic pressure at the leading profile, which is as deep as possible. Because of the dome-shaped bottom, this is not at 900 metres depth, but slightly above. The model for this calculation is based on the method from (Blom, 2009). The horizontal ring can be modelled as a half of a ring where the internal compressive forces of the concrete need to compensate the outside geostatic pressure. This can be seen in Figure 53.

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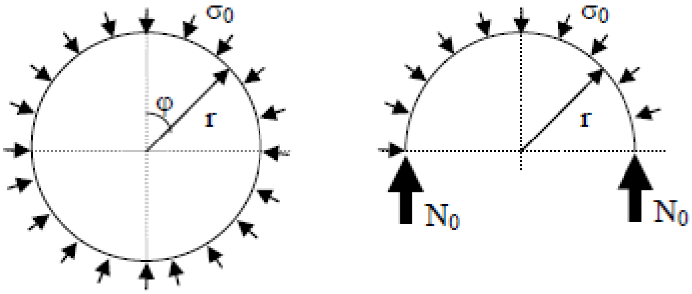

FIGURE 53 - CONCEPTUAL MODEL OF THE PRESSURE FROM THE SALT CAVERN WALL ON THE CONCRETE LINING. SOURCE: (BLOM, 2009)

As can be seen from the model, the model is defined by a $\varphi, r - axis\ system$ instead of a $x, y - axis\ system$ because of its simplicity in this case. The internal forces N_0 are equal to the outside pressure σ_0. As the outside pressure cancels itself out in one direction, only the component directly opposite to the internal forces have to be accounted for. This can be seen in the following formula:

$$\Sigma N_0 = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sigma_0 \cos(\varphi) \cdot r d\varphi$$

$$2N_0 = \sigma_0 \cdot r[\sin(\varphi]_{-\frac{\pi}{2}}^{\frac{\pi}{2}} = \sigma_0 \cdot r[1 - -1]$$

$$N_0 = \sigma_0 \cdot r \quad [N/m] \quad (Force\ per\ meter\ height)$$

When the numbers are inserted, this concludes to:

$$N_0 = 18.4 \cdot 10^6 \cdot 40 = 7.36 \cdot 10^8 N/m = 7.36 \cdot 10^5 kN/m$$

This compressive force needs to be endured by the shotcrete layer. If a concrete strength of C45/55 is used with $E_c = 45 \cdot 10^3 kN/m^2$, the needed area on each side is:

$$A_0 = \frac{7.36 \cdot 10^5}{45 \cdot 10^3} = 16.4\ m^2$$

Because the height of the concrete part was set at 1 m, this means that the shotcrete layer would have to be 16.4 metres thick. This is unacceptable due to construction time and costs. If the concrete bubble would be used instead of the complete concrete layer directly onto the salt cavern wall, the following would change:

$$Diameter\ concrete\ bubble = D_{cb} = 50m; pressure = p_{eq} = 13 \cdot 10^3 \cdot 850 = 11.1 \cdot 10^6 N/m^3;$$

$$N_{0,cb} = 11.1 \cdot 10^3 \cdot 25 = 2.77 \cdot 10^5 \frac{kN}{m};$$

$$A_{0,cb} = \frac{2.77 \cdot 10^5}{45 \cdot 10^3} = 6.4\ m^2$$

This would still result in a layer of more than 6 metres thick. The storage will be limited with such an amount that also this system is unacceptable. The thickness could be limited further with the use of struts inside the Concrete Bubble. These structural components can lead forces away from the compressive strength of the concrete construction, which means that lower amounts of concrete will be needed. However, the size of the struts and the construction method will need considerable designing and will lead to a risky construction phase. The use of struts will therefore be discouraged.

G.2.2. Pump turbine-station

This station has the big disadvantage that it is needed at the lower end of the Pumped Hydro Storage-system. The station should therefore be placed at cavern depth. Also here there are a few options:

- Separate underground station, where a different space will be created for the Pump turbine
- Cavern integrated underground station, where the Pump turbine will be placed inside the salt cavern
- Pipe integrated underground station, where the Pump turbine will be incorporated inside the pipe between the cavern and the surface

The difference between these options is mostly based on the decreasing amount of space needed from separate station to pipe-integrated station. The choice should be made based on mechanical arguments about the minimal size of the Pump turbine versus the additional costs of making and maintaining a larger diameter shaft.

The turbine will need a redesign if it has to fit inside a cavern or even a pipe. Another important thing to consider is the need for maintenance. This will most likely be the biggest problem when trying to apply the Pump turbine-station inside the cavern, because the cavern is an environment where no person can be allowed. This means that a system has to be designed to lift the Pump turbine back to the surface. This requirement will also be present when using the pipe-integrated alternative. However, this can be integrated inside the pipe much easier once the problem of fitting a Pump turbine inside the pipe is resolved.

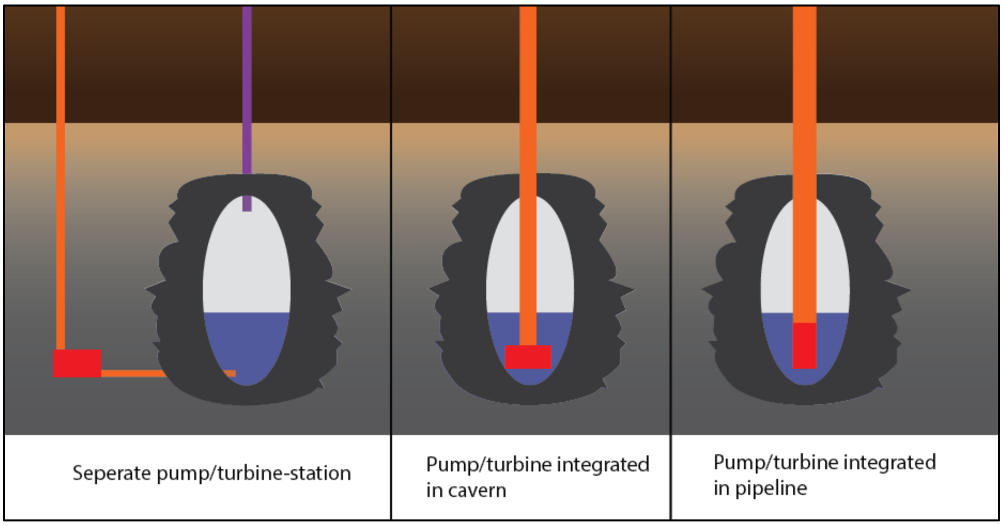

FIGURE 54 - SEVERAL OPTIONS FOR THE POSITION OF THE PUMP TURBINE-STATION

G.2.3. Pipelines

The pipelines will most likely be the easiest part of the system, as there are not many choices to be made when it comes to the connecting pipes. The size of the pipelines should be big enough to transport the highest Pump turbine capacity with allowable losses. The amount of pipelines and their placement depends on the conclusions for the other choices.

When it comes to amount of pipelines and connections needed, there is a big preference to placement of the Pump turbine-station inside the cavern or even the pipe. This will limit the amount of pipeline and connections needed.

G.2.4. Surface facilities

The surface facilities and the need for space at the surface is also a major factor in the system. The surface facilities needed for the salt solution mining are very limited, which makes it possible to use this kind of mining close to inhabited areas. Therefore, large surface facilities should be avoided.

The following facilities are needed:

- Borehole and brine well **Christmas tree**[27]
- Connection to the surface water system with possibly necessary purification system
- Space to store Pump turbine-station during maintenance

This shows that depending on the need for purification facilities and the size of the Pump turbine-station, the area can be limited quite well. As an indication, an area of around 100-400 m^2 is expected. When a cavern-based Pump turbine-station is chosen and purification facilities are needed, this value could be exceeded.

G.2.5. System design

It is clear that several options are possible and that some optimization is possible. In this stage in the project, it will be possible to make a first global estimate on the profitability of the system. A short overview on the structural components and possible considerations are listed below in Figure 55.

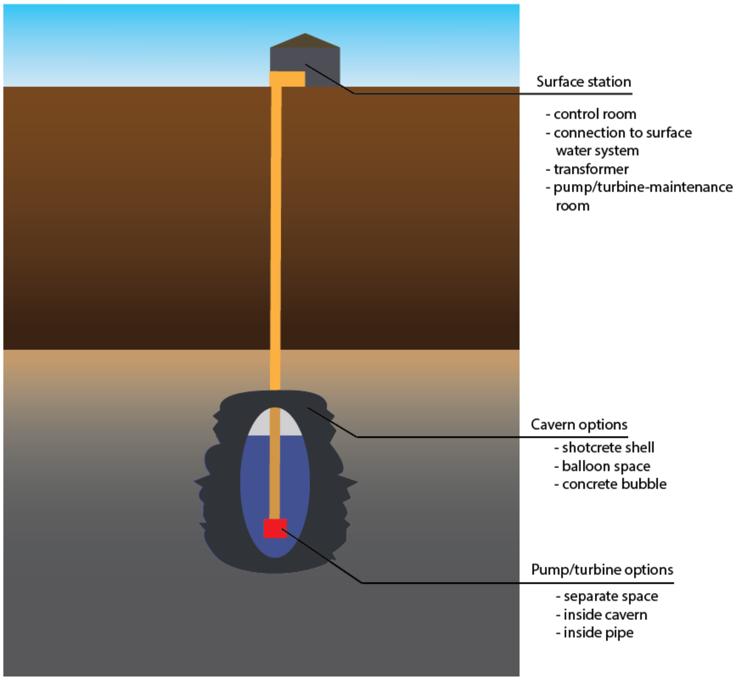

FIGURE 55 - SCHEMATIC OVERVIEW OF THE OPTIONS AND COMPONENTS OF THE PHS CONCRETE BUBBLE-SYSTEM

[27] Christmas tree: total system of valves, connections and fittings that are placed on top of the well to make operation possible.

G.3. Economic analysis: PHS Concrete Bubble

The economic value of the project is based on two important concepts: costs and revenues. These are calculated and used in the form of a Net Present Value (***NPV***)-analysis. This analysis discounts the costs and revenues towards a reference moment in time, usually the starting moment of the project. The discount factor is therefore very important and should be carefully determined with the use of a market risk and a comparison to other projects and their risks.

G.3.1. NPV-analysis PHS Concrete Bubble

The calculation of the Net Present Value is one of the most reliable forms of calculating the profitability of a long-scale project like an energy storage plant. The main concept of NPV is to divide the entire flow of money between costs and revenues for every year of the project. Subsequently, the figures are discounted over the years, to account for inflation, risk and opportunity costs. Some general notions are needed for this calculation, together with the total scheme of costs and revenues. These general notions are listed in the table below.

TABLE 44 - IMPORTANT NOTIONS CONSIDERING THE PHS CONCRETE BUBBLE-SYSTEM

Variable	Description	Value
Risk-free rate	The interest percentage that can be achieved without risk. Usually based on the interest rate of government bonds or interbank loans.	3%
Risk premium	The amount of additional interest that is demanded to offset the additional risk compared to the risk-free rate. Also incorporated is opportunity cost, which is the additional interest that can be achieved by investing in projects with comparable risks.	4%
Project time	The length of time in which the project is projected to generate costs and benefits.	50 years
Profit per kWh	The amount of money that can be earned by buying 1 kWh of energy at night and selling 1 kWh during the day	€0,04
Unit running price	The amount of money it costs to run the energy storage plant for 1 MWh	€0,50

Costs

The large problem that rises from the structural design is the thick layer of shotcrete needed. Whether this will eventually be a problem that causes an unworkable situation can be shown in this calculation. The costs have been divided into several structural components.

TABLE 45 - CONSTRUCTION COST CALCULATION OF THE PHS CONCRETE BUBBLE-SYSTEM

Component	**subcomponent**	***Costs***	***Component costs***
Cavern adjustments			
	Pump turbine	€ 53,063,000.00	
	Maintenance system	€ 5,000,000.00	
	Shotcrete + applying	€ 404,730,000.00	
			€ 462,793,000.00
Pipelines			
	Casing	€ 360,000.00	
	Connections	€ 5,000.00	
	Widening of borehole	€ 1.350.000,00	
	Placement Casing	€ 360.000,00	
			€ 2,075,000.00
Surface station			
	Brine well Christmas tree	€ 200,000.00	
	Connection to surface water	€ 50,000.00	
	Control system	€ 100,000.00	
	Transformer system	€ 3,000,000.00	
	Construction surface structure	€ 1,125,000.000	
			€ 4,475,000.00
Preparation			
	Design	€ 24,000,000.00	
	Acquiring permits	€ 2,400,000.00	
	Acquiring land	€ 75,000.00	
	Informing stakeholder	€ 6,000.00	
	Testing	€ 666,000.00	
	Risk	€ 30,000,000.00	
			€ 57,147,000.00
Subtotal			€ 526,490,000.00
	To be designed (10%)		€ 52,649,000.00
	Indirect costs (14%)		€ 73,708,000.00
	Unforeseen (10%)		€ 52,649,000.00
Total			€ 705,496,000.00

The costs show that a large amount of money is needed to buy and place the shotcrete. So apart from the constructional issues, where it will be nearly impossible to apply a 16.4 metre thick layer of shotcrete, also the costs are astronomical. It makes up more than half the total costs and more than 75 percent of the subtotal costs. Unless a solution can be found to stop the need for such thick walls, the benefits will have to be equally large to counter the costs.

Besides the shotcrete, also the Pump turbine itself is very expensive and needs special designing, construction and assembling, making it by far the most specialised part of the system. The costs for this Pump turbine is based on reference projects at €332 ($400) per kW it can produce.

The third part that needs additional attention is the amount of unknowns. Although a large part of the project can be quantified up unto an acceptable level, a lot is still unknown or still has to be designed in order for it to be accounted for. A part of these unknowns can be seen as indirect costs, like additional costs or desired profits for the construction company. The indirect costs are quantified based on experience and common use in this phase of a project at 14% of the subtotal amount. A part of these indirect costs, as well as the unforeseen and the 'to be designed' costs make up the before mentioned unknowns. Together they add up to around one third of the subtotal costs.

In the NPV-calculation, three other important notions are used. The first is the 'maintenance costs', which is the costs needed to keep the plant ready and able to run. These are chosen at 1% of the total building costs. Secondly, the 'running costs' are the variable costs needed to run the plant and store energy. These costs are chosen at €0.50 per MWh stored. When 1 cycle per day is assumed, running 90% of the year, this adds up to over €110,000 per year. The third important notion is the construction cost distribution. Because the amount of money spent and the moment of spending is crucial for a NPV-calculation, it is important to know what is constructed when. However, this is still unknown in this phase of the project, which is why it has been chosen that 30% of the costs will be accounted for in the first year, 40% in the second and 20% in the third. The construction time itself is assumed at 2.5 years.

Revenues

The hardest task for this calculation is to quantify the benefits from the use of this large-scale energy storage facility. Only a portion of the benefits from this project can be directly quantified into profits. The additional revenues will depend on the position and interest of the investors, especially when the link is made with gas-powered production plants. These peak load plants cost a large sum of money, while running a very small amount of the time. The construction of these plants will be made obsolete. A third benefit will be the increase in net stability, which will lead to a lower amount of outages. However, compared to the low amount of current outages, this advantage will not play a significant role. This could change when renewable energy sources make up a larger portion of the energy production of the Netherlands, but this may only be the case some decades in the future.

The problem with the named revenues is the uncertainty that they have when looking at future developments. The decisive and only direct source of income, revenue through arbitrage, depends on different markets and regularly changing political decisions. Mostly, it depends on the (international) market of renewable energy and the market for energy storage.

The second problem is concerning the production capacity deferral. When energy storage is used, there will be less need for investing in expensive production plants. However, this advantage will benefit the company that would have had to invest in the production plant otherwise. This company may not be the same company that invests in and exploits the energy storage facility. For this phase, a distinction will be made between direct arbitrage revenues and indirect production capacity deferral revenues. The amount of revenues from arbitrage is based on difference between the daytime price of electricity and the night-time price. A maintenance downtime of 10% of the days is also accounted for.

The revenues can be optimized in a later stage when a small study is done on the separate revenues compared to the costs of the facility. Possible revenues increase with an increasing head difference, but so do the costs of the borehole. A choice can be made to extend the running time of the plant with several hours, increasing the time that revenues can be made and decreasing the cost of the pump turbine. However, it reduces the average price difference between day and night and decreases the amount of power output that can be used for secondary services. The choice for four hours of running on full capacity resulted in a facility with an average head of 1000 meters, a power output of 160 MW and an average discharge of around $20\ m^3/s$. The quantified revenues stated below are based on arbitrage and production deferral. To limit the Pump turbine costs, a running time of four hours has been chosen rather than the three hours in the other alternative.

TABLE 46 - ARBITRAGE OPPORTUNITIES OF THE PHS CONCRETE BUBBLE-SYSTEM

Variable	Description	Value
Price difference	The difference in price between a kWh of electricity during daytime and night-time	€0.04
Storage capacity	Amount of kWh that can be stored in one cycle	638,000 kWh
Yearly revenues	Money earned from arbitrage by using one cycle every day for 90% of the days in a year.	€8.4 million/ year

The amount of revenues from production capacity deferral depends on the change that the companies operating in the grid are willing to make. The current thought and strategy of these companies is based on the need to be able to produce the amount of needed electricity at all times, even at peak moments. Energy storage will make it possible to leave this idea and temporarily have less production capacity than needed. The amount of revenues will rise with the increase of the willing to let go of the idea that every kWh should be produced directly. Therefore, a conservative estimate is made for the amount of production capacity that will be constructed less because of the presence of energy storage capacity. The value of this deferred production capacity is estimated with the use of cost projections of the U.S. Energy Information Administration (EIA, 2013).

TABLE 47 - PRODUCTION DEFERRAL REVENUES OF THE PHS CONCRETE BUBBLE-SYSTEM

Variable	Description	Value
Power output	Amount of MW that can be produced by the storage facility at full use.	160 MW
Deferred plant production	Amount of production capacity that will be used and made less due to the storage facility. Based on the estimate that this will be equal to 60% of the storage power output.	96 MW
Capital cost gas-powered plant	Costs to build a natural gas-powered plant per kW production capacity. Based on EIA estimate minus 25% financial costs.	€548.00/kW
Fixed O&M costs natural gas plant	Costs to operate and maintain a natural gas plant per kW production capacity.	€8.00/kW
Equivalent annual payments natural gas plant	Amount of yearly investments deferred due to the construction and use of the storage facility. A lower threshold rate is used because of the lower risk of conventional technology (5%).	€3.4 million/ year

Before a detailed scenario analysis is used on the numbers shown above, a first NPV-calculation is made in order to find out if the project can turn out profitable.

This first calculation uses the assumptions that the amount of arbitrage opportunities will not change during the project time and that the company investing in the energy storage plant is able to benefit from the production deferral. The graph showing the project NPV over time is shown below.

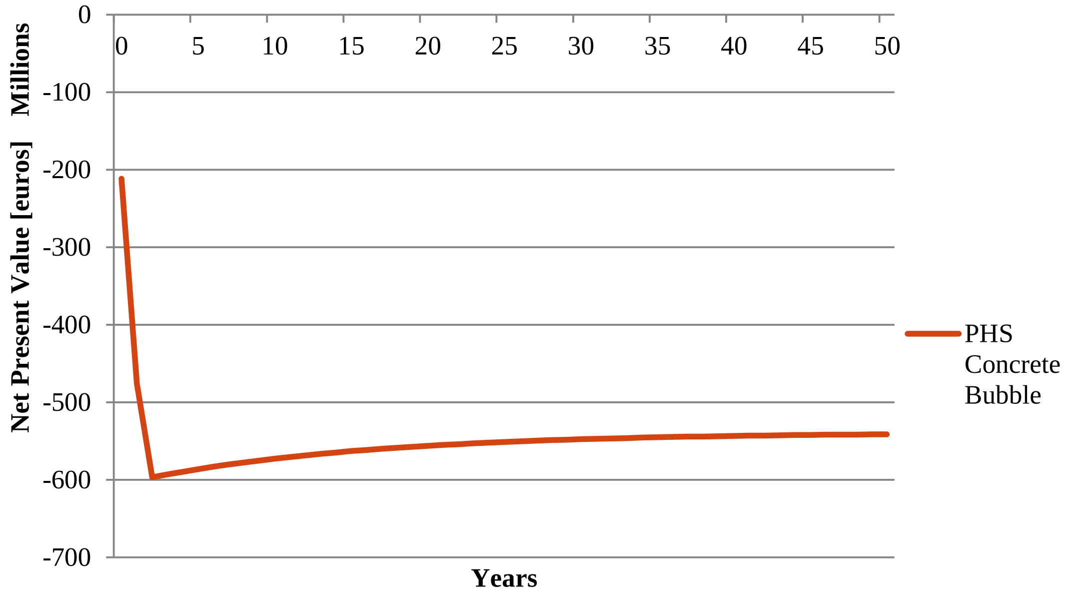

FIGURE 56 - NET PRESENT VALUE CALCULATION OVER TIME FOR THE PHS CONCRETE BUBBLE-SYSTEM

Clearly, the amount of revenues is much too small to counter the large costs from the shotcrete and the Pump turbine. The advantage of this alternative, the ability to use the entire underground space for water storage, has become useless as most of the space is used for concrete. Therefore, this alternative in this particular system is very hard to construct and economically not feasible.

If this sort of system is desired, a different approach to one of the subsystems is necessary. The large amount of shotcrete has to be limited. This means that one of the following solutions needs to be found:

- A stronger material which can counter the large forces without breaking.
- A different manner to transfer the forces around the cavern should be found.
- A different material could be used that is able to cope with deformations. The cavern would still shrink, but for some time the cavern could be used for water storage.
- The cavern could be kept under a different pressure than the atmospheric pressure of the current system.

Until one of these possible solutions can be fit into the system or another way of solving the shotcrete-problem is designed, this system can be considered a waste of shotcrete and money.

H. PHS Pressure Cavern

Here the background information can be found, used for the conceptual design of the PHS Concrete Bubble-alternative.

H.1. Boundary conditions

TABLE 48 - BOUNDARY CONDITIONS PHS PRESSURE CAVERN CONCEPTUAL DESIGN

Boundary Condition	Description	Value	Importance
BC.1	The underground condition at large depth results in high pressures on every construction	$p_{lith} = 21.6\ kPa/m\ depth$	Natural restriction
BC.2	Above the salt dome, a thick layer of sand is assumed	$h_{top,salt} = -700\ m + NAP$	Natural restriction
BC.3	Fresh water inside the salt cavern will react with the cavern wall, expanding it. Equilibrium exists by using brine.	$S_{brine} = 25\%$ $S_{fresh} = 0\%$ $\rho_{brine} = 1200\ kg/m^3$	Natural restriction
BC.4	Stability and environmental reasons lead to restriction to the size of the cavern. This varies lightly per situation. For conceptual design, these values are assumed.	(these values are realistic assumptions) $\phi_{cavern} = 80m$ $h_{cavern} = 200m$ $C_{cavern} = 1 \cdot 10^6 m^3$	Natural restrictions (assumed)
BC.5	Pressure inside the cavern exists at the pressure where the increase in pressure due to cavern shrinkage is equal to the decrease in pressure due to brine loss through the salt cavern wall	$p_{eq} = 13\ kPa/m\ depth$ (assumption based on reference project)	Natural restriction
BC.6	The salt cavern walls are impermeable for engineering purposes. Only high-pressure situations need to be accounted for.		Natural restriction
BC.7	Inside the salt cavern, a minimum and maximum pressure is present, to prevent excessive shrinkage and blowouts	$p_{min} = 30\%\ of\ p_{lith}$ $p_{max} = 85\%\ of\ p_{lith}$	Natural restriction
BC.8	The borehole has a maximum diameter. When a larger borehole is needed, shaft sinking is necessary.	$\phi_{max} = 0.5\ m$	Engineering requirement
BC.9	No human presence should be required inside the salt cavern at any time		Engineering requirement

Boundary Condition	Description	Value	Importance
BC.10	The brine used inside the salt cavern has to be kept separated safely from the surface water system at all times		Engineering requirement
BC.11	The air- and brine pressure should be monitored accurately to prevent too high or low pressures		Project requirement
BC.12	The needed surface space needed for the facilities should be limited as much as possible		Wish
BC.13	The materials used inside the salt dome should have minimal environmental impact		Wish
BC.14	As much work as possible should be done at the surface.		Wish
BC.15	As much work as possible should be done with use of known technology		Wish
BC.16	As much underground work as possible should be done through the original borehole/shaft		Wish
BC.17	The storage capacity should be as large as possible		Wish
BC.18	Inhabitants near the project site have to be informed sufficiently prior to construction of the energy storage plant		Wish

H.2. Structural design PHS Pressure Cavern

These boundary conditions can be used for the first conceptual design of this alternative. Like the already shown alternative, first the structural components will be clarified. Also, a first approximation of the efficiency will be made, because of the large importance of this property in this alternative.

The PHS Pressure Cavern-alternative consists of a system of the following structural elements:

- An extended pipe into the brine part of the salt cavern
- Surface facilities:
    - Pump turbine station
    - Surface brine storage reservoir
    - Space and tools for maintenance of the well
    - Salt cavern pressure control facilities
    - Connection to the electricity grid

H.2.1. Efficiency of the system

Before the structural elements are clarified, a conceptual estimate is made of the efficiency of the system. Because of the innovative way of storing electric energy, the efficiency is still unknown. Energy in the form of pressure can be stored by switching between two possible positions of the system. Both are limited by the air pressure. To evaluate the efficiency of the system, a typical Dutch salt cavern is used. This will later be changed with the use of a sensitivity analysis. For now, the salt cavern will have the following dimensions:

- Depth of top of salt cavern: $h_{top} = -700m\ depth$
- Diameter of salt cavern: $\phi = 80m$
- Height of salt cavern: $h_{cavern} = 200m$
- Water depth inside cavern: $d_{brine} = 50m$

The first state is will be called the 'uncharged state', because no direct accessible energy is stored in the cavern at that point. The system will be positioned as follows:

- The air inside the cavern is pressured at minimum pressure P_{min}, which is limited by the shrinkage of the cavern. The cavern will shrink faster when the pressure is lowered. To limit this shrinkage, in practice a minimum pressure is defined at 30% of the geostatic pressure. This means that the air pressure in uncharged state is 4.5 MPa.
- The brine inside the cavern is at its lowest point
- The surface storage reservoir is full

The second state will be called the 'charged state', because the maximum amount of direct accessible energy is stored in the cavern at that point. The system will be positioned as follows:

- The air inside the cavern is pressured at maximum pressure P_{max}, which is limited by the connection between the concrete casing shoe and the salt layer at the top of the cavern. A higher pressure could cause the connection to crack and a blowout could occur. In practice a safe value of 85% of the geostatic pressure used, which means that the air pressure in charged state is 12.9 MPa.
- The brine inside the cavern is at its highest point
- The surface storage reservoir is at its lowest point

All following calculations have been done with the use of the software program Maple 17. The exact Maple files and explanations are given in Chapter 0.

First, the uncharged state is considered. At the interface between the air and the brine, a pressure of 4.5 MPa is present. First the positions of the systems are assumed, where brine level of -850 m is chosen. The bottom end of the borehole should reach in the brine, so a bottom level of the casing of -860 m is chosen. The pressure inside the brine will cause the brine to rise up into the casing. The amount of brine rise can be calculated using the formula of Bernoulli:

$$\frac{1}{2}\rho v^2 + \rho g h + p = constant; \quad (general\ formula\ of\ Bernoulli)$$

When two points are chosen where one point is positioned at the interface between brine and air inside the cavern and the second point is positioned at the interface between brine and atmospheric pressure inside the casing, the following can be concluded:

$$\frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 + p_1 = \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + p_2$$

Where:

- $\rho_1, \rho_2 = the\ density\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively\ \ [kg/m^3]$
- $v_1, v_2 = the\ velocity\ of\ the\ fluid\ at\ position\ 1\ and\ 2\ respectively\ \ [m/s]$
- $h_1, h_2 = the\ elevation\ of\ the\ fluid\ compared\ to\ a\ reference\ plane$ $at\ position\ 1\ and\ 2\ respectively\ [m]$
- $p_{min}, p_{atmospheric} = the\ pressure\ at\ position\ 1\ and\ 2\ respectively\ \ [Pa]$

The velocities at the interface are chosen at zero, because stationary situations are considered. When the other known parameters are used as input, this concludes to:

$$\rho_1 = \rho_2 = 1.20 \cdot 10^3 kg/m^3; h_1 = -850\ m\ ; p_{min} = 4.5 \cdot 10^6 Pa; p_{atmospheric} = 1.0 \cdot 10^5 Pa;$$

$$0 + 9.81 \cdot -850 \cdot 1.20 \cdot 10^3 + 4.5 \cdot 10^6 = 0 + 9.81 \cdot 1.20 \cdot 10^3 \cdot h_2 + 1.0 \cdot 10^5$$

$$h_2 = -476m$$

This means that the interface between the brine and outside air inside the casing is situated at a depth of -553 metres. The water heights in this situation can be seen in the figure below.

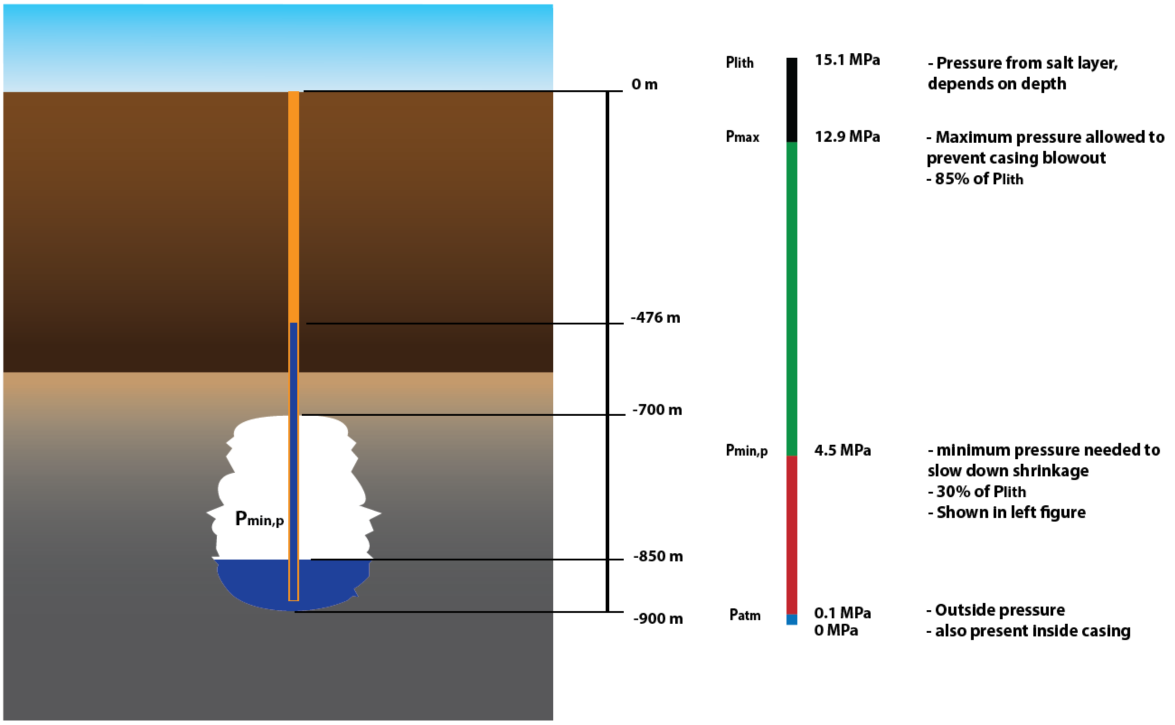

Figure 57 - Schematic overview of the PHS Pressure Cavern-system with working pressures, only taking into account salt layer boundaries

The next step is to calculate the amount of brine that has to be pumped into the cavern to achieve the maximum pressure. To do this, the air inside the cavern is considered to be an ideal gas in order for the ideal gas law to be applied:

$$pV = nRT$$

Where:

- $p = the\ pressure\ of\ the\ gas\ [Pa]$
- $V = the\ volume\ of\ the\ gas\ [m^3]$
- $n = the\ amount\ of\ molecules\ inside\ the\ \ volume\ [mol]$
- $R = the\ molar\ gas\ constant\ \left(R = 8.31\ \frac{m^3 \cdot Pa}{K \cdot mol}\right)\ \ [m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}]$
- $T = the\ temperature\ of\ the\ gas\ in\ Kelvin\ [K]$

For the conceptual design, the amount of gas molecules inside the volume, the molar gas constant and the temperature are kept constant. This could change in a later stage because of limited heat generation from losses. Because of these assumptions, the pressure times the volume is equal to a constant value at any time. When considering the uncharged- and charged state:

$$p_{es} = 4.5 \cdot 10^6 Pa; p_{fs} = 12.9 \cdot 10^6 Pa;$$

$$V_{es} = \pi \cdot 40^2 \cdot (-700 + 850) = 7.5 \cdot 10^5 m^3$$

$$V_{fs} = \frac{V_{es} \cdot p_{es}}{p_{fs}} = 2.6 \cdot 10^5 m^3$$

Where:

- $p_{es} = the\ pressure\ of\ the\ gas\ at\ the\ empty\ state\ [Pa]$
- $p_{fs} = the\ pressure\ of\ the\ gas\ at\ the\ full\ state\ [Pa]$
- $V_{es} = the\ volume\ of\ the\ gas\ at\ the\ empty\ state\ [m^3]$
- $V_{fs} = the\ volume\ of\ the\ gas\ at\ the\ full\ state\ [m^3]$

This volume at charged state means that the cavern is filled with brine up to:

$$V_{fs} = \pi \cdot 40^2 \cdot \left(-700 - h_{fs}\right) = 2.6 \cdot 10^5 m^3$$

$$h_{fs} = -753\ m$$

Here the h_{fs} is defined at the depth where the new interface will occur at maximum pressure. The amount of brine pumped in and out of the cavern can easily be found:

$$V_{displaced} = V_{es} - V_{fs} = (7.5 - 2.7) \cdot 10^5 = 4.9 \cdot 10^5 m^3$$

This is equal to 49% of the total volume of the cavern. To find out the amount of energy that can be produced with this amount of water, also the change in head difference is important. To account for the change in pressure, the pressures are recalculated into meters of brine head.

$$H_{ph} = \frac{\rho_b}{\rho_w} \cdot 0.102 \cdot 10^{-3} \cdot p \qquad [m]$$

Where:

- $H_{ph} = the\ head\ due\ to\ pressure\ in\ meters\ of\ water\ [m]$
- $p = pressure\ inside\ the\ fluid\ [Pa]$

The amount of power needed for pumping can be calculated with:

$$E_{pump} = \eta \cdot \rho \cdot g \cdot \Delta H \cdot V \quad [J]$$

The difference in head is changing over time, because of the change in water height difference and the change in pressure over time. The following changes will occur:

At the uncharged state, the water height will be at -476 metres with atmospheric pressure. The first difference in pressure at the salt cavern can be achieved by letting brine fall into the well. This can be done until the water reaches the surface. This process can be used to generate electricity. After this, the pump is needed because the head inside the well is higher than the head inside the surface reservoir. In the following timeline, the uncharged state is defined as t=0:

TABLE 49 - PHS PRESSURE CAVERN PRESSURES AND BRINE LEVELS IN THE UNCHARGED STATE

Position	Property	Value
Cavern	Pressure	4.5 MPa
	Brine level	-850 m
Borehole	Pressure	0.1 MPa
	Brine level	-476 m

TABLE 50 - PHS PRESSURE CAVERN PRESSURES AND BRINE LEVELS AT MOMENT WHEN BRINE REACHES SURFACE

Position	Property	Value
Cavern	Pressure	9.2 MPa
	Brine level	-774 m
Borehole	Pressure	0.1 MPa
	Brine level	0 m

TABLE 51 - PHS PRESSURE CAVERN PRESSURES AND BRINE LEVELS AT CHARGED STATE

Position	Property	Value
Cavern	Pressure	12.9 MPa
	Brine level	-752 m
Borehole	Pressure	4.0 MPa
	Brine level	0 m

This results in the following heads (taking pressure into account):

TABLE 52 - PHS PRESSURE CAVERN SUMMARY OF PRESSURES, BRINE- AND HEAD LEVELS AT DIFFERENT MOMENTS

Time	Property	Value
t_0	Pressure	0.1 MPa
	Brine level	-476 m
	Head	-476 m
t_1	Pressure	0.1 MPa
	Brine level	0 m
	Head	0 m
t_2	Pressure	4.0 MPa
	Brine level	0 m
	Head	488 m

When running through an entire cycle from uncharged state to charged state to uncharged state, four phases can be distinguished. The first phase, water is let into the borehole and a turbine is needed for power output. In the second phase the pump should be able to pump water from the reservoir into the borehole. In the third phase, water is pushed from the borehole through the turbine and in the fourth phase, water should be pumped from the borehole to the reservoir.

These four phases mean that both the pump and the turbine should be able to work both ways, which will cause problems. To avoid these problems, the working space can be decreased to 9.2-12.9 MPa inside the cavern. This way, the borehole is always filled with brine and the pump is only needed to pump water from the reservoir into the borehole and the turbine is only needed when water runs from the borehole to the reservoir. This decreases the storage capacity even further.

The workings space is decreased further to a situation where only 7% of the total cavern can be used for storing additional brine. The total power output/ needed input depend on the amount of water displaced and the head difference.

When using an assumed roundtrip efficiency of 75%, the total stored capacity is equal to 0.04 GWh, which is significantly lower than the first assumed potential of 1.72 GWh. This is mainly caused by the unused space which is needed for the pressurized air at maximum pressure, the minimum amount of water needed at minimum pressure. Also, space is needed to increase the pressure further up to the point where the head inside the well will not fall below surface level. This will be further illustrated below:

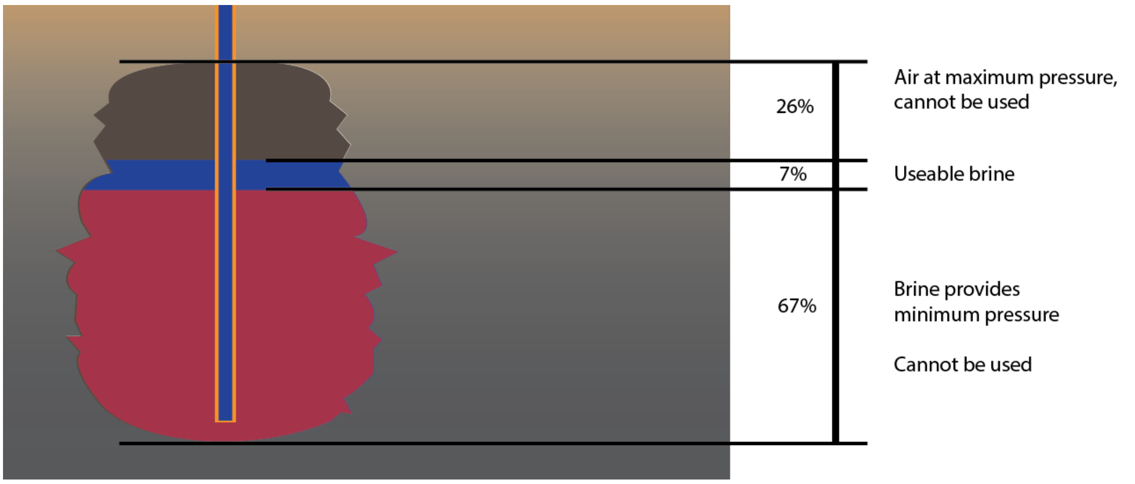

FIGURE 58 - SALT CAVERN USED IN PHS PRESSURE CAVERN-SYSTEM DIVIDED IN PARTS THAT CAN AND CANNOT BE USED

To find out what the effect is of all the variables involved, a sensitivity analysis will be done below. Here, the effect of a small decrease or rise in one of the variables on the total needed underground space will be evaluated.

As a starting point, the same case as above is used:

- Cavern capacity: $1 \cdot 10^6\ m^3$
- Cavern dimensions: 80 m diameter; 200 m high;
- Cavern depth: top of the cavern at -700 m
- Water depth inside cavern: 50 m at uncharged state (at low pressure water level at -850 m)
- Efficiency: 75%

In this case, the amount of energy stored is 0.04 GWh. The total produced amount of energy in the Netherlands is $98.4 \cdot 10^3\ GWh\ per\ year\ or\ 270\ GWh\ per\ day$. If it were desirable to store the entire amount of production for one day, a total of $6.07 \cdot 10^9\ m^3\ of\ underground\ space$ is needed. In the following table, this figure is represented with the value 100.

TABLE 53 - SENSITIVITY ANALYSIS FOR PHS PRESSURE CAVERN-ALTERNATIVE (INDEX=100 FOR STANDARD CASE DESCRIBED ABOVE)

Changed property	Value	Lower (-10%)	Higher (+10%)	Remarks
Capacity	$1 \cdot 10^6\ m^3$	97	103	Ratio height: diameter and water table level (-850 m) is kept constant. Increasing capacity has minor advantage.
Height	200 m	93	110	Also slightly increases capacity. Water table level (-850m) is kept constant. Increasing height has major positive effect.
Diameter	80 m	100	100	Change in capacity is offset completely by the need for more/less caverns. Diameter has no effect at all.
Top depth	700 m	123	84	Also changes water table level. Increasing depth of cavern has major positive effect.
Water depth	50 m	98	102	Dimensions of cavern are kept constant. Lower water depth has positive effect.
Efficiency	75%	111	91	Increasing efficiency has major positive effect.

From the sensitivity analysis above, a few things can be concluded. First of all, size and depth are crucial. Both the height and the depth of the cavern have a significant impact on the amount of underground space needed. Changing the diameter however, has no effect at all. This can be explained by the fact that a change in diameter does not result in a change of pressures or height difference. Therefore, the amount of caverns needed, will change but not the total amount of underground space needed.

Secondly, the water depth also affects the amount of underground space needed. As air is much better compressible than water, having a larger ratio of air:water inside the cavern will increase the amount of water (and therefore energy) that can be stored inside the cavern. This effect is dampened by the increase in height difference between the brine level inside the cavern and the surface. This means that the brine has to be pushed up further and will decrease the head difference over the pump. As can be seen from the table, the positive effect of increasing the air inside the cavern has a larger result than the negative effect of the increased height difference.

However, when the height of the cavern is decreased significantly, other conclusions can be drawn. Although the efficiency rises, the total energy storage in that specific cavern decreases. When working with large heights of the cavern, decreasing the height of the cavern will also increase the energy storage capacity. This occurs because of the following formula:

$$E_{capacity} = \eta \cdot \rho_{brine} \cdot g \cdot H_{average} \cdot V_{displaced} \cdot \frac{1}{3.6 \cdot 10^9}$$

Where:

- $E_{capacity}$ is the total energy storage capacity of the salt cavern [MWh]
- η is the roundtrip efficiency [-]
- ρ_{brine} is the density of the brine $[kg/m^3]$
- $H_{average}$ is the average head difference over the pump turbine [m]
- $V_{displaced}$ is the total amount of brine moved in and out of the cavern $[m^3]$

The constant $\frac{1}{3.6 \cdot 10^6}$ is used to convert from J/s to MWh. Both the average head difference and the displaced amount of brine is important in this formula. When the diameter is constant, lowering the height of the cavern will result in a smaller underground space and a smaller amount of displaced brine. This could result in a higher energy storage capacity, as long as the increase in average head difference is more significant than the decrease in displaced amount of brine. The optimal cavern height depends on several variables, of which the depth of the top of the cavern is the most important. A connection between the two variables will be attempted to find later.

The water depth therefore has actually no effect when both the water depth and the cavern height is variable. A cavern of 200 meters with 50 meters water depth will be able to store roughly the same amount of energy as a 160 meter cavern with 10 meters water depth. However, the goal is to store as much energy as possible with an underground space as small as possible. Therefore, the water depth will be minimized at minimum pressure to minimize the amount of unused space.

A third and obvious observation is the positive effect of the efficiency. As can be seen in the table, a higher efficiency (82.5% instead of 75%) will result in much less underground space needed. This amount decreases with 9% to a total of $1.61 \cdot 10^9\ m^3$ underground space needed.

To increase the potential and the economic feasibility of this alternative, a few measures can be taken:

- The water level inside the cavern should be as low as possible. This is a challenge for the construction phase. Because the water level inside the borehole should not come below the surface and there should always be water between the outside atmosphere and the pressurized cavern, a good measurement is needed to ensure that a sufficiently large height between the bottom of the borehole and the water level inside the cavern. A minimum needed height of 10 metres is assumed until further research.

- The depth and size of the cavern have a large influence on the profitability. However, changing these properties for already made caverns is very hard or even impossible. On the other hand, it is possible to work together with salt solution mining companies to steer the shape and depth of the cavern towards a situation where it is most profitable for electric energy storage. The following advice should be given:
    - The cavern should be as deep as possible

- The cavern diameter should be large as possible

- The efficiency needs specialized attention. Because of the large impact on the needed underground space and the even bigger influence on the economic feasibility of the project, every increase in efficiency has a positive impact. Using this alternative has a large positive and negative effect. First of all, the Pump turbine is easily installed and maintained. On the other hand, the effect of the salt cavern wall on the high pressure is unknown.

The Higher Low-alternative

To increase the amount of water displaceable with the use of the pumps and turbines, as small change can be made to the pressures and water pressures inside the cavern. This can be done by increasing the minimum pressure to the point where the water head inside the borehole is equal to the surface level. Thus, the following situation appears:

- At p_{min}, the water level is minimal. Here, p_{min} is not the pressure which is minimally needed to withstand the outside pressure, but the pressure needed to keep the water head inside the borehole equal to the surface level.

This replaces a lot of the incompressible water with highly compressible air and therefore increases the amount of water which can be transported in and out of the cavern when going from the minimum pressure to the maximum pressure. Summarizing, the minimum pressure is higher but the displaceable volume is increased.

When used in the standard case used in the previous chapter, the pressure at which the water level is minimal increased from 4.5 MPa to 10.1 MPa. This increases the part of the cavern that can be used for energy storage from 7% to 11%. The exact calculations from Maple 17 can be seen in chapter 0. The next figure shows the situation and the pressure range for this adaptation.

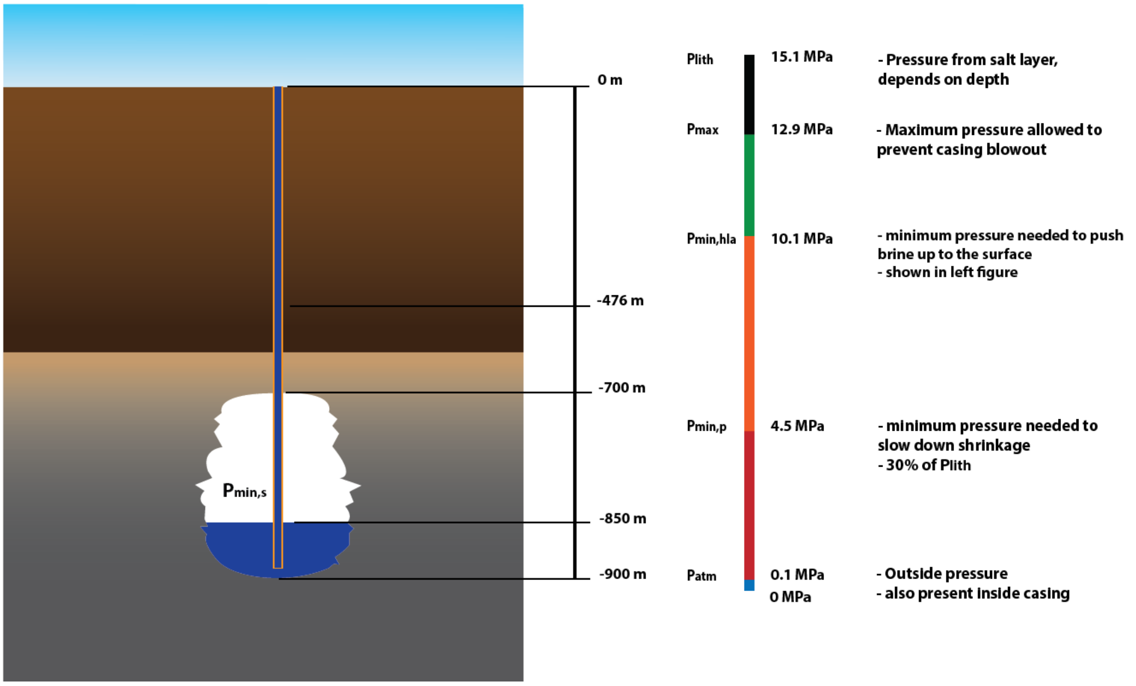

FIGURE 59 - SCHEMATIC OVERVIEW OF THE SYSTEM WITH WORKING PRESSURES, TAKING INTO ACCOUNT THE HIGHER-LOW ALTERNATIVE

Turbine efficient range considerations

The calculations above leave out an import consideration concerning the Pump turbine. Because the head over the turbine is pressure-based and not height-based, the head will vary over time. The pressure and the head will decrease when water runs through the turbine. Theoretically, this will continue until the head reduces to zero and the flow stops. However, the turbine will run less efficient with lower head differences than the head difference it was designed for. Common practice is to assume a turbine range from within the turbine can produce efficiently. This range is assumed to be:

$$\text{Turbine head range:} \quad \frac{2}{3} \cdot H_{max} < H_{turbine} < H_{max}$$

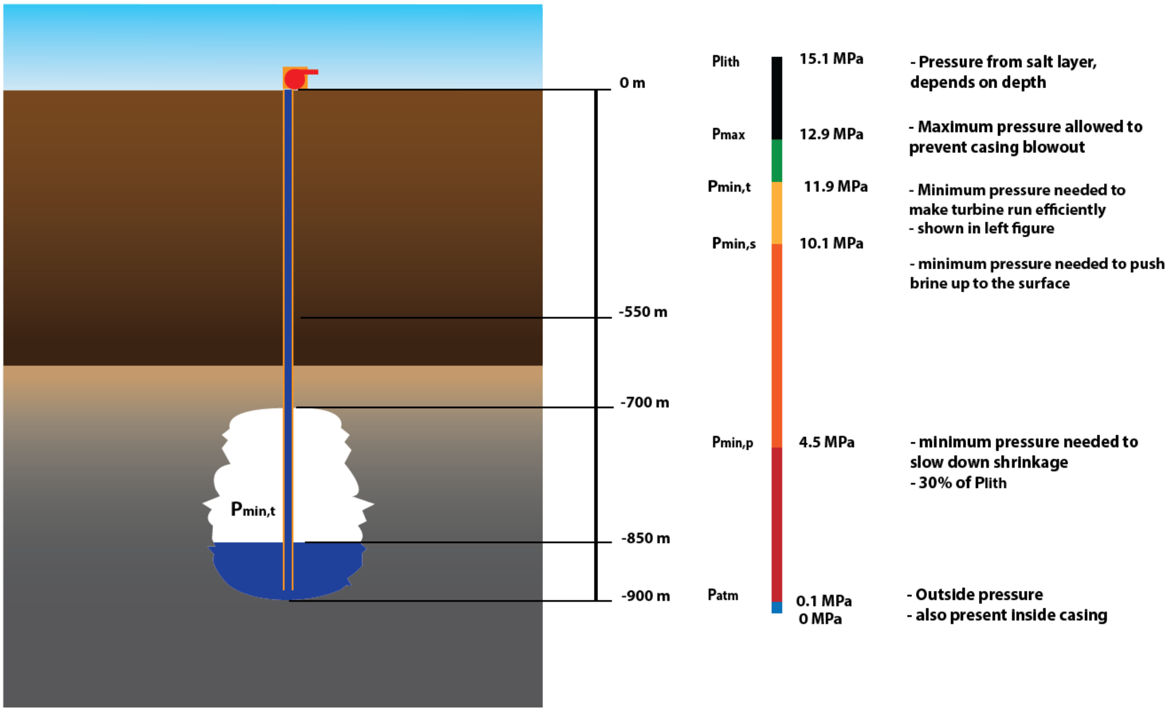

FIGURE 60 - SCHEMATIC OVERVIEW OF THE SYSTEM AND THE WORKING PRESSURES, TAKING INTO ACCOUNT THE PUMP TURBINE EFFICIENCY.

Only a small part of displaceable and storable brine is left, as can be seen from the green working pressure range in the figure above. However, the average head difference increases. To slightly increase the displaceable volume, the same principle as the Higher Low-alternative is used again. $p_{min,t}$ is defined as the pressure where the head difference over the turbine is two-thirds of the maximum head. The water level at this pressure should be at a minimum. This means that the cavern is practically constant under high pressure. The amount of storage and output left is show below with an example.

The perfect cavern

The next challenge is to design the perfect cavern. Besides the demands as stated above, other external variables are important. The stability of the cavern is for instance very important. This could lead to a maximum diameter compared to the height. Available surface area could also limit the amount of storable brine. For the next part of this project, a cavern will be assumed that has favourable circumstances when it comes to these restrictions. The following dimensions will be used:

- Depth of the top of the cavern: $h_{top} = -900m$
- Diameter of the cavern: $D_{cavern} = 150m$
- Efficiency of the system: $\eta = 75\%$
- Water depth: $d_{brine} = 10m$

The optimal height of the cavern (and therefore the underground capacity) can be calculated with the use of these variables. By running the calculations with different cavern heights, the relation between the cavern height and the energy storage capacity can be found. The results can be found below.

TABLE 54 - THE PUMP HEAD, DISPLACED VOLUME AND ENERGY STORAGE CAPACITY FOR DIFFERENT CAVERN HEIGHTS

Cavern Height [m]	Average pump head [m]	Displaced Volume [m^3]	PHS Pressure Cavern storage capacity [MWh]
100	353	1.49E+05	128.8
110	344	1.62E+05	136.7
120	336	1.73E+05	142.5
130	328	1.83E+05	147.4
140	321	1.92E+05	151.1
150	313	2.00E+05	153.3
160	305	2.08E+05	155.6
170	297	2.14E+05	155.7
180	288	2.20E+05	155.6
190	280	2.25E+05	154.5
200	273	2.29E+05	153.0
210	264	2.33E+05	151.0
220	256	2.35E+05	147.5
230	248	2.37E+05	144.3
240	240	2.38E+05	140.1
250	232	2.38E+05	135.2

Table 54, which can be seen above, states the different cavern heights for which the pump head, displaced volume and the storage capacity is calculated. The turning point in maximum storage capacity can be seen in the last column. The results from the calculations are further clarified in the figures below.

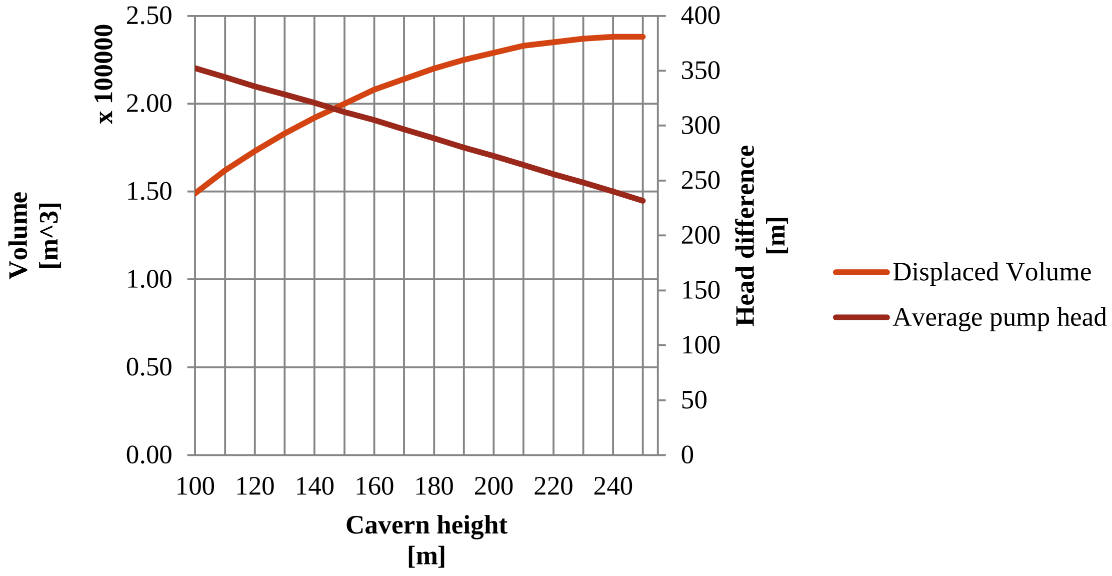

FIGURE 61 - CHANGE OF DISPLACED VOLUME AND AVERAGE PUMP HEAD FOR DIFFERENT CAVERN HEIGHTS

When the lines in Figure 61 are studied in more detail, it is clear why the storage capacity has a maximum. The average pump head has a steady and linear decline when the cavern height is increased. However, the displaced volume shows a different path. While it increases rapidly when increasing the cavern height for relative low heights, this increase declines when the height is further increased. This will lead to a point where the relative increase of the displaced volume is equal to the relative pump head decrease, where the storage capacity is at its peak.

FIGURE 62 - CHANGE OF ENERGY STORAGE CAPACITY FOR DIFFERENT CAVERN HEIGHTS

This peak is illustrated in Figure 62. The peak is situated at a cavern height of 170 meters. The optimal cavern height depends on the depth of the cavern. The displaceable volume is however not directly affected by the height of the cavern itself, but on the height difference between the top of the cavern and the brine level at uncharged state. In this case, a minimal brine level of 10 meters was assumed. This means that the optimal height difference is 160 meters. Only the compressibility of air is considered in the calculations in this phase of the project. This means that there is no difference between a 170 meter high cavern with a 10 meter brine depth and a 260 meter cavern with a minimal brine level of 100 meter when the storage capacity is concerned.

This may turn out convenient when an abandoned salt cavern is chosen to be used for energy storage with the use of PHS Pressure Cavern. When a cavern is chosen that is too small, the cavern can be enlarged by extending the salt solution mining for a certain amount of time. This is not possible for caverns that are too high. These caverns can however use the principle stated above. The minimal brine level can be enlarged up to the level where the cavern has an optimal storage capacity.

H.2.2. Structural components

As previously stated, the PHS Pressure Cavern consists of only a few structural components. Besides, almost all of these are safe and easily accessible placed at the surface. The only underground part consists of the pipe, which needs to be extended into the brine and needs to be air-tight around it.

To find out what the dimensions of the pipe would possibly be and the possible storage and power output, the extreme case of a very big and deep cavern is used. This cavern will have the following characteristics:

- Cavern top: -900 m.
- Dimensions: 150 m diameter, height of 170 m.
- Brine height: 10 m
- Pump turbine can efficiently operate between $\frac{2}{3}H_{max} and\ H_{max}$
- p_{min} at point where head over turbine is $\frac{2}{3}H_{max}$

When these variables are used as input, these properties will result:

TABLE 55 - PHS PRESSURE CAVERN CAVERN PROPERTIES AND THEIR VALUES FOR A CHOSEN CAVERN

Cavern property	Description	Value	[unit]
Capacity	The total underground space	$2.8 \cdot 10^6$	m^3
Displaceable capacity	Total amount of water that can be used for storage	$2.1 \cdot 10^5$	m^3
Minimum pressure	Pressure at which the water is at its lowest point	15.3	MPa
Maximum pressure	Pressure at which the water is at its highest point	16.5	MPa
Well pressure	Maximum pressure inside borehole	4.2	MPa
Minimum head	Minimum head level inside borehole (brine)	$2.4 \cdot 10^2$	m
Maximum head	Maximum head level inside borehole (brine)	$3.6 \cdot 10^2$	m

When the cavern is used for night-day time shift, it should be possible for the facility to run for several hours at capacity. For this calculation, a total time of three hours is chosen. This amount of time is based on the daily differences in energy use. This shows that during the day two peaks are present. These peaks will last for a couple of hours each. A choice for three hours is chosen as approximation for the optimal duration. A shorter duration will result in a more expensive pump turbine, because of the higher power output, which runs only a small portion of the day. A longer duration however limits the difference between the average peak price and the average off-peak price. Also, less power output can be sold for secondary services. Further calculations might change the optimal running time. For the remainder of this research, a running time of three hours is assumed. The cavern should therefore be able to run three hours on full capacity between charged- and uncharged state. The discharge becomes:

$$Q_{average} = \frac{V_{displaced}}{t_{runtime}} = \frac{2.1 \cdot 10^5}{10800} = 19.8\ m^3/s;$$

The average discharge is needed for capacity and revenue calculations. During operation, this average discharge will be maintained. Because the head difference decreases over time, this means that the power output will decrease linearly from beginning towards the end of operation. The Pump turbine needs to be designed for the highest power output. This is needed because the effective range of a pump turbine reaches much further below the design output than above. Therefore, a value closer to the maximum output is chosen for cost purposes. Also input for this formula is the average head difference during a cycle. The head starts at full capacity at maximum head level. It gradually declines until the minimum head level is reached at $\frac{2}{3} \cdot H_{max}$. When operation is continued, the turbine will run below economic efficiency. The average head difference can be computed:

$$H_{average} = \frac{H_{max} + \frac{2}{3}H_{max}}{2} = \frac{3.6 \cdot 10^2 + 2.4 \cdot 10^2}{2} = 3.0 \cdot 10^2\ m$$

The maximum head is also an important factor. Like was the case for the discharge, the maximum power output is needed, which depends on the maximum head difference. The average power output of this facility is determined at:

$$P_{average\ output} = \eta_{rountrip} \cdot \rho_{brine} \cdot g \cdot H_{average} \cdot Q_{average} = 52\ MW$$

To give an indication of this output: the total worldwide energy storage capacity in 2013 was $1.4 \cdot 10^5\ MW$. Therefore, 100 of these caverns would take up 4% of the total worldwide capacity. Besides, if traditional Pumped Hydro Storage would not be taken into account, it would take only eighteen of these caverns to be able to provide more energy storage output than all other technologies worldwide combined.

Borehole design

The borehole needs special attention, because it will be exposed to high pressures and a constant change in pressures. Besides, it will be almost a kilometre long through different soil layers and the last 160 meters will run free within the salt cavern. The most extreme situations appear when the water inside the cavern is at the lowest level and at the highest level.

When the pressure inside the cavern is at a minimum, the pressure from the water on the inside of the pipeline is at its lowest. On the other side, the ground is also pushing on the borehole. The casing should therefore be able to withstand the ground pressures. When the pressure inside the cavern is at a maximum, the casing would be exposed to large forces from the inside.

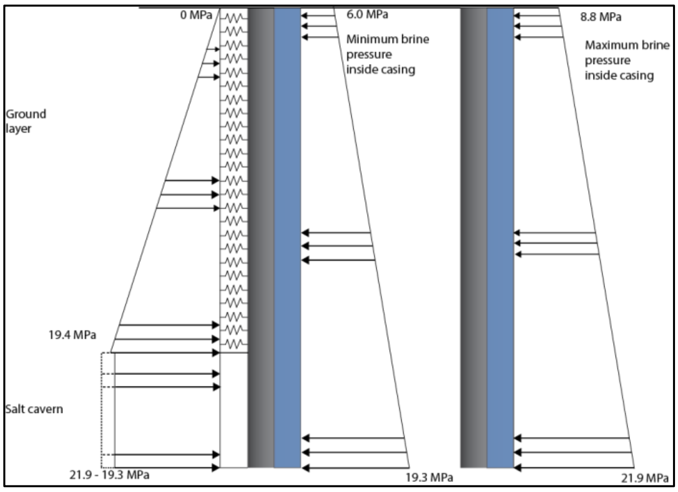

FIGURE 63 - PRESSURES ON THE PIPELINE FROM THE OUTSIDE AND THE INSIDE FOR DIFFERENT SCENARIOS

Using the same form of simplification as used earlier, these pressures can be used to calculate the compressive or tensile forces inside the casing material. First however, the diameter of the pipeline is needed. This can be determined with both the discharge and the wanted brine velocity inside the pipeline according to:

$$D_{shaft} = 2 \cdot \sqrt{\frac{Q_{max}}{U \cdot \pi}}; \quad [m]$$

A trade-off appears with the construction costs at one end and the need for a high power output at the other. For the construction of the PHS Pressure Cavern, a shaft of 1.5 meter is choses in this phase.

Surface facility design

This part of the system consists of two main components: the surface reservoir and the Pump turbine- and control station. For both components, the demand to limit the surface space use is important. The initial salt solution mining takes a very limited space[28] and can therefore be placed relatively close to urban environments. The surface reservoir however, needs a lot of space. This can be a problem, depending on the individual situation. For this cavern, a square reservoir with sides of 400 metres is needed, provided an average depth of 5 metres. This can be a problem when permits are concerned. The surrounding inhabitants will only agree when the safety can be assured, which is however hard to prove with this new technology.

The Pump turbine- and control station (PTC-station) needs to house all other components of the energy storage facility and will act as the heart of the system. The turbine needs to be connected with a power generator, which is in turn connected to the national grid. The output might have to be changed in a transformer before it can be used at the grid. Another important part of this station is the measuring and control of the entire system. Especially important is the control for possible losses. When the system has an inexplicable loss of pressure or brine, this could indicate a problem in one of the reservoirs. This could mean that the high pressure has forced the air through the salt layer, the well cap losing its air-tightness, or a leak in the surface reservoir.

TABLE 56 - PHS PRESSURE CAVERN SURFACE STRUCTURES AND THEIR SURFACE IMPACT

Structure	Component	Description	Required area
Surface reservoir	Reservoir	Closed-off brine storage (5m deep)	$43{,}000\ m^2$
PTC-Station			
	Pump turbine	Pumping brine in- and out the cavern	$625\ m^2$
	Control room	Measuring pressures and controlling activities	$150\ m^2$
	Transformer room	Transforms power out to useable electricity for the grid	$200\ m^2$
		Total PTC-Station	$\pm 1000\ m^2$

[28] Most of the time the need for surface space is not more than a shed of some square metres.

H.3. Economic analysis: PHS Pressure Cavern

This second option can be analysed economically much easier than the first alternative. Due to the lower efficiency, the benefits will be lower. However, the costs will be much lower as well, as all the construction is done above ground and almost all components are composed of commonly used parts. This lowers the risk significantly and therefore increases the possibility of an economic feasible option.

There are only two downsides to this story. Firstly, the borehole needs to be widened in order to enable the maximum flow through the shaft. This shaft will have to resist major forces from all sides, while having a much larger diameter than the usual boreholes.

Secondly, the impact on the surface is much higher. Therefore, acquiring of the needed space could result in additional costs and the project could be delayed due to resistance from the surrounding neighbourhood. Also this alternative will be quantified with the use of a NPV-calculation

H.3.1. PHS Pressure Cavern NPV-calculation

A NPV-calculation can objectively judge whether a project has a high chance of becoming profitable or not. A couple of variables are needed, that can have a large impact on the possible profitability of the project.

TABLE 57 - IMPORTANT NOTIONS CONCERNING THE PHS PRESSURE CAVERN-SYSTEM

Variable	Description	Value
Risk-free rate	The interest percentage that can be achieved without risk. Usually based on the interest rate of government bonds or interbank loans.	3%
Risk premium	The amount of additional interest that is demanded to offset the additional risk compared to the risk-free rate. Also incorporated is opportunity cost, which is the additional interest that can be achieved by investing in projects with comparable risks.	4%
Project time	The length of time in which the project is projected to generate costs and benefits.	50 years
Profit per kWh	The amount of money that can be earned by buying 1 kWh of energy at night and selling 1 kWh during the day	€0,04
Unit running price	The amount of money it costs to run the energy storage plant for 1 MWh	€0,50

Costs

One of the major components of a NPV-calculation is the costs. A good approximation of the costs can be achieved by breaking down the project in its components and valuating these accordingly. Below, the costs are divided into the structural components of the project, which in turn are divided into components again. The amount of costs of the smaller components is drawn from experience, reference projects or other literature. The sources are listed in the program and can be found in **Appendix 123G.3**.

TABLE 58 - CONSTRUCTION COSTS PHS PRESSURE CAVERN

Component	subcomponent	*Costs [euros]*	*Component costs [euros]*
PTC-station			
	Pump turbine	15.6 million	
	Control System	0.1 million	
	Transformer system	2 million	
	Construction PTC-station	0.8 million	
			18.5 million
Pipelines			
	Casing	0.4 million	
	Connections	5,000	
	Air-tight seal	10,000	
	Widening of borehole	1.5 million	
	Placement Casing	0.4 million	
			2.2 million
Surface reservoir			
	Ground removal	1.2 million	
	Dike construction	0.3 million	
	Surface reservoir watertight foil	0.2 million	
	Construction surface reservoir	20,000	
			1.7 million
Preparation			
	Design (5% of subt.)	1.5 million	
	Acquiring permits	0.2 million	
	Acquiring land	2.1 million	
	Informing stakeholders	6,000	
	Testing	0.5 million	
	Risk (6% of subt.)	2 million	
			6.3 million
Subtotal			28.6 million
	To be designed (10%)		2.9 million
	Indirect costs (14%)		4.0 million
	Unforeseen (10%)		2.9 million
Total			38.4 million

The costs of this alternative show several similarities with the Concrete Bubble-system. Still a lot has to be designed and several unknowns need to be clarified. The Pump turbine is the most important cost, which fills up half of the total projected costs. Maintenance costs are kept at 1% of the total construction costs. The construction costs themselves are divided over the first years. It has been chosen that 30% of the costs will be accounted for in the first year, 50% in the second and 20% in the third. The construction time is assumed at 2.25 years.

Revenues

The revenues are computed in the same way as the revenues of the Concrete Bubble-alternative. A few differences emerge when the storage capacity and the height difference is concerned. Although the storage capacity is significantly lower, the average height difference is higher. Together, the power output which can be maintained for three hours is lower for the PHS Pressure Cavern-system. Also slightly less energy can be stored, which will affect the yearly revenues. The amount of revenues from arbitrage can be seen in the following table:

TABLE 59 - ARBITRAGE OPPORTUNITIES FOR THE PHS PRESSURE CAVERN-SYSTEM

Variable	Description	Value
Price difference	The difference in price between a kWh of electricity during daytime and night-time	€0.04
Storage capacity	Amount of kWh that can be stored in one cycle	156,000 kWh
Yearly revenues	Money earned from arbitrage by using one cycle every day for 90% of the days in a year.	€2.5 million

The amount of revenues from production capacity deferral is also calculated. Again, because of the lower power output, the revenues will be slightly lower.

TABLE 60 - PRODUCTION DEFERRAL OPPORTUNITIES FOR THE PHS PRESSURE CAVERN-SYSTEM

Variable	Description	Value
Power output	Amount of MW that can be produced by the storage facility at full use.	52 MW
Deferred plant production	Amount of production capacity that will be used and made less due to the storage facility. Based on the estimate that this will be equal to 60% of the storage power output.	40 MW
Capital cost gas-powered plant	Costs to build a natural gas-powered plant per kW production capacity. Based on EIA estimate minus 25% financial costs.	€548.00/kW
Fixed O&M costs natural gas plant	Costs to operate and maintain a natural gas plant per kW production capacity.	€8.00/kW
Equivalent annual payments natural gas plant	Amount of yearly investments deferred due to the construction and use of the storage facility. A lower threshold rate is used because of the lower risk of conventional technology (5%).	€1.2 million/ year

Scenarios

The future is uncertain, which is even more the case when the future of energy use and production is concerned. Political standpoints, international agreements and technological innovation are constantly changing the future projections. This can however have a large impact on the economic feasibility of the project. To examine the influence that this difference in future scenarios can have on the profitability of the project, six scenarios are sketched.

The first distinction is made based on the future of arbitrage revenues. This is directly linked to the difference in price between daytime- and night-time electricity. Whether this price difference will decrease, due to a thriving energy storage market, or increase due to a rapid rise in renewable energy production, is still uncertain. The second distinction is based on the production deferral. The main issue is whether or not a way has been found to redirect the benefits from production deferral toward the investing companies. Examples on how to do this have been named in previous subchapters.

These six scenarios can be calculated with the use a NPV-calculation. The costs and revenues are discounted over the years with a threshold rate of 7%. This rate is based on a risk-free rate of 3% and a risk premium of 4%. This means that a profit of 7% is expected for investments with comparable risk involved. Every positive NPV value will therefore lead to the conclusion that a higher profit is expected for comparable risk, which will increase the incentive to invest in the project. The table below shows the six scenarios and the amount of NPV that it will lead to. Also projected is the payback period.

TABLE 61 - NET PRESENT VALUE CALCULATIONS AND PAYBACK PERIODS FOR DIFFERENT SCENARIOS

Scenario	*Description*	*Total project NPV [euros]*	*Payback Period*
1A	Decreasing arbitrage, no production deferral	-15.2 million	-
2A	Constant arbitrage, no production deferral	-8.6 million	-
3A	Increasing arbitrage, no production deferral	0.8 million	46 years
1B	Decreasing arbitrage, with production deferral	2.5 million	28 years
2B	Constant arbitrage, with production deferral	9.2 million	24 years
3B	Increasing arbitrage, with production deferral	18.5 million	21 years

The development of the NPV's of the scenarios over the years is shown in the figure below.

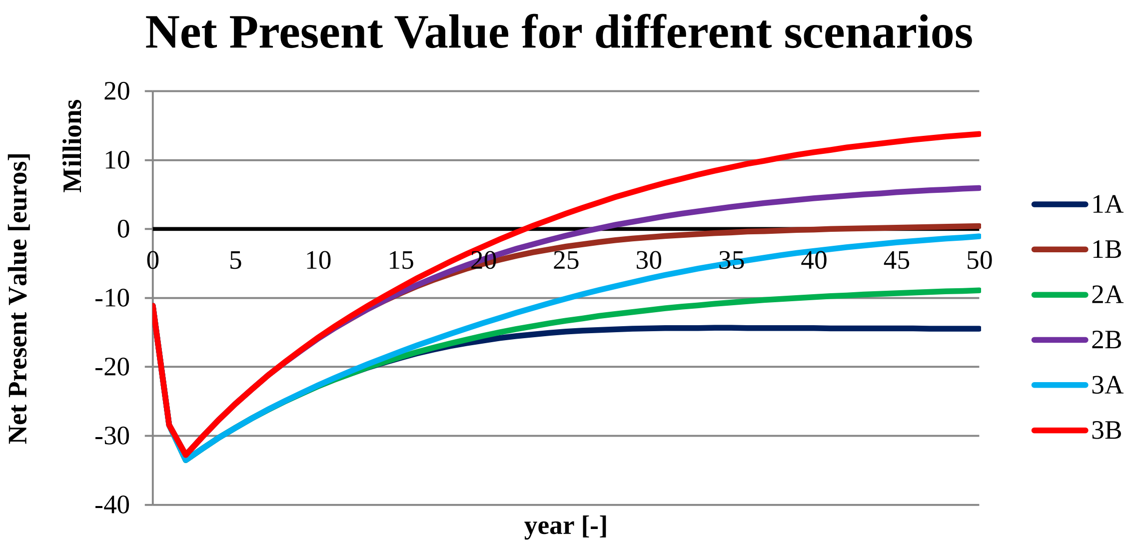

FIGURE 64 - NET PRESENT VALUE CALCULATIONS OVER TIME FOR DIFFERENT SCENARIOS OF THE PHS PRESSURE CAVERN-SYSTEM

H.3.2. Maple files used

These calculations have been done with use of Maple 17 and are used for the calculation of pressures and brine heights for the use of PHS Pressure Cavern.

Input

First, the starting constants and variables are stated. The following abbreviations are used:

TABLE 62 - PHS PRESSURE CAVERN CONCEPTUAL DESIGN MAPLE INPUT VARIABLES

Input variable	Description	Value	
***rho*1**	density of fluid inside the cavern	1200	kg/m^3
rho2	density of fluid inside the shaft	1200	kg/m^3
rhow	Density of fresh water	1000	kg/m^3
***v*1**	Velocity of fluid inside the cavern	0	m/s
***v*2**	Velocity of fluid inside the shaft	0	m/s
g	Gravitational constant	9.81	m/s^2
htop	Depth of top of the cavern	-900	m
diam_cavern	Cavern diameter	150	m
h_cavern	Cavern height	170	m
h_surface	Surface level	0	m
p_atmospheric	Atmospheric pressure	$1 \cdot 10^5$	Pa
eta_roundtrip	Roundtrip efficiency	75	%

Also calculated is the 'hes', which is the height of the water level inside the cavern in uncharged state. This is equal the depth of the top of the cavern minus the height of the cavern plus 10 meters minimum water height.

> $rho1 := 1200; rho2 := 1200; v1 := 0; v2 := 0; g := 9.81; htop := -900; diam\_cavern := 150; h\_cavern := 170; h\_surface := 0; p\_atmospheric := 1E5; eta\_roundtrip := 0.75; hes := htop - h\_cavern + 10;$

$$\rho1 := 1200$$

$$\rho2 := 1200$$

$$v1 := 0$$

$$v2 := 0$$

$$g := 9.81$$

$$htop := -900$$

$$diam\_cavern := 150$$

$$h\_cavern := 170$$

$h\_surface := 0$

$p\_atmospheric := 1.\ 10^5$

$eta\_roundtrip := 0.75$

$hes := -1060$

Process

This script calculates the first option. It forms the main boundaries for the water levels at minimum and maximum pressure. The following important input parameters are used:

TABLE 63 - PHS PRESSURE CAVERN CONCEPTUAL DESIGN MAPLE PRESSURE INPUT VARIABLES

Input variable	Description	Formula	Value	
plith	Geostatic pressure	$0.216 \cdot 10^6 \cdot (-htop)$	$19.4 \cdot 10^6$	Pa
pmin	Minimum pressure	30% of plith	$5.8 \cdot 10^6$	Pa
pmax	Maximum pressure	85% of plith	$16.5 \cdot 10^6$	Pa
p1	Pressure in cavern at minimum level	Equal to pmin	$5.8 \cdot 10^6$	Pa

The volume of the cavern at uncharged state (V_empty_state) is also calculated by simplifying the shape of the cavern as a cylinder and multiplying the area with the height at uncharged state. The volume and water height at maximum pressure (V_full_state and hfs respectively) can then be calculated with the ideal gas law. The amount of air and the temperature are kept constant, which results in:

$$p_{min} \cdot V_{empty\ state} = p_{max} \cdot V_{full\ state}$$

Also stated is the formula of Bernoulli, which compares the situation at the water level inside the cavern with the situation at the water level inside the shaft. With this formula, the water head inside the shaft (hwell) can be calculated. The answer is given in the next part.

> $A\_cavern := 3.1415 \cdot \left(\frac{diam\_cavern}{2}\right)^2; Vcavern := A\_cavern \cdot h\_cavern;$

$A\_cavern := 17670.93750$

$Vcavern := 3.004059375\ 10^6$

> $plith := 0.216 \cdot (-htop) \cdot 100000; pmin := 0.30 \cdot plith; pmax := 0.85 \cdot plith; p1 := pmin;$

$plith := 1.944000000\ 10^7$

$pmin := 5.832000000\ 10^6$

$pmax := 1.652400000\ 10^7$

$p1 := 5.832000000\ 10^6$

> $eq1 := \frac{1}{2} \cdot rho1 \cdot v1^2 + rho1 \cdot g \cdot hes + p1 = \frac{1}{2} \cdot rho2 \cdot v2^2 + rho2 \cdot g \cdot hwell + p\_atmospheric;$

$$eq1 := -6.646320000\ 10^6 = 1.\ 10^5 + 11772.00\ hwell$$

> $V\_empty\_state := A\_cavern \cdot (htop - hes); V\_full\_state := \frac{V\_empty\_state \cdot pmin}{pmax}; hfs := \mathrm{htop} - \left(\frac{V\_full\_state}{\mathrm{A\_cavern}}\right);$

$$V\_empty\_state := 2.827350000\ 10^6$$

$$V\_full\_state := 9.978882353\ 10^5$$

$$hfs := -956.4705882$$

Output

This part shows the answers of the computations. First the height of the water head inside the shaft is derived from the formula in the last part. It shows to be -573 m, which is somewhat more than half of the depth. Another important property is the totally displaceable volume (Vdisplaced) and the part of the cavern which can be used for displaceable water (Cavern_usage). This turns out to be 61%, but has the problem that the water head is much lower than the surface level.

> $hwell := solve(eq1, hwell);$

$$hwell := -573.0818892$$

> $Vdisplaced := V\_empty\_state - V\_full\_state;$

$$Vdisplaced := 1.829461765\ 10^6$$

> $Cavern\_usage := \frac{Vdisplaced}{Vcavern};$

$$Cavern\_usage := 0.6089965399$$

One way Pump turbine

These calculations are used to simulate the situation where the water head is not decreased below the surface level. This way, the pump and turbine only have to work one way. This is done by using the Bernoulli equation at the points of the water level inside the cavern (h_oneway) with matching pressure (p_oneway) and the point of the water head, which is at the surface.

Also included is the pressure inside the shaft and the corresponding water head at maximum pressure (p_well and H_ph).

> $eq2 := A\_cavern \cdot (htop - h\_oneway) = \frac{V\_empty\_state \cdot pmin}{p\_oneway};$

$$eq2 := -1.590384375\ 10^7 - 17670.93750\ h\_oneway = \frac{1.648910520\ 10^{13}}{p\_oneway}$$

> $eq3 := \frac{1}{2} \cdot rho1 \cdot v1^2 + rho1 \cdot g \cdot h\_oneway + p\_oneway = \frac{1}{2} \cdot rho2 \cdot v2^2 + rho2 \cdot g \cdot h\_surface + p\_atmospheric;$

$$eq3 := 11772.00\ h\_oneway + p\_oneway = 1.\ 10^5$$

> $solutions := solve(\{eq2, eq3\}, \{h\_oneway, p\_oneway\}, useassumptions)$ assuming $h\_oneway :: negative;$

$$solutions := \{h\_oneway = -980.1744940, p\_oneway = 1.163861414\ 10^7\}$$

> $assign(\%);$

> $V\_oneway := A\_cavern \cdot (htop - h\_oneway);$

$$V\_oneway := 1.416758473\ 10^6$$

> $V\_displaced\_oneway := V\_oneway - V\_full\_state;$

$$V\_displaced\_oneway := 4.188702377\ 10^5$$

> $Cavern\_usage\_oneway := \frac{V\_displaced\_oneway}{Vcavern};$

$$Cavern\_usage\_oneway := 0.1394347399$$

> $p\_well := rho1 \cdot g \cdot hfs + pmax;$

$$p\_well := 5.26442823\ 10^6$$

> $H\_ph := \frac{1000}{rho1} \cdot \frac{0.102}{1000} \cdot p\_well;$

$$H\_ph := 447.4763996$$

Capacity calculation

Next step is to calculate the amount of energy that can be stored this way. The capacity that can be stored is determined by the power output of the turbine and the amount of water which can be displaced inside the cavern:

$$E_{capacity} = \eta_{roundtrip} \cdot \rho_{brine} \cdot g \cdot H_{average} \cdot V_{displaced}; \qquad [J]$$

When compared to the amount of energy produced every day (Total_Production_NL_Daily), this turns out to be 0.09% of this figure. From this, the amount of underground space needed can be calculated (Salt_cavern_capacity_needed). This can be compared to the amount of underground space needed in for the standard case (indexed_change), which was explained in Chapter H.2.1.

> $E\_capacity := eta\_roundtrip \cdot rho1 \cdot g \cdot \left(\frac{H\_ph}{2}\right) \cdot V\_displaced\_oneway;$
> $Total\_Production\_NL\_Daily := \frac{98.4E+3}{365};$

$$E\_capacity := 8.274298025\ 10^{11}$$

$$Total\_Production\_NL\_Daily := 269.5890411$$

> $E\_capacity\_GWh := \frac{E\_capacity}{3.6 \cdot 10^{12}};$

$$E\_capacity\_GWh := 0.2298416118$$

> $portion\_production\_stored := \frac{E\_capacity\_GWh}{Total\_Production\_NL\_Daily};$

$$portion\_production\_stored := 0.0008525628893$$

$$> Salt\_cavern\_capacity\_needed := \frac{1}{portion\_production\_stored} \cdot Vcavern;$$

$$Salt\_cavern\_capacity\_needed := 3.523563379\,10^{9}$$

$$> Comparable\_size\_caverns\_needed := \frac{Salt\_cavern\_capacity\_needed}{Vcavern};$$

$$Comparable\_size\_caverns\_needed := 1172.934000$$

$$> indexed\_change := \frac{Salt\_cavern\_capacity\_needed}{6.069688873\,10^{9}} \cdot 100;$$

$$indexed\_change := 58.05179563$$

Higher low-alternative

The computations below show the situation in which the 'Higher low'-alternative is used. This is further explained in Chapter H.2.1. Also here the formula of Bernoulli is used. This time however, the water heights and the pressure inside the shaft are fixed. This results in the minimum pressure needed inside the cavern to keep the water level inside the cavern at minimum level and the water level inside the shaft at the surface (p_hla).

All previous calculations are repeated to make it possible to compare the option with the previous situations. It shows that a larger part of the cavern can be used (Cavern_usage_hla) and a significantly smaller amount of underground space is needed (Salt_cavern_capacity_needed_hla).

$$> eq5 := \frac{1}{2} \cdot rho1 \cdot v1^2 + rho1 \cdot g \cdot hes + p\_hla = \frac{1}{2} \cdot rho2 \cdot v2^2 + rho2 \cdot g \cdot h\_surface + p\_atmospheric;$$

$$eq5 := -1.247832000\,10^{7} + p\_hla = 1.\,10^{5}$$

$$> p\_hla := solve(eq5, p\_hla);$$

$$p\_hla := 1.2578320\,10^{7}$$

$$> V\_full\_state\_hla := \frac{V\_empty\_state \cdot p\_hla}{pmax}; \mathrm{hfs\_hla} := \mathrm{htop} - \left(\frac{V\_full\_state}{\mathrm{A\_cavern}}\right);$$

$$V\_full\_state\_hla := 2.152221802\,10^{6}$$

$$hfs\_hla := -956.4705882$$

$$> V\_displaced\_hla := V\_empty\_state - V\_full\_state\_hla;$$

$$V\_displaced\_hla := 6.75128198\,10^{5}$$

$$> Cavern\_usage\_hla := \frac{V\_displaced\_hla}{Vcavern};$$

$$Cavern\_usage\_hla := 0.2247386332$$

$$> p\_well\_hla := rho1 \cdot g \cdot hfs\_hla + pmax;$$

$$p\_well\_hla := 5.26442823\,10^{6}$$

$$> H\_ph\_hla := \frac{1000}{rho1} \cdot \frac{0.102}{1000} \cdot p\_well\_hla;$$

$$H\_ph\_hla := 447.4763996$$

$$> E\_capacity\_hla := eta\_roundtrip \cdot rho1 \cdot g \cdot \left(\frac{H\_ph\_hla}{2}\right) \cdot V\_displaced\_hla;$$

$$E\_capacity\_hla := 1.333637822\,10^{12}$$

$$> E\_capacity\_GWh\_hla := \frac{E\_capacity\_hla}{3.6 \cdot 10^{12}};$$

$$E\_capacity\_GWh\_hla := 0.3704549506$$

$$> \ efficiency\_potential := \frac{E\_capacity\_GWh\_hla}{1.72};$$

$$efficiency\_potential := 0.2153807852$$

$$> \ portion\_production\_stored\_hla := \frac{E\_capacity\_GWh\_hla}{Total\_Production\_NL\_Daily};$$

$$portion\_production\_stored\_hla := 0.001374146920$$

$$> \ Salt\_cavern\_capacity\_needed\_hla := \frac{1}{portion\_production\_stored\_hla} \cdot Vcavern;$$

$$Salt\_cavern\_capacity\_needed\_hla := 2.186126775\ 10^{9}$$

$$> \ Comparable\_size\_caverns\_needed\_hla := \frac{Salt\_cavern\_capacity\_needed\_hla}{Vcavern};$$

$$Comparable\_size\_caverns\_needed\_hla := 727.7242232$$

$$> \ indexed\_change := \frac{Salt\_cavern\_capacity\_needed\_hla}{6.069688873\ 10^{9}} \cdot 100;$$

$$indexed\_change := 36.01711424$$

Turbine efficient range

A large drawback to this design is the head difference decreasing towards zero. This affects the efficiency of the turbine and pump for a great deal. In common practice, a Pump turbine is designed for the largest head. After this, a range is defined between which the Pump turbine can operate. Usually this is defined as:

$$Turbine\ efficient\ range\colon\ \frac{2}{3}H_{max} < H_{operation} < H_{max}$$

This largely limits the amount of water than can be used for the storage of energy. In the computations below, the minimal and maximum head is defined (H_min and H_max). With the use of calculations that have used earlier, the displaced volume is calculated. This turns out to be much less than the amount of water than can be displaced in the previous cases. Although this also leads to a much higher average head, the smaller volume will lead to a much smaller plant in the end. Instead of a 1.17 GWh storage facility, only 0.16 GWh of energy can be stored now.

To discover the consequences of implementing such a plant, the power output of the storage facility is calculated. The discharge is a necessary variable in this equation. The chosen discharge is the discharge needed to be able to run three hours on full capacity before the cavern is uncharged.

The result is a 52 MW average power output Pumped Hydro Storage facility with the use of a Salt Cavern, able to store enough energy to run on full capacity for three hours.

$$> \ eq1 := rho1 \cdot g \cdot h\_empty + P\_min = P\_well\_min;$$

$$eq1 := P\_min + 11772.00\ h\_empty = P\_well\_min$$

$$> \ eq2 := rho1 \cdot g \cdot h\_full + P\_max = P\_well\_max;$$

$$eq2 := P\_max + 11772.00\ h\_full = P\_well\_max$$

$$> \ eq3 := V\_full = \frac{V\_empty \cdot P\_min}{P\_max};$$

$$eq3 := V\_full = \frac{2.827350000\ 10^{6}\ P\_min}{P\_max}$$

$$> \ eq4 := V\_full = (htop - h\_full) \cdot A\_cavern;$$

$$eq4 := V\_full = -1.590384375\ 10^{7} - 17670.93750\ h\_full$$

$$> eq5 := P\_well\_min = \frac{2}{3} \cdot P\_well\_max;$$

$$eq5 := P\_well\_min = \frac{2}{3} P\_well\_max$$

$$> eq6 := \mathrm{P\_max} = \mathrm{pmax}$$

$$eq6 := P\_max = 1.652400000\ 10^{7}$$

$$> eq7 := h\_empty = hes;$$

$$eq7 := h\_empty = -1060$$

$$> solutions := solve(\{eq1, eq2, eq3, eq4, eq5, eq6, eq7\}, \{P\_min, h\_empty, P\_well\_min, P\_max, h\_full, P\_well\_max, V\_full\})$$

$$solutions := \{P\_max = 1.6524000\ 10^{7}, P\_min = 1.527068130\ 10^{7}, V\_full = 2.612900071\ 10^{6}, h\_empty = -1060., h\_full = -1047.864259, P\_well\_max = 4.188541949\ 10^{6}, P\_well\_min = 2.792361299\ 10^{6}\}$$

$$> assign(\%)$$

$$> V\_displaced := V\_empty - V\_full;$$

$$V\_displaced := 2.14449929\ 10^{5}$$

$$> Cavern\_usage := \frac{V\_displaced}{Vcavern};$$

$$Cavern\_usage := 0.07138671452$$

$$> H\_min := \frac{rhow}{rho1} \cdot \frac{0.102}{1000} \cdot P\_well\_min; H\_max := \frac{rhow}{rho1} \cdot \frac{0.102}{1000} \cdot P\_well\_max; H\_average := \frac{H\_min + H\_max}{2};$$

$$H\_min := 237.3507104$$

$$H\_max := 356.0260656$$

$$H\_average := 296.6883880$$

$$> E\_capacity := eta\_roundtrip \cdot rho1 \cdot g \cdot H\_average \cdot V\_displaced;$$

$$E\_capacity := 5.617433923\ 10^{11}$$

$$> E\_capacity\_MWh := \frac{E\_capacity}{3.6 \cdot 10^{9}}; Total\_Production\_NL\_Daily := \frac{98.4E+6}{365};$$

$$E\_capacity\_MWh := 156.0398312$$

$$Total\_Production\_NL\_Daily := 2.695890411\ 10^{5}$$

$$> portion\_production\_stored := \frac{E\_capacity\_MWh}{Total\_Production\_NL\_Daily};$$

$$portion\_production\_stored := 0.0005788062844$$

$$> Salt\_cavern\_capacity\_needed := \frac{1}{portion\_production\_stored} \cdot Vcavern;$$

$$Salt\_cavern\_capacity\_needed := 5.190094607\ 10^{9}$$

$$> Comparable\_size\_caverns\_needed := \frac{Salt\_cavern\_capacity\_needed}{Vcavern};$$

$$Comparable\_size\_caverns\_needed := 1727.693750$$

$$> Hours\_full := 3; t := 3600 \cdot Hours\_full; Q\_brine := \frac{V\_displaced}{t};$$

$$Hours\_full := 3$$

$$t := 10800$$

$$Q\_brine := 19.85647491$$

$$> P\_pumpturbine\_average := \frac{eta\_roundtrip \cdot rho1 \cdot g \cdot H\_average \cdot Q\_brine}{1E+6};$$

$$P\_pumpturbine\_average := 52.01327707$$

H.3.3. Excel files used

To aid in the economic analysis in the conceptual design, Microsoft Excel has been used. In this Appendix, the sheets will be shown and clarified to give a more clear view on some of the choices that have been made and assumptions that have been done. Four sheets will be covered in this Appendix:

- Costs
- Benefits from arbitrage
- Benefits from other revenues
- Scenarios

Costs

The costs are very important to calculate accurately. However, in the current conceptual phase of the project several choices still need to be made that can have an influence on the total costs. To approach the real costs as close as possible, the costs are broken down into small pieces or tasks. Subsequently, these tasks are broken down in units, with a certain unit price. Unknown parts will be valuated based on reference projects.

The total costs are firstly broken down into the structural components. The table shows different colours. Orange indicates and input cell, where information based on other calculations or reference projects is put into the model. Red cells are the same, with the exception that sufficiently representative information is found. Because of the innovative nature of the project, these parts may be hard to valuate. Their impact is mostly small and therefore tolerated in this phase of the project. There is however some improvement possible here.

Cells without special colours are a result from other calculations.

TABLE 64 - CONSTRUCTION COSTS CALCULATION PHS PRESSURE CAVERN, CONCEPTUAL PHASE (EXCEL)

Construction costs - PHS Pressure Cavern								**Properties**	
		Total for project		**Costs per unit**				**% of sub total**	**% of total**
Costs		*Amount*	*[unit]*	*Amount*	*€/unit*	*Costs*	*Component costs*		
PTC-station[29]									
	Pump turbine	1	[-]	€ 18,636,800.00	€	€ 18,636,800.00		59%	44%
	Control System	1	[-]	€ 100,000.00	€	€ 100,000.00		0%	0%
	Transformer system	1	[-]	€ 2,000,000.00	€	€ 2,000,000.00		6%	5%
	Construction	1000	m2	€ 750.00	€/m2	€ 750,000.00		2%	2%
							€ 21,486,800.00	68%	51%
Pipeline[30]									
	Casing	620	ton	€ 600.00	€/ton	€ 372,000.00		1%	0%
	Connections	1	connections	€ 5,000.00	€/connection	€ 5,000.00		0%	0%
	Air-tight seal	1	[-]	€ 10,000.00	€	€ 10,000.00		0%	0%
	Widening borehole	900	m depth	€ 1,500.00	€/m depth	€ 1,350,000.00		4%	3%
	Placement Casing	1060	m depth	€ 400.00	€/m depth	€ 424,000.00		1%	1%
							€ 2,161,000.00	7%	5%

[29] Information on the (unit) costs of the structural elements of the PTC station are based on reference projects, with the most prominent one being (Hatch, 2010).

[30] The costs of the pipeline are based on reference projects with limited representative value. However, due to the small portion of the costs related to pipelines, this is not considered a large problem at this phase of the project.

Surface reservoir									
	Ground removal	300000	m3	€ 4.00	€/m3	€ 1,200,000.00		4%	3%
	Dike construction	30000	m3	€ 10.00	€/m3	€ 300,000.00		1%	1%
	Surface reservoir watertight foil	350000	m2	€ 0.50	€/m2	€ 175,000.00		0%	0%
	Construction reservoir	1	[-]	€ 20,000.00	€	€ 20,000.00		0%	0%
							€ 1,695,000.00	5%	4%
Preparation									
	Design	5%				€ 1,500,000.00		4%	3%
	Acquiring permits	0.5%				€ 170,000.00		1%	0%
	Acquiring land	43000	m2	€ 50.00	€/m2	€ 2,150,000.00		7%	5%
	Informing stakeholders	104	hours	€ 60.00	€/hour	€ 6,240.00		0%	0%
	Testing	5760	hours	€ 80.00	€/hour	€ 460,800.00		1%	1%
	Risk	6%				€ 2,000,000.00		6%	5%
							€ 6,287,040.00	20%	15%
Subtotal							€ 31,629,840.00	100%	75%
	To be designed	10	% of subtotal				€ 3,162,984.00	10%	7%
	Indirect costs	14	% of subtotal				€ 4,428,177.60	14%	10%
	Unforeseen	10	% of subtotal				€ 3,162,984.00	10%	7%
Total							€ 42,383,985.60	134%	100%

Some important conclusions can be drawn from Table 64. Firstly, by far the most important component of the system is the Pump turbine itself. Therefore, the costs estimate for this particular part should be worked out in more detail.

Table 65 - Calculation of construction costs for Pump turbine and running costs

Power output Plant		52	MW	
Storage capacity		156	MWh/cycle	
Yearly storage		78,624	MWh/year	
unit running price plant	€	0.50	€/MWh	
running price plant	€	39,312.00	€/year	
Levelled capital cost per MW	€	332,800.00	€/MW	Based on price of 400 $/kW in 2012
Capital costs PT		€ 46,592,000.00	€	

Arbitrage revenues

The revenues through arbitrage are split up into two parts. The first part consists on the base level of arbitrage revenue. The second focusses on the change over time, which is based on the future developments in the markets of energy, energy storage and renewable energy. The base level of arbitrage revenue can be found by multiplying the amount of revenue per kWh with the amounts of kWh that can be stored. This is shown in the table below.

Table 66 - Calculation of base level of arbitrage revenues

kWh storage	156000.0	kWh
Profit per kWh	0.04	€/kWh
profit per cycle	8960.0	€/cycle
Non-availability of plant	10	%
Days operative	328.5	days
Maximum yearly profit	2.9	million €

The second part of the revenues is depending on the different scenarios for the future of energy storage and renewable energy sources. This will be covered in the subchapter ‘scenarios’.

Revenues from other sources

Arbitrage is not the only revenue for energy storage facilities. Also named in the main report are production capacity deferral and fuel revenues. Firstly calculated is the revenue from production capacity deferral. Important to note is the portion of deferral conventional plant. This is the amount of conventional production capacity that will most likely be built less as a result of the construction of the energy storage facility. This has been chosen to be 60%, although this number could be much higher. Prices for conventional gas plant construction and maintenance are based on numbers from the US Energy Information Administration (EIA, 2013).

TABLE 67 - CALCULATION OF POSSIBLE REVENUES FROM PRODUCTION DEFERRAL

Power output	52	MW	
portion deferral conventional plant	60%		
Equivalent deferred plant production	31.2	MW	
Capital costs natural gas plant per kW	€ 548.04	€/kW	from EIA minus 25% financial costs
Capital costs natural gas plant	€ 21,483,000.00	€	
Fixed O&M costs natural gas plant per kW	€ 8.23	€/kW-yearly	from EIA minus 25% financial costs
Fixed O&M costs natural gas plant	€ 322,770.00	€ annual	
Conventional plant risk premium	2		Due to lower risk
Conventional plant threshold rate	5		
NPV Equivalent gas plant (capital only)	€ 19,485,714.29		Discounted for constr. time
Equivalent annual payments gas plant capital	€ 1,077,919.13		
Equivalent annual payments gas plant total	€ 1,400,689.13		equal to total deferred production capacity

As already mentioned earlier, the occurrence of revenues from production capacity deferral is still uncertain and depends on the investing company and its responsibilities. Therefore, a distinction is made where both the scenario with and without production deferral is taken into account.

Fuel revenue is another possible benefit from energy storage. Energy storage will lower the demand at peak moments, which will decrease the need for expensive gas production. Also it increases demand at off-peak moments, increasing the need for cheap coal and potential renewable energy sources. However, energy storage takes energy of the grid instead of individual production plants and these production facilities supply the grid as well. Therefore, the advantage that is caused by the energy storage is divided between the national production facilities. Because of this uncertainty, revenues from fuel substitution are not taken into account in this phase

Scenarios

For the development of arbitrage revenues over time, three scenarios are used. The first scenario predicts that the market of energy storage will play in significant factor the valuation of energy over time. This will result in a smaller difference between night-time and daytime prices and therefore lower revenue per kWh. This is modelled with a gradual decrease over a period of 30 years, starting ten years from the start of the project. This decrease will lower the revenues from base level to 10% of the base level.

The second scenario will keep the arbitrage revenues constant over time for the entire project period. This will simulate a situation where energy storage plays a small role in the world of electric energy, but the stabilizing effect it will have is offset by the increasing market for renewable energy. The last scenario will simulate the effect of a booming renewable energy market compared to a small energy storage market. The difference in price will increase over a course of 35 years, starting a few years after the start of the project. The increase will result in a total of double yearly revenues from arbitrage at the end of the project period. The change over time compared to the base level of arbitrage revenue can be seen in the figure below.

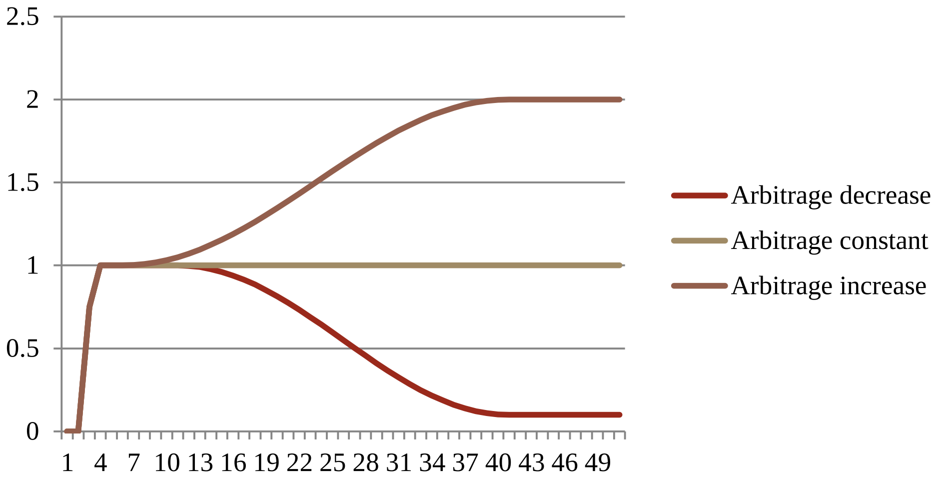

FIGURE 65 - CHANGE OF ARBITRAGE REVENUES COMPARED TO BASE LEVEL OVER TIME FOR DIFFERENT FUTURE PROSPECTS

When combined with the base level of arbitrage revenues and the presence (or non-presence) of production deferral, six scenarios of revenues can be distinguished. These scenarios refer to the decrease (1), constant (2) or increase (3) of arbitrage revenues and the difference between the companies that cannot (A) take production deferral into account and companies that can (B).

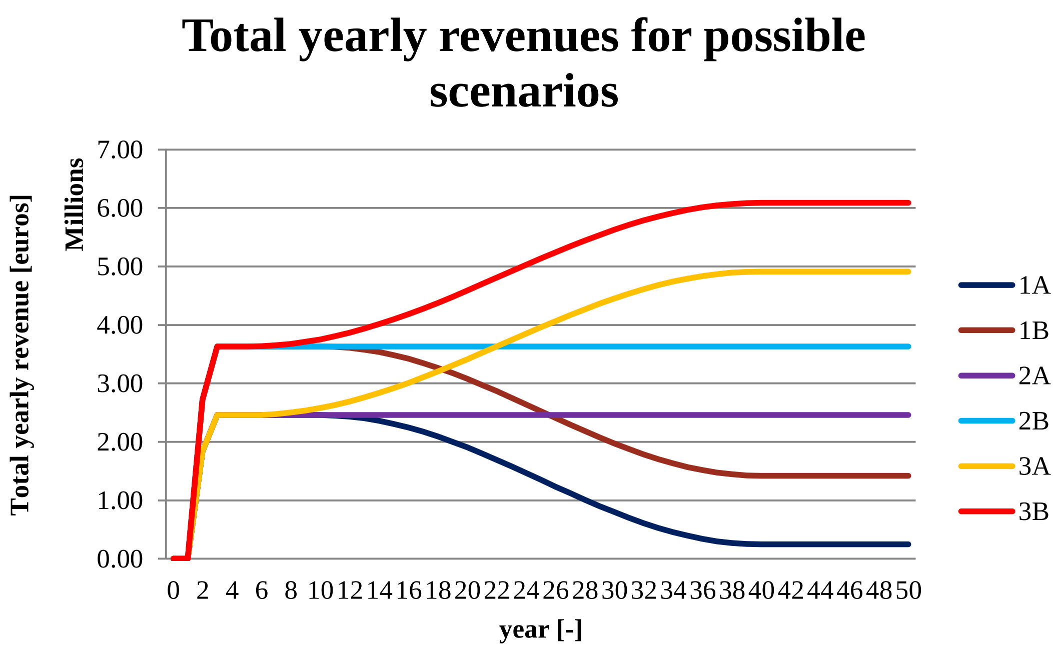

FIGURE 66 - REVENUES FROM ARBITRAGE FOR DIFFERENT SCENARIOS

These construction costs and revenues can be used as input for a Net Present Value calculation. Some other notions are important here. By far the most important is the discount factor. This factor decides with what percentage the future revenues will be discounted every year. This factor depends on the base level, which is based on amount of interest one would get from the safest form of investment possible. This safe form would normally be based on government bonds. This value is set at 3%. On top of this interest rate, also a risk-premium is used. This premium refers to the extra profit that is required to offset the additional risk. This is normally based on the principle of opportunity costs, which means that an investment done in energy storage is the loss of an investment done in another project. Therefore, to be really profitable it needs to be more profitable than other projects with equal risk. Although this cannot be calculated in this phase of the project yet, a risk premium of 4% is chosen. The total discount factor is therefore 7%.

Also important is the dividing of the construction costs over the construction period. No accurate calculations can be made yet, so an assumption is made of 30% in the first year, 50% in the second and 20% in the third. The resulting NPV over time can be found in the figure below.

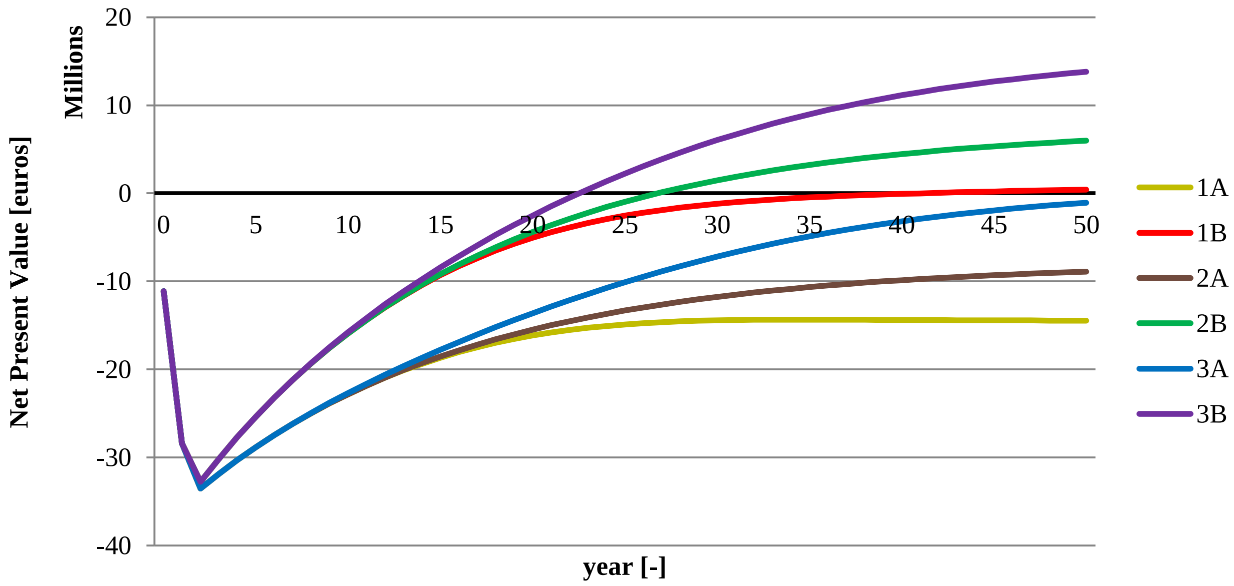

FIGURE 67 - NET PRESENT VALUE CALCULATIONS FOR SIX POSSIBLE FUTURE SCENARIOS FOR THE PHS PRESSURE CAVERN-SYSTEM

I. Preliminary Design: PHS Pressure Cavern

After the conceptual design, the large parts of the system are clear. However, further detailing the design can give important insights on how to build the facility and how much it will cost. In this Appendix the preliminary design will try to clarify the most important parts of the construction.

As has been mentioned before, the construction consists of three major components: The surface structure, the reservoir and the bore shaft. The most important components of this system are the Pump turbine inside the surface structure and the shaft. As the Pump turbine is highly specialized equipment, a detailed design is not possible to construct without the knowledge and resources of a pump turbine-manufacturer. All general considerations concerning the Pump turbine are listed in the main report. The shaft is another important part, with a complicated construction method that needs further investigation. This will be done in Appendix J.1 below. The surface station and the reservoir will be mentioned shortly as well.

I.1. Shaft design

The shaft is one of the three structural components of the system and is the only one which is in contact with the salt cavern itself. Although it is mostly designed on the amount of brine that needs to be transported through the shaft at any given moment, there are a lot of influences that need to be considered. For example the pressures at different depths of the pipe between the surface and the salt cavern and the high air-pressure inside the cavern itself will load the shaft from the outside. Inside the cavern the casing is not supported by the surrounding soil, which can have a negative effect on the possible deformations as a result of operational fluctuations in pressure.

First the diameter of the shaft needs to be determined. From reference penstock design, velocities of 6-8 meters per second are considered relatively high, but can still be used. This may be necessary as a lower velocity will lead to a larger diameter and higher construction costs. This results in a trade-off that needs to be investigated further. In concrete, smaller velocities are possible. The diameter can be calculated as:

$$v_{max} = 7\ m/s\ (assumed);$$

$$A_{pipe} = \frac{Q_{max}}{v_{max}} = 2.8\ m^2; \quad D_{pipe} = 2 \cdot \sqrt{\frac{A_{pipe}}{\pi}} = 1.9\ m$$

The casing of the shaft should be able to withstand large pressures from the both outside and the inside. From the surface down to the top of the cavern, the outside pressure will always be present. The inside pressure is more complicated. Although the inside pressure should also be present at all times, a blowout should be considered as well. When a problem occurs, leading to pressure loss, atmospheric pressure shall occur inside the casing. In addition, the maximum inside pressure should be considered. This pressure will occur when the cavern is filled and the head difference over the pump is at its maximum. The leading situation for the casing design depends on the depth. At the top of the cavern, the situation where no brine is present is leading, which results in a large compressive pressure. At the surface however, almost no outside pressure is present. The inside pressure can reach far higher than the outside pressure, which leads to a large tensile force in the casing.

Different materials can be used to withstand these forces. The most common material for these kinds of structures is steel. Steel has a large compressive and tensile strength with only small amounts of material needed. However, it is more expensive to construct and place than concrete. Concrete is the other candidate for the shaft, although the tensile strength of concrete can cause problems. It would probably lead to some prestressing in the top part of the shaft.

With use of the same formula used in the conceptual design of the PHS Concrete Bubble alternative, the pressure inside the casing at the most critical point can be calculated, which is at the cavern top. At the depth of the top the cavern, compressive force is active. This force only reaches this value when a pressure drop occurs. The force leads to the following casing requirements:

$$N = 16.5 \cdot 10^6 \cdot 0.95 = 15.7 \cdot 10^6 N = 15.7 \cdot 10^3 kN$$

$$Steel\ (E_s = 235\ N/mm^2): \qquad t_{steel} = 67\ mm$$

$$Concrete\ \left(E_c = 45\frac{N}{mm^2}\right): \qquad t_{concrete} = 349\ mm$$

During the operational stage both inside and outside pressure is present at all times, resulting in lower forces than explained above. Using a precautionary approach, the following casing will be chosen:

TABLE 68 - MAIN DIMENSIONS SHAFT CASING

Description	Value	Unit
Width shaft	2.00	m
Diameter casing	1.90	m
Thickness casing	0.07	m

The shaft will be excavated with the use of a tunnel boring machine. This will lower the casing simultaneously. This 7 mm thick casing will be able to withstand the pressure from the surrounding soil in the unlikely case of a pressure drop. The construction method will be explained later.

Inside the cavern

The cavern will pose another problem for the steel casing. Although the pressure will mostly be equal at both sides of the casing, the strength of the casing will easily be enough to withstand these forces. However, the casing will reach for the entire depth of the cavern without any support from the soil and therefore depends on the friction. This could lead to unwanted dynamic situations during the operational phase.

Experience with the use of salt caverns has shown that this will probably not cause any problems. During the stage of solution mining the casing of the borehole also runs down to the bottom of the salt cavern in order to mine the saltiest brine. For the operational phase, no additional measures were needed here.

However, the conditions for the PHS-casing differ somewhat from the salt solution mining borehole. For instance, the pressures on the inside and outside of the casing are different. Secondly, and most important, the diameter of the PHS case will be much larger. Further analysis and modelling should point out if further measures are needed. If necessary, the casing can be extended a bit further than the bottom of the cavern. By anchoring the bottom of the casing into the salt layer, unwanted movements of the casing will be limited for a large part. Slots in the side of the casing should provide the needed connection between the brine layer in the cavern and the brine inside the casing.

Until further research is done, no additional measures are presumed to be necessary. The situation does not deviate enough from the known salt solution situation to assume that these measures are needed. Besides, if research concludes that changes are needed to assure the stability of the system, small alterations will most likely be sufficient.

Construction phase

A part that will be more problematic is the question how the construction will take place. The shaft diameter of 2.0 meters is much larger than is common in salt solution mining. However, it is also too small for conventional mining techniques. To make the needed shaft, specialized equipment is needed. The chosen construction method is called Microtunnelling, which is a small form of Shield tunnelling.

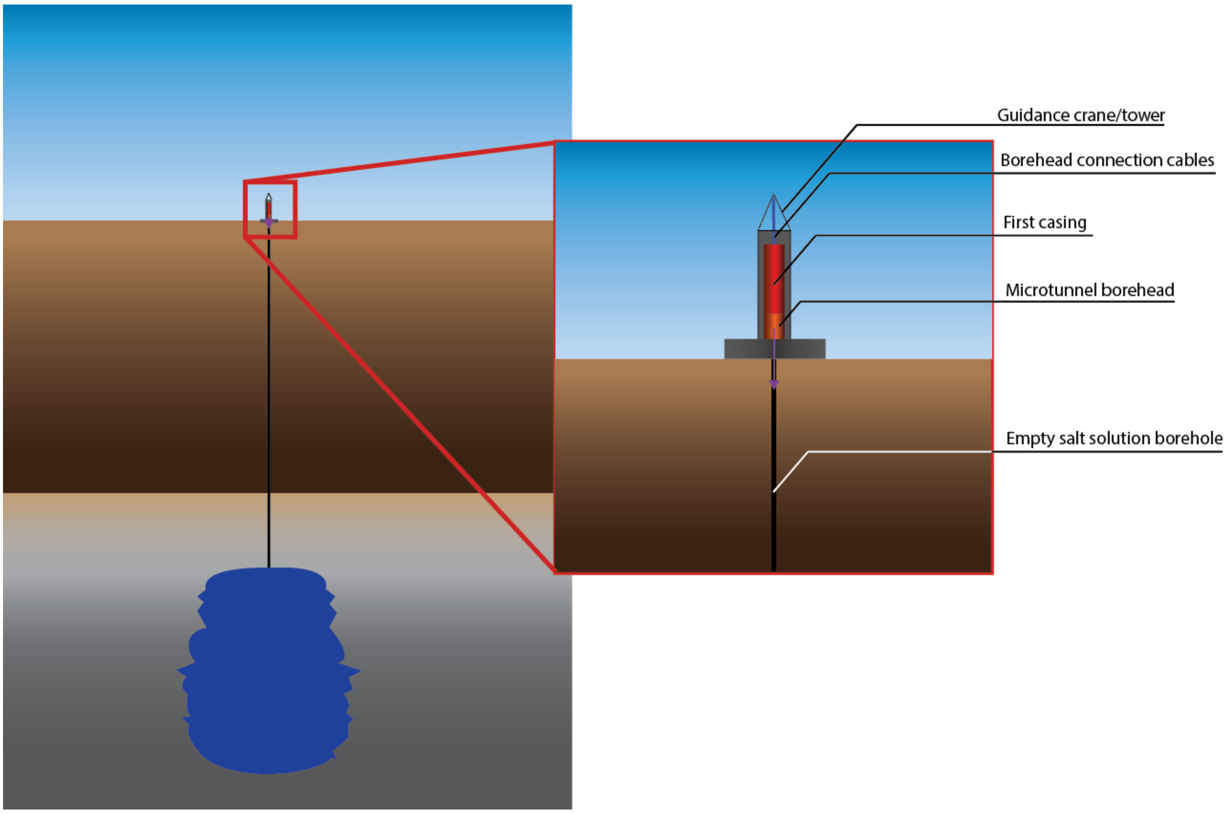

FIGURE 68 - STARTING POSITION OF DRILL HEAD WITH CASING

The technique involves a drill head that has the right dimensions right away. On top of it, the first part of the casing is placed, which is about 10 meters long. The drill head drills a certain amount into the ground, after which a second part of the casing is placed on top. This is repeated until the salt cavern is reached. At this point, the casing is already 900 meters into the ground and it would be impossible or uneconomical at least to retrieve the entire casing in order to retrieve the drill head.

To handle this problem, a retractable drill head will be used. When the drilling is done, which is when the salt cavern is reached, the drill head is able to decrease its diameter. The smaller drill head will then be pulled up to the surface through the casing. This is illustrated in Figure 69. The casing will be pushed further into the salt cavern until the wanted depth is reached.

The costs for normal shield boring operations are estimated at €2000 per meter length, but because of the long length of the casing and the specialized casing and drill head, the drilling will become more expensive. On the other side, pure vertical shield boring has its advantages where the weight of the casing can be used as pulling force and less guidance is needed. Still, the costs are estimated between €2000 and €4000 per meter. In further cost calculation, €4000 per meter will be chosen to be on the safe side. The material costs of the steel have not been taken into account.

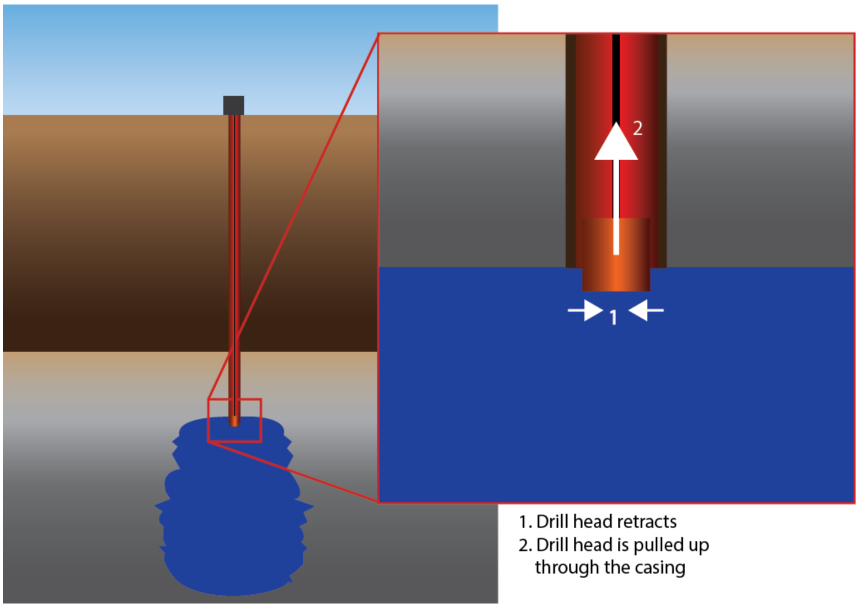

FIGURE 69 - RETRACTION OF THE DRILL HEAD BY DECREASING ITS DIAMETER

When this form of drilling is applied, the drill head is estimated to be able to dig 25 meters per day, when used all day and night. Operating the drill constantly has other advantages when the wall friction is concerned, which will be explained further below. As the casing will have to be dug through 900 meters of soil and 160 meters of brine, a total digging time of a bit more than one month should be enough for only the digging activities. When the preparations on site and finishing is taken into account, a construction time of 2-2.5 months is assumed.

Shield boring details

The explanation above leaves room for questions. Therefore, some of the common problems of shield boring will be explained and applied on the current case. The following subsystems will be discussed:

- The casing
- Wall friction
- Pushing power
- Reaching the salt cavern
- Risk

The casing

As it is the only component that will stay in the ground after the construction phase, the casing needs special attention. The casing will be pushed into the ground, which is crushed and removed with the use of the drill head. The drill head needs several cables in order to work. This includes electricity, a water inflow, water and soil outflow, a bentonite inflow and a cable that is able to pull the drill head out of the casing. The presence of these cables will make the construction phase a lot harder at the moment when a new casing part has to be connected to the existing casing. This is resolved by using a divisible casing. The casing is divided into two equal parts, which are placed around the cables, after which the two parts are joined together with the use of bolts. This is a method used more often, but also raises the price of construction.

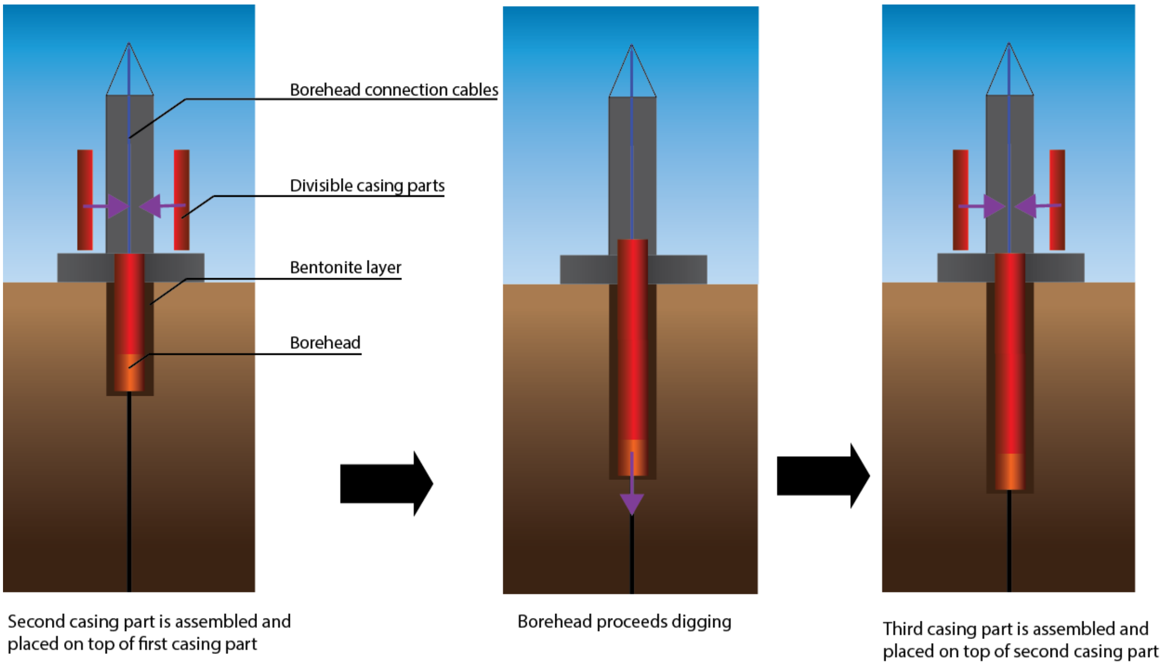

FIGURE 70 - PLACEMENT OF CASING AND PROGRESS OF THE DRILL HEAD THROUGH THE SOIL

Another option would be to disconnect all the cables and attach them to the last casing. When the new casing part is joined to the existing casing, the cables can be connected to the cables above ground and drilling can begin again. This method is more common when drilling horizontal shafts, because it is easy to walk inside the casing and the casing itself is cheaper. However, in this case the divisible casing is the best solution.

Wall friction

The biggest problem is the friction of the soil and the steel casing. Common use for drilling companies is to use the number of 10 kN of power is needed per square meter.[31]. This would lead to:

$$F_{push} = 10 \cdot \pi \cdot 1.9 \cdot 900 = 5.4 \cdot 10^4 \ kN$$

This large force needs to be provided by the pipe thrusters on the surface and the weight of the construction itself. The push force assumes full friction between soil and casing. However, by using bentonite as a lubricant on the outside of the casing, the needed force can be lowered to:

$$c_{lubricant} = 0.7; \quad F_{push,lubricated} = 0.7 \cdot 5.4 \cdot 10^4 = 3.8 \cdot 10^4 kN$$

Where $c_{lubricant}$ is the reduction factor caused by the bentonite layer. This factor is chosen as a very conservative factor, where it should always be possible to put the casing into motion. From practice it is known that the actual factor will be $c_{lubricant,moving} = 0.3$, provided that the casing is kept in motion and does not stay in one position for a several days. If the casing would stay in a single position for a few days, the friction will rise up to the higher boundary of 0.7. When the casing is put into motion however, the factor drops back quickly.

The final scheme of forces and movement should be worked out in a later phase, where more is known about the soil, the available machinery and the amount of bentonite used. The final scheme can be optimized by making good use of the self-weight of the casing. This could decrease the amount of force

[31] Based on conversation with Ir. J. Blok (Visser & Smit Hanab) on 15th of September 2014

needed from the pipe thrusters. The own weight can be increased by letting water into the casing. As the drill head can operate under water and is water-tight, the full weight of the water inside the casing will aid to the self-weight of the casing itself.

However, when the casing starts moving, the friction factor drops and less weight is needed. This shows that the division between self-weight and pipe thruster force needs additional attention at a later stage. A possible division could be to use the self-weight for the minimum force needed when moving and only use the pipe thrusters when additional force is needed.

The self-weight of the steel casing would be:

$$W_{casing} = W_{steel} \cdot h_{underground} \cdot \left[\left(\pi \cdot \frac{D_{casing} + d_{casing}}{2}\right) - \left(\pi \cdot \frac{D_{casing}}{2}\right)\right]$$

$$W_{casing} = 78.5 \cdot \left[\pi \cdot \left(\frac{1.9 + 0.07}{2}\right)^2 - \pi \cdot \left(\frac{1.9}{2}\right)^2\right] \cdot h_{underground}$$

$$W_{casing} = 15.7 \cdot h_{underground} \qquad [kN]$$

Where:

- W_{casing} is the weight of the steel casing [kN]
- W_{steel} is the weight of a cubic meter of steel [kN/m^3]
- $h_{underground}$ is underground position of the drill head [m]
- D_{casing} is the diameter of the casing [m]
- d_{casing} is the thickness of the casing [m]

When the casing almost reaches the salt cavern, the weight will add up to:

$$h_{underground} = 900m; \quad W_{casing} = 15 \cdot 900 = 1.35 \cdot 10^4 kN$$

This will have to pull the casing down into the ground as much as possible. When the casing is moving, a force of $0.3 \cdot 5.4 \cdot 10^4 = 1.62 \cdot 10^4 kN$ is needed. Only a small amount of water or brine needs to be added to fulfil this requirement in order for the pipe thruster to be able to focus totally on the additional force needed for initial movement.

To keep the casing lubricated along the entire height, grease fitting might have to be used on several places along the 900 meter route down. This will spray bentonite through the casing into the soil on the outside. Before completion, these grease fittings need to be removed to ensure a casing with as little friction as possible during the operational stage.

Reaching the salt cavern

A change in circumstances appears when the salt cavern is reached. The drill head can stop drilling, because only brine is present below the casing. The salt cavern will need to be totally filled with brine to prevent the possibility of the drill head falling down and to keep the pressure on the salt cavern walls during the construction phase. Another advantage is that the brine, which was used at the sides of the casing, will not fall down as well. Instead, it will float on top of the heavier brine and stay next to the casing. This is necessary because the casing will have to lower another 160 meters into the cavern. Before the casing is lowered further, the drill head is retracted and pulled up to the surface.

Subsequently, only the casing will have to be lowered into position. When the casing is in its final position, the casing will have to be locked in place. This can be done by choosing a position where concrete is sprayed through the casing into the soil. This will lock the casing into the soil and will make it impossible for the brine to find a way to the surface on the outside of the casing at the same time.

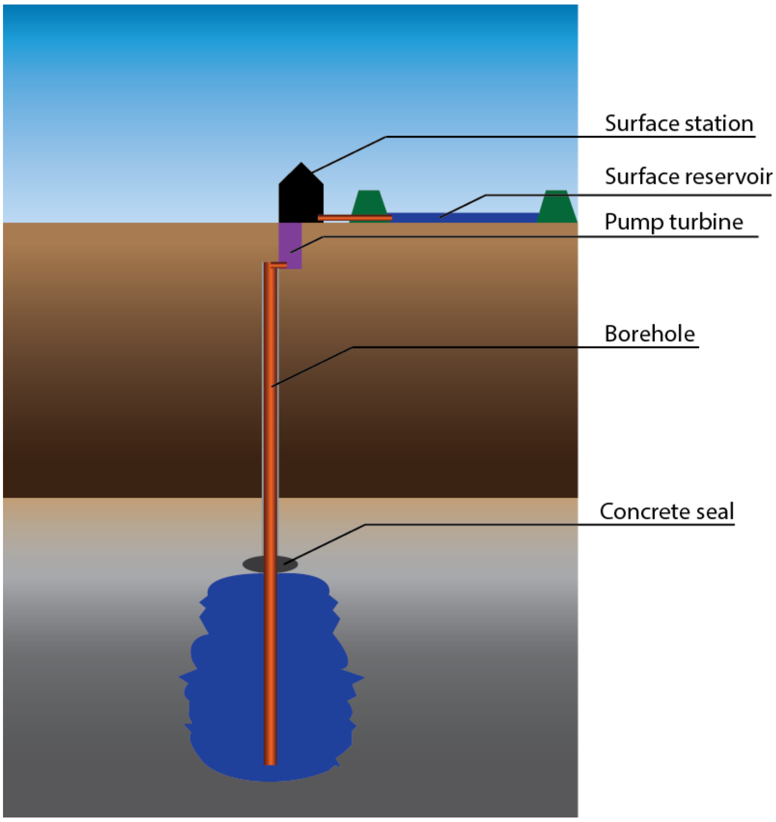

FIGURE 71 - SHAFT CONSTRUCTION FINAL POSITION

Risk

Although salt solution mining and shield tunnelling are both common practices, they have not been linked in a similar way before. This means that additional research is needed for some parts of the design. However, the description above has shown that the technique itself is possible when trying to achieve the required depth and diameter.

The use of Micro tunnelling for reaching salt cavern requires a very deep borehole and a drill head that is capable of drilling through different soil layers. It is unknown if the concept of Micro tunnelling has been used on these depth ($\pm 1000\ m$) before, but depths of hundreds of meters have been done in the past. The increased depth will require additional research and calculations, but most likely will not lead to unworkable situations.

A drill head used for Micro tunnelling is very well capable of drilling through different soil layers, as projects running through solid rock are also reported. A problem that could occur is the need for a change of the drill head cutters when the drilling length through solid rock becomes too long. However, when applied in mostly sand, this will not be necessary.

The largest process risk is the acquiring of the permits, which will require special safety measures. This is needed due to the fact that the construction will be qualified as a deep mining project, while this was not needed in earlier projects. Additional safety is provided in the form of more surface facilities during construction and a blowout-preventer to be able to prevent a disaster when a sudden change in pressure occurs at the depth of the drill head. The need for blowout prevention could potentially be averted by drilling down at the same location as the salt solution borehole.

Vertical Direction Drilling

A possible opportunity to lower the costs is to use a different drilling method. Instead of shield tunnelling, also Vertical Direction Drilling or VDD can be used. This method is usually used for horizontal purposes (HDD), but can also be used vertically. It involves a gradually wider diameter cutting head, which has to be pushed down the borehole that has been made before. Although pulling the turning rod is more common, this is not possible in thin project.

As a starting point, the borehole from salt solution drilling can be used. A turning steel rod is pushed down the borehole with two special parts attached to it. On the front, a guider is placed, which has the same diameter as the last constructed borehole, this will keep the borehole centered to the right direction. After the guider, a cutter disk is attached with a larger diameter than the guider. This will cut the new borehole. The widening can be continued until the wanted diameter can be used.

When the wanted diameter borehole is constructed, the casing can be lowered down. This method is easier, faster and cheaper. However, it is significantly more risky, which makes it unacceptable to use in this phase of the project when another method like Shield Tunnelling is available.

Therefore, this method will not be used in the preliminary phase. The relatively large uncertainties considering the drilling direction, needed forces and the stability of the bentonite lead to a method that is unnecessarily risky for the preliminary design. During a later stage, more research can be done to find out if the method can be used, which can influence the costs positively. For now, Shield Tunnelling will be used.

I.1.1. Shaft losses

When the brine is pumped down and pushed up the shaft, losses will occur. These losses will mainly depend on the casing material, shaft diameter and the brine velocity, which were calculated to be 1.9m and 7m/s respectively.

There are two types of losses that can be found when considering just the shaft itself, which are the local losses and the friction losses. The local losses appear when the flow changes diameter or direction, which is hardly the case in the long straight shaft. However, friction losses will most definitely appear. To quantify the losses two main balances will be used, the mass balance and the momentum balance. Important to note here is that the situation in the operational phase will always be a totally filled, pressurized shaft, which needs to start running at the begin of operation. During operation itself, it will continue as a steady flow until the operation stops.

When considering the operational stage, in which the entire height of the column is moving with equal and constant velocity, the following applies:

$$\Delta H_{loss} = \left(\lambda \frac{L}{D} + \Sigma\xi_{\mathrm{i}}\right)\frac{U^2}{2g}$$

In which:

- ΔH_{loss} is the total loss of head due to friction- and local losses [m]
- λ is the resistance coefficient as used in the Darcy-Weisbach-formula [-]
- L is the length along which the friction is active [m]
- D is the diameter of the shaft [m]
- $\Sigma\xi_i$ is the summation of all local losses [-]
- U is the average velocity inside the shaft [m/s]
- g is the gravitational constant $[\mathrm{m/s^2}]$

The use of this formula needs the acceptance of several assumptions. The most important of which is that the brine inside the shaft is modelled as a rigid column with uniform and stationary flow of incompressible brine. Although the stationary nature of the flow is a given, due to the uniform shape of the shaft and the regulated flow into the pump turbine, uniformity over the cross section is not. However, the approximation will be assumed sufficient for both the uniformity and the compressibility.

First, the friction loss will be calculated. The most important unknown for this calculation is the resistance coefficient. This depends among others on the Reynolds number, which shows the relative turbulence of the flow:

$$Re = \frac{UD}{\nu} \quad [-]$$

Where:

- Re is the Reynolds number $[-]$
- U is the average velocity of the flow $[m/s]$
- D is the diameter of the shaft $[m]$
- ν is the kinematic viscosity $[\mathrm{m^2/s}]$

Both the velocity and the diameter can be chosen, but the kinematic viscosity is a property of the fluid itself. The viscosity varies with different pressures and different salt concentrations. From literature, a dynamic viscosity of around $1500\ \mu Pa \cdot s$ can be found, when assuming an average pressure of 5-10 MPa and a temperature of $30\ °C$. The kinematic viscosity results from:

$$\nu = \frac{\mu}{\rho} = \frac{1.5 \cdot 10^3}{1.2 \cdot 10^3} \cdot 10^{-6} = 1.25 \cdot 10^{-6}\, m^2/s$$

This is slightly higher than the viscosity of fresh water. The Reynolds number can be found by inserting the chosen dimensions:

$$Re = \frac{7 \cdot 1.9}{1.25 \cdot 10^{-6}} = 1.1 \cdot 10^6$$

The flow can therefore be considered turbulent. Most likely, the resistance coefficient can be approximated best with the use of the Von Karman-formula, which is designed for high Reynolds-numbers. The Moody-diagram can check whether this actually applies. For both, the relation k_s/D is needed. k_s is the equivalent wall roughness in [m]. For steel, the k_s value of 0.15mm is chosen to be appropriate.[32] This results in:

$$\frac{1}{\sqrt{\lambda}} = 2\log_{10}\frac{k_s/D}{3.7} = 2\log_{10}\frac{0.15 \cdot 10^{-3}/1.9}{3.7} = -9.3$$

$$\lambda_{vK} = 0.012$$

Or from the Moody-diagram:

$$\frac{k_s}{D} = \frac{1.5}{1.9} \cdot 10^{-4}\,; from\ diagram: \lambda_M = 0.013$$

For further calculation, the value of $\lambda = 0.013\ will\ be\ used.$

The loss of the shaft can be calculated now. With a length of 1060 meters of casing to pass through, the total loss of one passing will add up to:

$$\Delta H_{fr} = 0.013 \cdot \frac{1060}{1.9} \cdot \frac{7^2}{2 \cdot 9.81} = 18\, m$$

Next to the friction losses, also local losses are present. However, these will only make a significant difference when the shaft is relatively short (L/D <500) or the casing has a lot of local changes, like corners or bifurcations. Therefore, the local losses will be neglected here.

The losses mean that the pressure at the turbine will lower when the velocity of the flow inside the shaft increases. During filled stage, when the pressure inside the cavern is increased to 85% of the geostatic pressure, the flow in the shaft will be zero. When the flow starts running through the shaft, the friction loss will increase to 18 meters of pressure difference by the time the velocity reaches the design velocity. This needs to be taken into account during design.

During the roundtrip from grid-to-grid, the shaft will be passed twice, which means that the loss will have to be accounted for twice. The first loss can be compensated for. This does mean that more energy has to be taken from the grid, which only has a minor influence due to the low price of off-peak electricity. The second passing will result in a lower head difference on the pump turbine, which has to be taken into accounted when designing the pump turbine itself.

[32] http://www.engineeringpage.com/technology/pressure_drop/wall_roughness.html

I.2. Reservoir design

The reservoir will be the largest surface structure, and therefore needs some attention as well. The size of the reservoir depends on the capacity of the cavern and the amount of brine that has to be moved in and out of the cavern. For the measurements, the amounts from the example of Chapter 5 are used, which means that a total of 210.000 cubic meters of brine should be stored.

For specific locations and projects, a different shape can be chosen if necessary. For this phase a dike is chosen, half-submerged in the surrounding grounds, made out of the sand dug for the reservoir. Because it does not have to withstand large forces like a sea- or lake-dike would, the dike can be designed as a fairly simple construction. Much attention is needed when choosing and applying the geotextile cover for the reservoir, as it has to maintain water-tightness for its entire lifetime.

To lower the chance of contamination and to prevent people from walking on the geotextile, there will always be a layer of brine inside the reservoir. In this phase, a layer of two meters has been chosen. The two meter layer is deep enough to ensure permanent inundation of the entire reservoir bottom. In addition, the layer can dilute possible contaminations and dampen the forces on the reservoir sides and bottom protection from filling operations. When costs of dike construction and disposal of redundant soil turn out to be high, a smaller layer can be chosen. The reservoir will have the following dimensions:

TABLE 69 - MAIN DIMENSIONS OF THE RESERVOIR

Dimension	Value	[unit]
Total height	8.0	m
Dike height	3.5	m
Dike slope	1/4	
Water depth	2.0 – 7.0	m
Inner slope protection	Geotextile	
Outer slope protection	Grass	

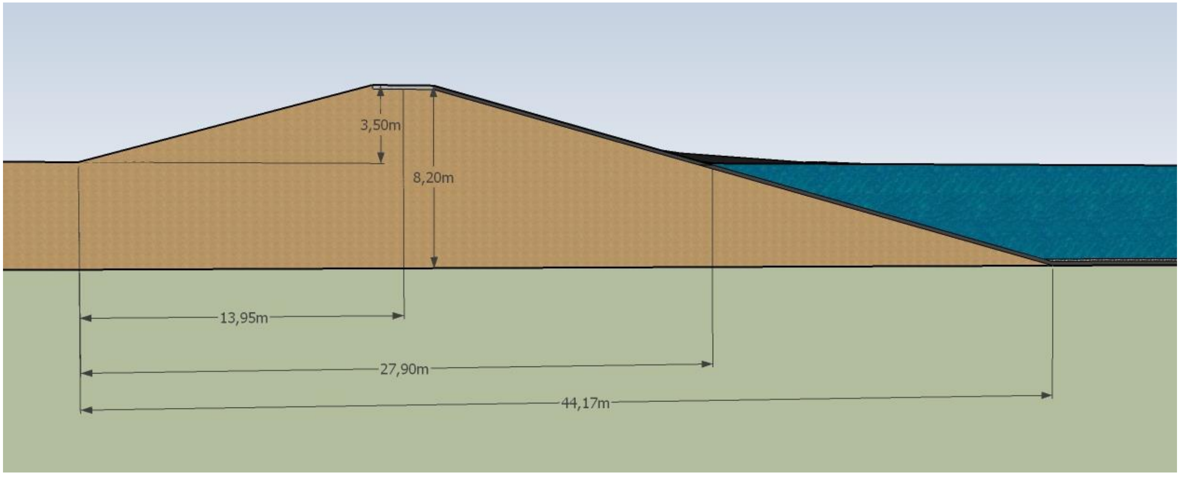

FIGURE 72- PROFILE OF THE DIKE

The construction of the reservoir will mean that large amounts of sand have to be moved. Some of the sand dug from the reservoir below-ground level portion can be used for the construction of the dike around it. It also leaves an portion of the soil unused.

The costs of the construction of the reservoir will be relatively small, because of the simple construction method that has been done numerous times before. The costs mainly depend on the amount of displaced soil and materials needed. The important values can be found below:

TABLE 70 - QUANTITIES USEFUL FOR COST ESTIMATE

Description	Value	[unit]
Total displaced soil	$1.6 \cdot 10^5$	m^3
Dike volume	$4.9 \cdot 10^4$	m^3
Unused soil	$1.2 \cdot 10^5$	m^3
Surface protected by geotextile	$5.4 \cdot 10^4$	m^3
Ballast stone needed (30cm)	$9.2 \cdot 10^3$	m^3

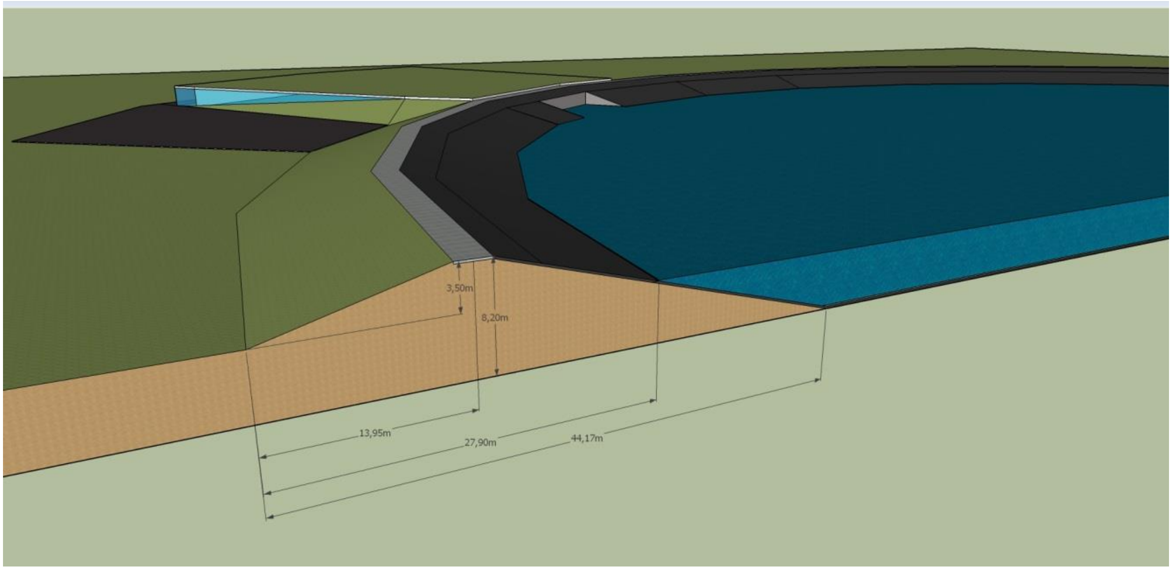

FIGURE 73 - OVERVIEW OF A PART OF THE DIKE WITH MAIN DIMENSIONS

These values have been calculated with the use of Maple. The used codes can be found below. As can be seen from Table 70, a large part of the removed soil is not used for the dike. Although this lower position limits the impact of the rural view, an optimization is possible for economic purposes. This optimization will not be done in this phase of the project, as it does not directly contribute to the feasibility of the project, which is the main goal of this phase and the research as a whole.

The reservoir design can be optimized by placing the reservoir higher. This way, less excavation is needed and less unused soil will remain. Another possibility is to find a nearby project that can use the sand, like dike improvements or building sites. This mainly depends on the wishes and influence of the surrounding inhabitants and the quality of the soil. As a reservoir dike will block the view, the surrounding inhabitants will want the reservoir to be built as low as possible. This will be less of a problem when the sand is of good quality and it can be sold easily.

I.2.1. Used maple files for reservoir dimensions

Below is the Maple file used to calculate the amount of ground that has to be transported during construction. First, the main dimensions are defined with the reservoir depth and the average area. These dimensions have been chosen to be enough to fill the cavern if the reservoir would be shaped like a cylinder with the specified area and depth. This shape will be changed later by adding slopes, which will slightly increase the volume that can be stored. This difference will be considered insignificant in this phase of the project.

$$> reservoir\_depth := 5; Average\_area := \frac{V\_displaced}{reservoir\_depth}; slope := \frac{1}{4};$$

$$reservoir\_depth := 5$$

$$Average\_area := 42889.98580$$

$$slope := \frac{1}{4}$$

The *avg_radius_round_reservoir* calculates the radius in meters that the reservoir would have if it was round. This is also the radius at the level of the ground around the dike. The radii show the radius of the reservoir at the lowest point that the brine will get (*lower_radius*), the highest point that the brine will get (*upper_radius*) and the lowest point that will be dug (*ground_radius).* Subsequently, the amount of ground displaced can be calculated.

$$> avg\_radius\_round\_reservoir := \mathrm{sqrt}\left(\frac{Average\_area}{3.141592}\right);$$

$$avg\_radius\_round\_reservoir := 116.8430971$$

$$> lower\_radius := avg\_radius\_round\_reservoir - \frac{reservoir\_depth}{2 \cdot slope}; upper\_radius := avg\_radius\_round\_reservoir + \frac{reservoir\_depth}{2 \cdot slope};$$

$$lower\_radius := 106.8430971$$

$$upper\_radius := 126.8430971$$

$$> ground\_radius := lower\_radius - \frac{2}{slope};$$

$$ground\_radius := 98.8430971$$

$$> V\_ground\_displaced := \frac{1}{3}\left(3.141592 \cdot \left(\frac{reservoir\_depth}{2} + 2\right) \cdot \left(avg\_radius\_round\_reservoir^2 + ground\_radius^2 + avg\_radius\_round\_reservoir \cdot ground\_radius\right)\right);$$

$$V\_ground\_displaced := 1.647988094\ 10^5$$

Next is to calculate the volume of the dike. First the height of the dike is defined as the highest point where the brine can get plus an extra meter. After this, the important radii of the crest and the outermost radius of the dike are defined. After the cross-sectional area of the dike is calculated (*area_dike)*, the volume of the dike is calculated. This is done by taking a blunt or truncated cone with the radius of the outer dike radius up to the radius of the outer crest. Subsequently, another truncated cone is subtracted with the radius of the inner crest down to the radius at ground level.

$$> H\_dike := \frac{reservoir\_depth}{2} + 1; radius\_dike\_innercrest := avg\_radius\_round\_reservoir + \frac{H\_dike}{slope}; radius\_dike\_outercrest := radius\_dike\_innercrest + 3; radius\_dike\_outer := radius\_dike\_outercrest + \frac{H\_dike}{slope};$$

$$H\_dike := \frac{7}{2}$$

$$radius\_dike\_innercrest := 130.8430971$$

$$radius\_dike\_outercrest := 133.8430971$$

$$radius\_dike\_outer := 147.8430971$$

$$> area\_dike := \frac{1}{2}\left(\left(radius\_dike\_outercrest - radius\_dike\_innercrest\right) + \left(radius\_dike\_outer - avg\_radius\_round\_reservoir\right)\right) \cdot \frac{reservoir\_depth}{2};$$

$$area\_dike := 42.50000000$$

$$> V\_dike := \frac{1}{3}\left(3.141592 \cdot (H\_dike) \cdot \left(radius\_dike\_outer^2 + radius\_dike\_outercrest^2 + radius\_dike\_outer \cdot radius\_dike\_outercrest\right)\right) - \frac{1}{3}\left(3.141592 \cdot (\mathrm{H\_dike}) \cdot \left(radius\_dike\_innercrest^2 + avg\_radius\_round\_reservoir^2 + avg\_radius\_round\_reservoir \cdot radius\_dike\_innercrest\right)\right);$$

$$V\_dike := 49476.3937$$

$$> V\_ground\_unused := V\_ground\_displaced - V\_dike;$$

$$V\_ground\_unused := 1.153224157\ 10^5$$

$$> surface\_protected := 3.141592 \cdot (radius\_dike\_innercrest + lower\_radius) \cdot \mathrm{sqrt}\left(\left(H\_dike + \frac{reservoir\_depth}{2}\right)^2 + (radius\_dike\_innercrest - lower\_radius)^2\right) + 3.141592 \cdot lower\_radius^2;$$

$$surface\_protected := 54335.33880$$

$$> Ballast\_needed := 3.141592 \cdot ground\_radius^2 \cdot 0.3;$$

$$Ballast\_needed := 9207.966421$$

I.3. Geotechnical analysis

This Appendix will focus on the effect of the storage facility on the surrounding salt layer during the operational phase. During this phase, the cavern will constantly be under high pressure, which could have a negative effect on the efficiency of the system.

The pressure that will be present during the operational phase will vary between 75% and 85% of the local geostatic pressure. When the cavern calculated in chapter 5 is used as reference, this means that a pressure between 15.3 and 16.5 MPa is present at all times.

The exact influence on the salt layer can only be found by conducting an extensive geotechnical investigation into the local soil and salt layer. With use of among others a triaxial compression test, the main characteristics of the soil can be found. These characteristics, like creep, porosity and cohesion are important parameters for the design of a PHS-facility in a salt cavern.

To be able to make first calculations before these geotechnical investigations, estimates are made based on experience. Companies like AkzoNobel have extensive experience with the salt layers beneath the Netherlands. Based on this experience, the following estimates can be made for the reaction of the salt layer on the operational pressures[33]:

- The salt layer can be considered fully impermeable for all pressures below the geostatic pressure. This applies as long as the temperature does not rise too high (<100 ^{0}C)

- Cracks and failure of the salt layer will occur when the local pressure approaches the geostatic pressure. In most locations, this does not pose any problems. Only on the top of the cavern at the casing shoe, this could lead to a blowout when the crack proceeds along the casing to the surface. Therefore, sensors are placed at this location to keep the pressure at this location far from the geostatic pressure. A safe margin as used in other salt cavern projects is chosen to be at 85% of this geostatic pressure.

- Any pressure below the geostatic pressure will result in creep and therefore shrinkage of the salt cavern. An economic minimum is chosen to be at 30% of the geostatic pressure, which is also used in other salt cavern applications like gas-storage. To counter the shrinkage of the gas-storage caverns, regular re-using of the cavern for salt production will keep the capacity of the salt cavern between limits. For the use of Pumped Hydro Storage, which keeps the pressure between 75-85% of the geostatic pressure, a volume loss of about 10% can be expected after 10 years of operation.

- Due to the impermeability and the small creep of the salt cavern wall, losses due to the salt layer reaction can be estimated to be insignificant compared to the pump turbine-losses. These losses can therefore be neglected when calculating the roundtrip efficiency.

The estimates as shown above can be applied on both salt layers present in the Dutch soil. After the geotechnical investigation, more information will be present. For an optimal design of the pump turbine, this geotechnical design has to be done in time.

[33] These first estimates, as used by AkzoNobel, are based on an interview with Dr. R. Groenenberg from AkzoNobel Industrial Chemicals B.V. on July 30th 2014.

I.3.1. System efficiency

As one of the most important factors of the system, the efficiency of the total system can be reviewed by running through the total system from begin to start:

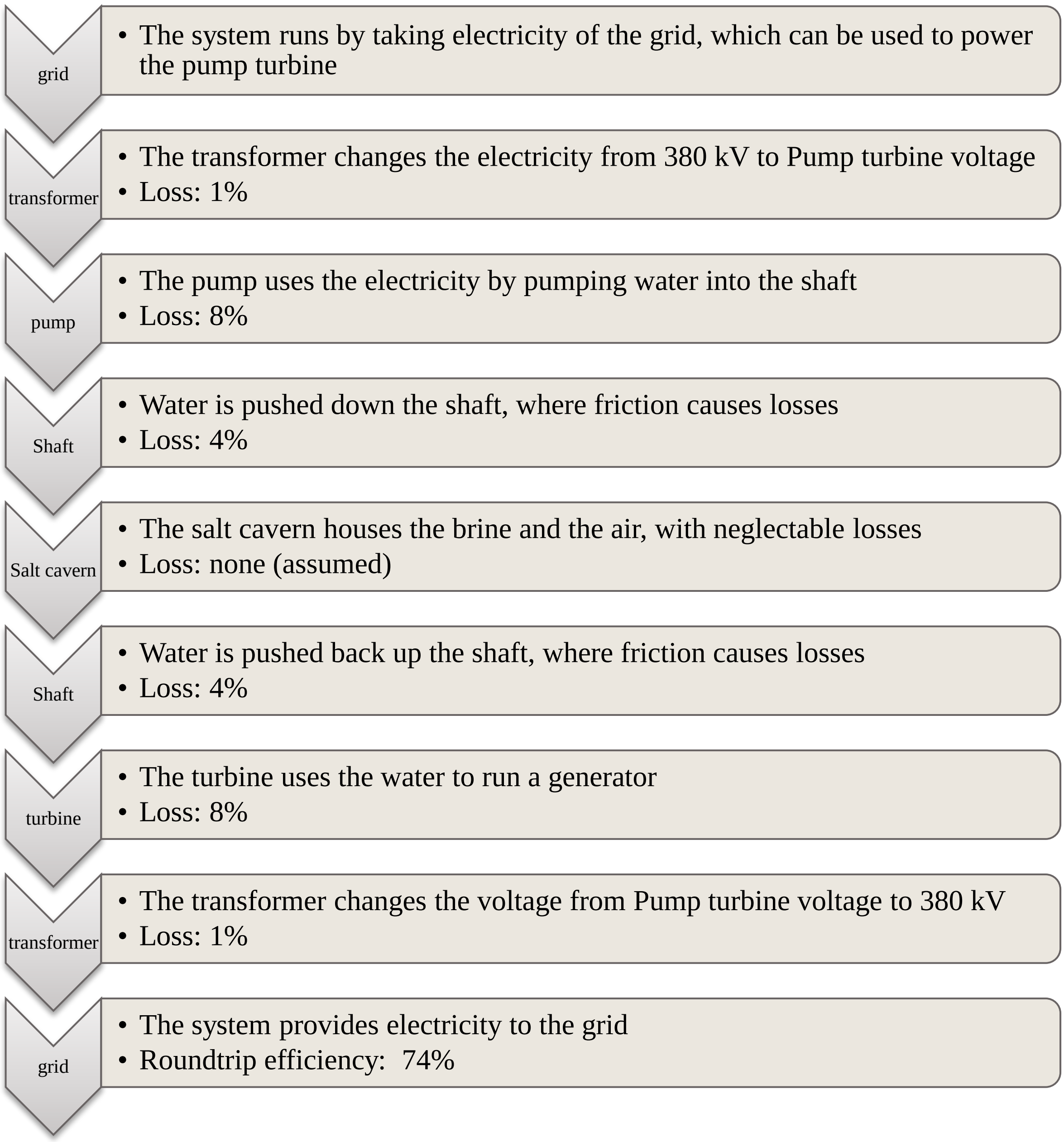

Figure 74 - The efficiency of the system during one roundtrip of the PHS Pressure Cavern

This diagram shows the importance of the shaft. The losses from the shaft casing wall will be accounted for twice, because the water passes two times during a roundtrip.

On the other side a large optimisation step is possible for the parts of the shaft and the pump turbine. A possible change could be to extend the running time from three to five or six hours. This would result in lower power output and lower costs. It will also decrease the velocities and losses. However, the longer running time will result in a lower average difference between night tariff and day tariff. Also, the pump turbine will run a few hours a day more, making it more probable that error will occur.

The efficiency of the system is estimated to be around 74%. This is slightly lower than most conventional Pumped Hydro Storage facilities, which operate around 80%. As these facilities depend on the same sort of pump turbines and transformers are also needed here, the difference is made in the connection. The shaft of the PHS Pressure Cavern is restricted in diameter because of the large costs. Therefore, a standoff between shaft costs and friction losses is inevitable. After all, a smaller diameter means higher velocities, which in turn will result in much higher friction losses.

When compared to other Pumped Hydro Storage alternatives, the PHS Pressure Cavern stands out positively. Although higher efficiencies have been recorded (in flywheels and SMES), these mainly operate on small scale storage and can only keep this high efficiency for a short amount of time. The PHS Pressure Cavern hardly loses pressure and therefore efficiency over time. The only other large scale energy storage facilities, which are Hydrogen- and CAES-storage, lack the roundtrip efficiency in both short-term and long-term compared to the PHS Pressure Cavern.

I.4. Risk Analysis

The risk associated with the construction and operation of the PHS-facility is a crucial part of the feasibility of the project. Most other alternatives to traditional Pumped Hydro Storage show potential as was shown in the first part of this research. However, they lack the certitude of a common, low-risk technology that the PHS provides. Higher risk means that a higher return is demanded, which none of the alternative technologies have been able to provide so far. The risks need to be clarified further to be able to quantify the amount of additional risk premium the technology needs to provide in order to become a feasible option for investors. The Return on Investment relative to the risk needs to be higher or comparable to the current traditional PHS-technology if it wants to compete on a large scale.

There are several ways to systematically take a closer look to the different risks in the project. The first of which is a risk table, in which the separate risks are listed and their consequences evaluated. To find the links between the different structural components also a fault tree can be used. The advantage of a fault tree is that it shows more clearly the risks that are unique to the technology. The risk table on the other hand also shows general risks that will be present at every civil engineering project.

I.4.1. Fault tree analysis

A fault tree analysis can be used to discover the many different ways in which a problem can occur. The top event will be defined as the failure to store or produce electric energy. The main system of the fault tree can be seen in Figure 75.

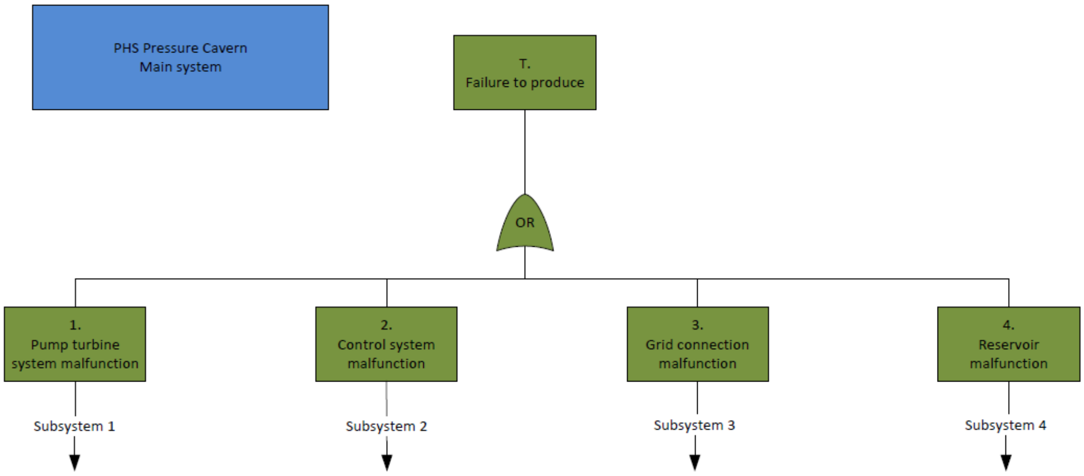

FIGURE 75 - MAIN SYSTEM OF PHS FAULT TREE ANALYSIS

This figure shows that several sorts of malfunctioning can lead to the failure to produce. The four main components that can lead to malfunction of the PHS-facility will be covered separately in four subsystems. These four subsystems are shown below.

The fault tree is shown in a further detail than is necessary at this point in the design. This has been done to clarify the kind of errors that one has to consider when addressing the different possible events. These separate base events will not be quantified at this point in the design. Events up to the second order will be quantified in this analysis in order to give a clearer view on the risks and which risks need additional measures. The distinction between events that will be quantified can be seen by a change in colour, where green events will be quantified and orange events are mainly for informative purposes.

When the system in Figure 75 is investigated in more detail, one can see that the cavern itself is not named in the risk analysis. This is chosen because the salt layer and the salt cavern in it will not cause failure as long as the geotechnical investigation is done properly and the resulting regulations are followed accordingly. Therefore, the cavern can only fail, without taking a natural disaster into consideration, when a human or mechanical error occurs. These errors are represented through sensor failure, connection failure and human error.

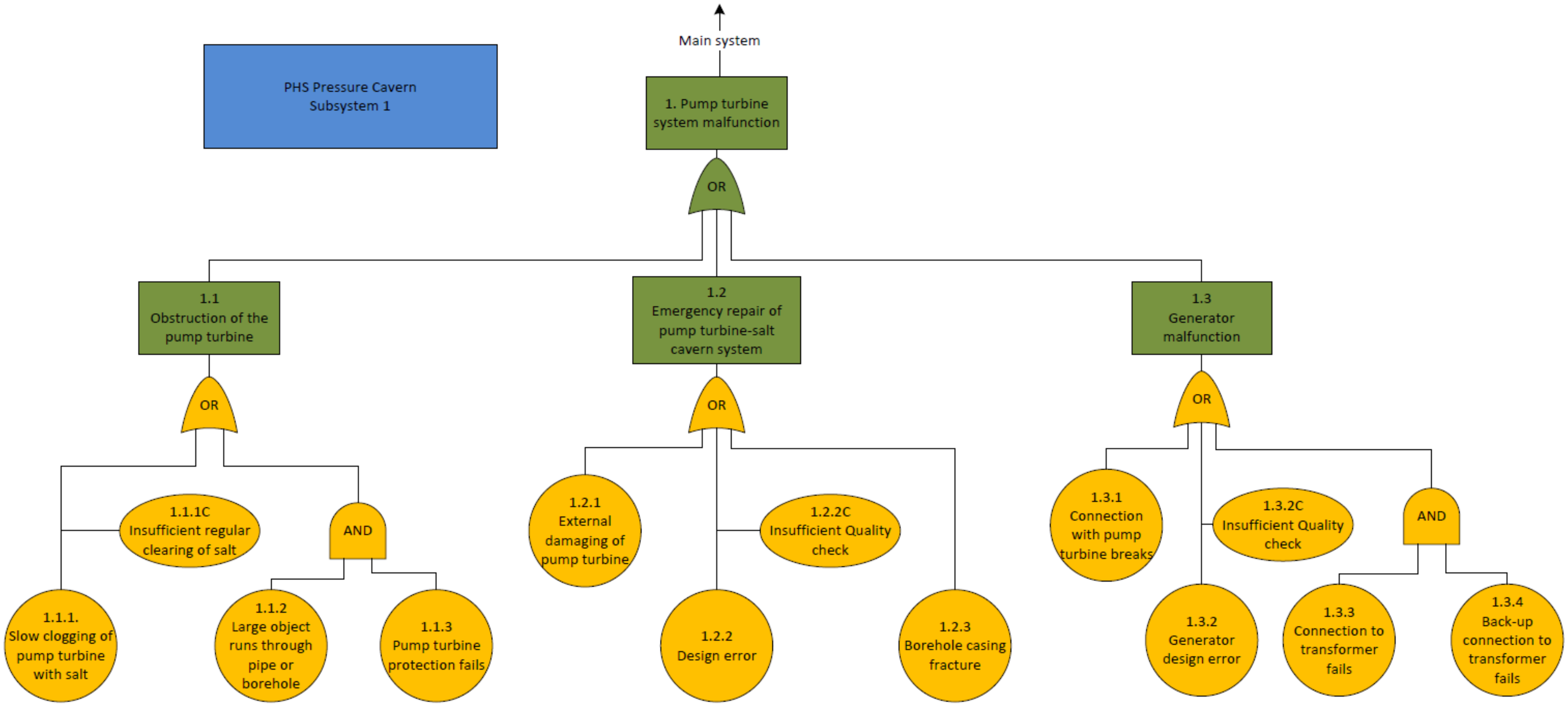

FIGURE 76 - SUBSYSTEM 1 OF PHS FAULT TREE ANALYSIS

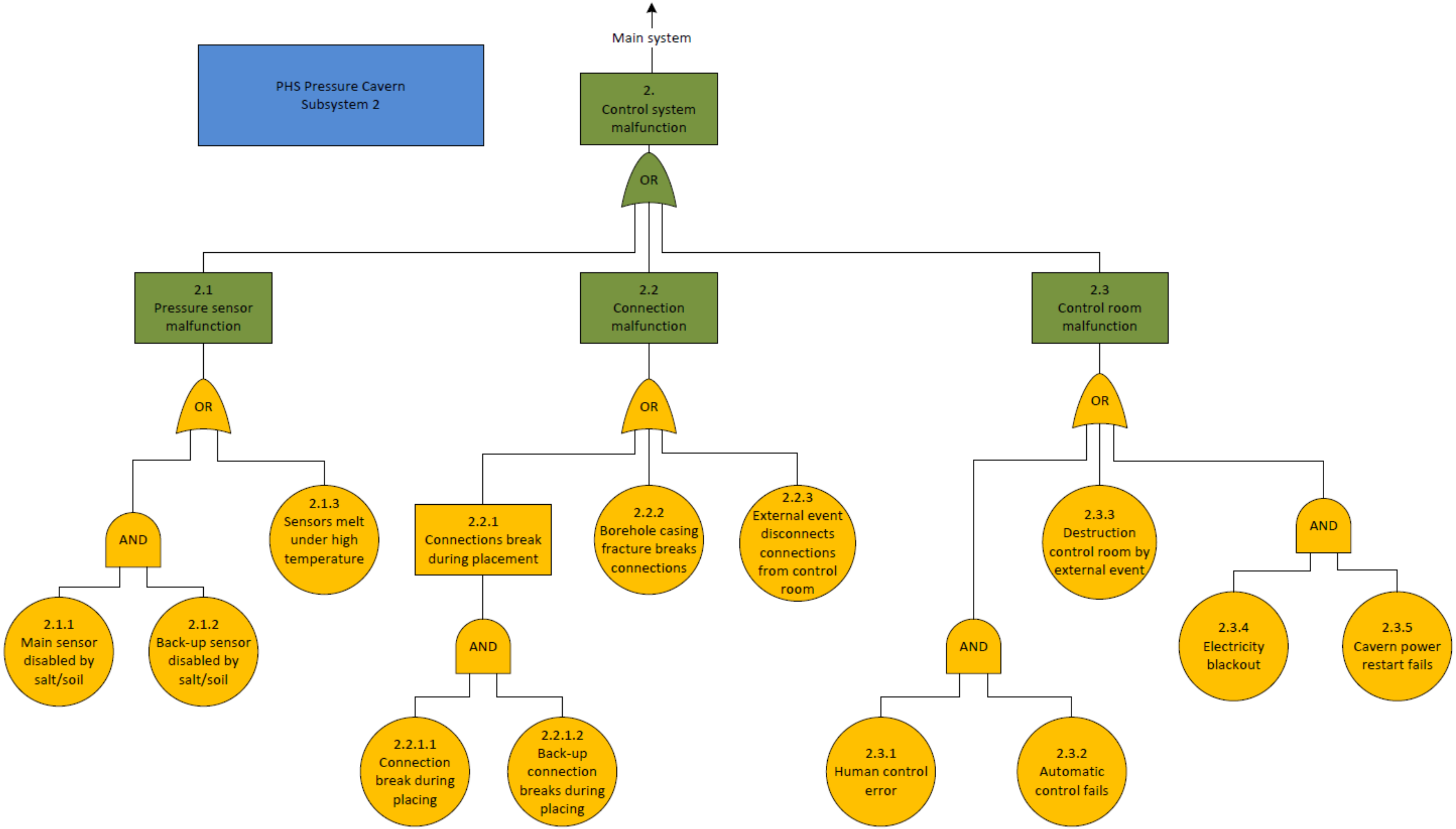

FIGURE 77 - SUBSYSTEM 2 OF PHS FAULT TREE ANALYSIS

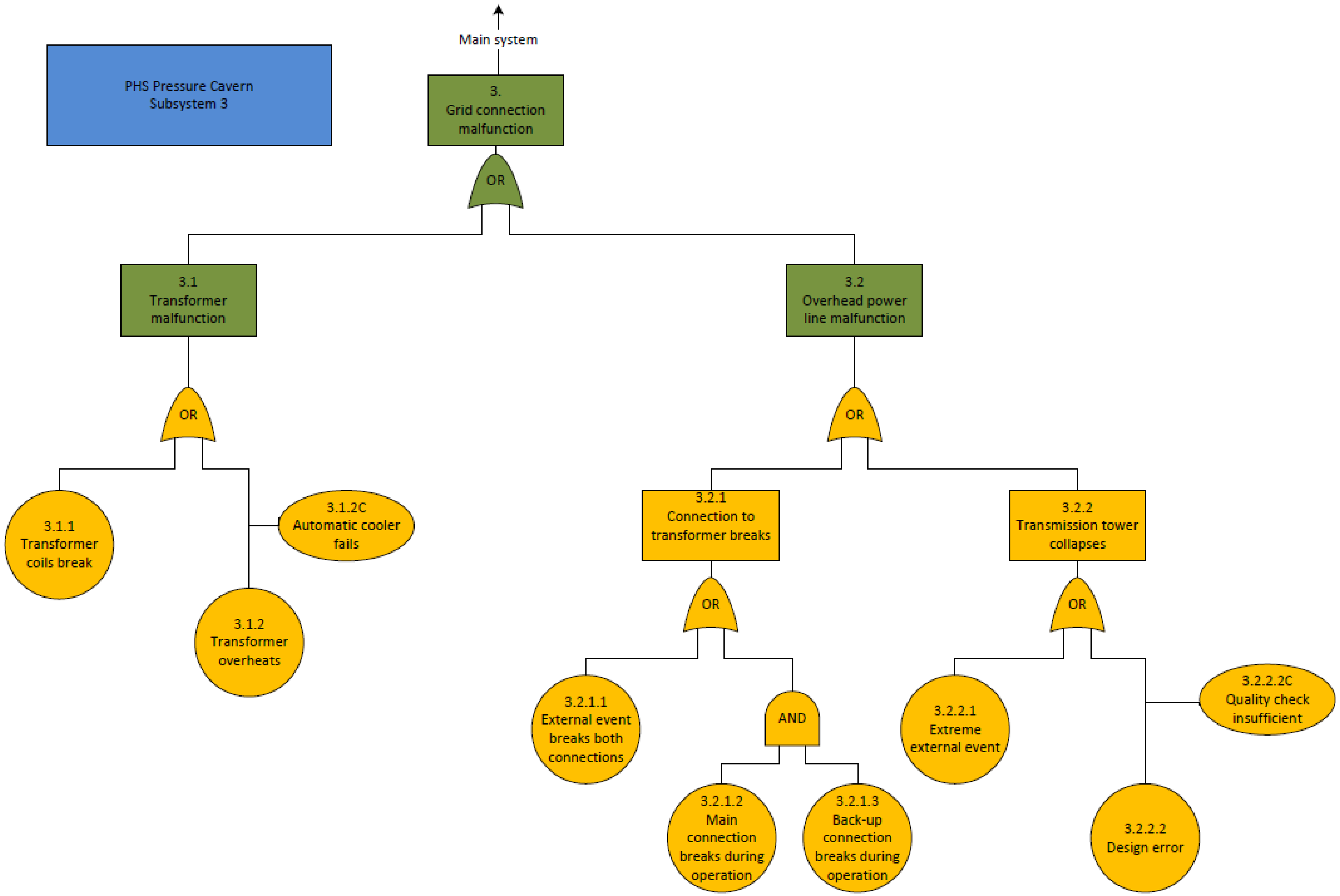

Figure 78 - **Subsystem 3 of PHS fault tree analysis**

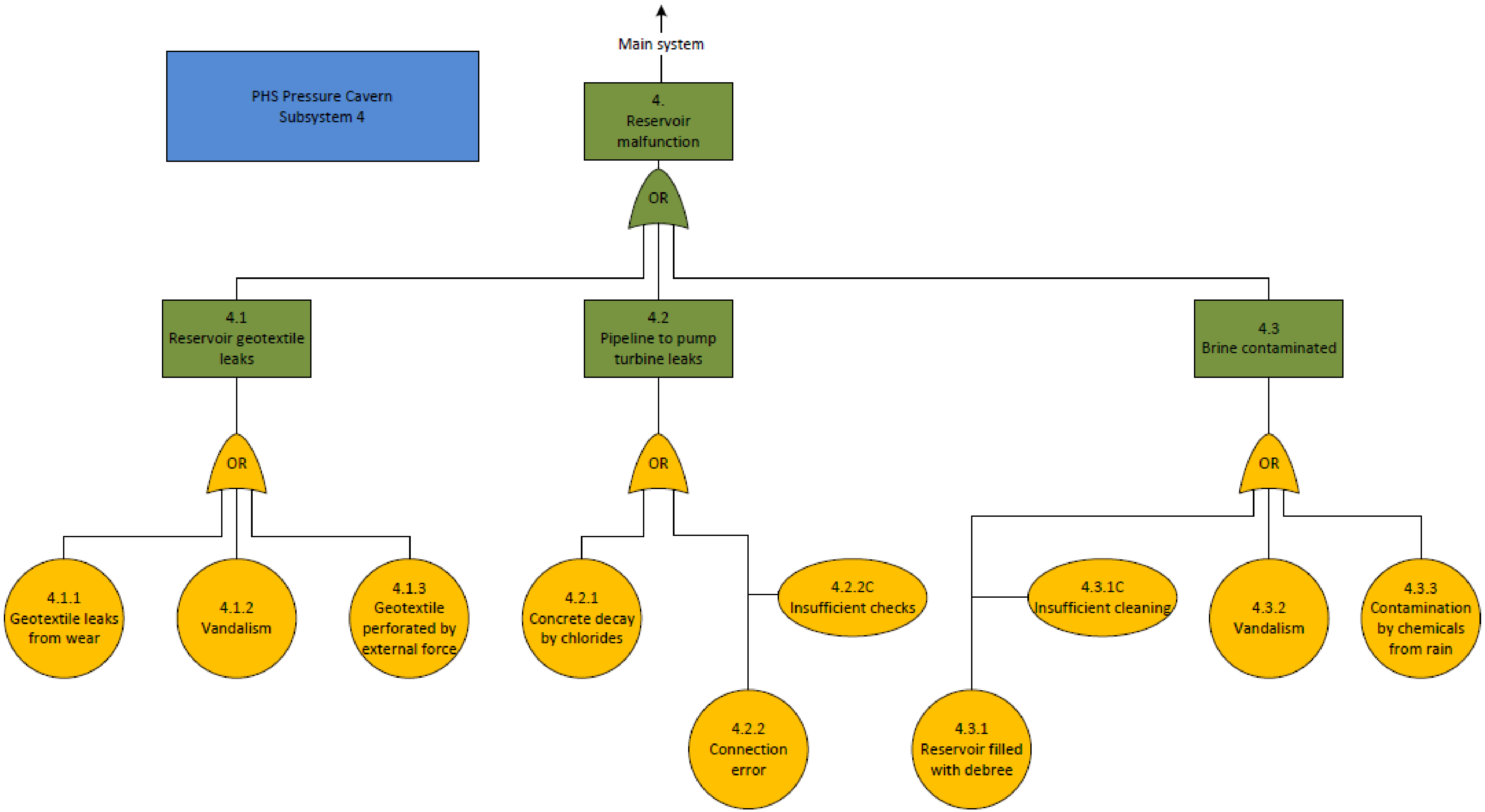

FIGURE 79 - SUBSYSTEM 4 OF PHS FAULT TREE ANALYSIS

The next step is to try to quantify the risks that will result from the operation of the energy storage facility. This will show which risks are most important to deal with during the design phase. It is also used to counter the 'gut-feeling' that an innovative project like the PHS Pressure Cavern will always be risky. By showing that the top event 'failure to produce' will only occur rarely, interested companies can be shown that the risk can actually be rather low. To achieve this high security of production, the fault tree analysis can be used to find the most vulnerable spots of the system. Next step is to improve these parts of the system in order to lower the possible risk of loss of production. The chances of failure are defined as 'chance of malfunction per year'. In this calculation, fatigue is not taken into account.

Subsystem 1: Pump turbine system malfunction

The separate subsystems will be covered and quantified first after which the risk of the top event can be calculated. Subsystem 1 consists of the part of the system that is concentrated around the pump turbine.

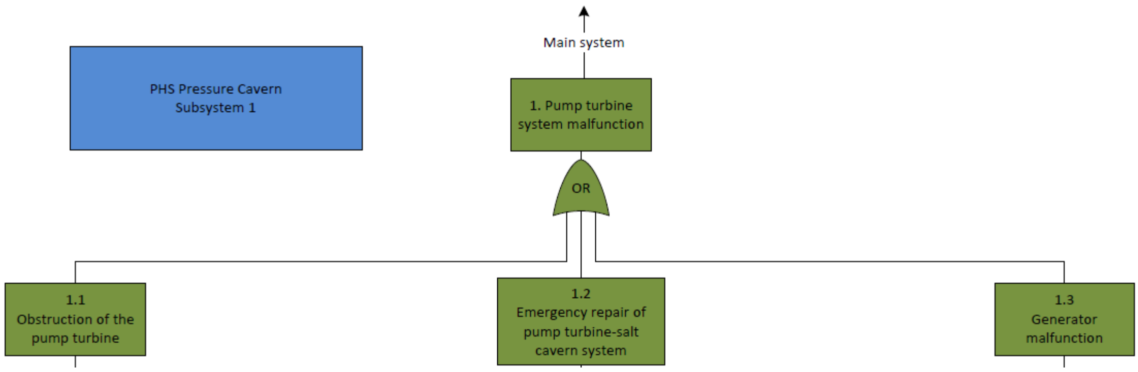

FIGURE 80 - SUBSYSTEM 1 MAIN COMPONENTS

For the obstruction of the pump turbine several factors are needed. It can occur because of slow clogging or by a large object. The slow clogging has to be taken care of by regular cleaning and quality checks. When these quality checks are not done correctly, the clogging of the pump turbine might go unnoticed. The chance for clogging is relatively small because of the long time scale in which the problem can be seen and the regularly planned cleaning and quality checks. Large objects will only pass if the protective grid is broken without noticing. From the salt cavern, large pieces are very rare because of the uniformity of the salt layer. From the reservoir, several protective grids should be in place, supported by camera surveillance.

Emergency repair is mainly based on problems with the construction of the pump turbine itself. Whether it is an external force or a design error, the pump turbine needs time to be repaired. These errors can be easily controlled by quality checks, which keep the chance of error small. The same counts for the chance of generator malfunction, which needs to be countered by design checks and careful placement and construction of the connections.

TABLE 71 - SUBSYSTEM 1 FAULT APPROXIMATIONS

Fault	Chance	Source
Obstruction of pump turbine	$2 \cdot 10^{-3}$	(TAW, 2003)
Emergency repair	$1 \cdot 10^{-4}$	Assumption
Generator malfunction	$3 \cdot 10^{-4}$	Design requirement
Pump turbine system malfunction	$2.4 \cdot 10^{-3}$	

Subsystem 2: Control system malfunction

The second subsystem covers the control room, which is the heart of the system. All the sensors inside the cavern and the reservoir are linked to the control room.

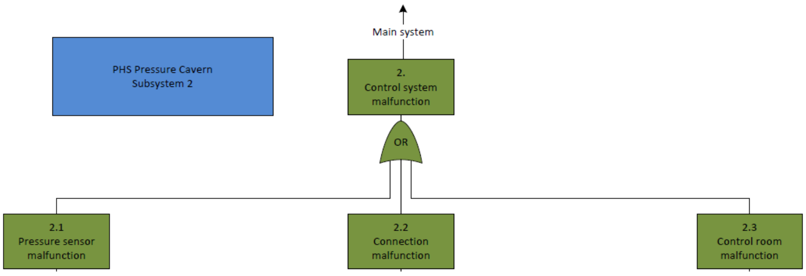

FIGURE 81 - SUBSYSTEM 2 MAIN COMPONENTS

The possible faults can easily be divided in three categories. First of all, the sensors themselves can fail. To counter this, all sensors are installed in twofold. The sensors that will enter the cavern should be built and implemented as strong and reliable as possible, because it isn't easy to replace these sensors and they have to survive in other circumstances like high temperatures.

Another common, but easily controlled risk is that of connections. To keep the system running, numerous wires are running between the control panel and the sensors or between the control panel and the working components. Connection errors could become catastrophic, which means that a large reliability is needed. Therefore, all wired connections will be done in twofold and tested extensively. To make sure that a common cause cannot take out the main and back-up connection at the same time, the wires must run through different cables.

The last risk that could lead to a malfunctioning control system is a problem in the control room itself. On could think of a fire or the situation that something happens when no one is around. Human error is always one of the largest risks, which needs to be countered in this system with the use of an automatic control system which takes over when needed. Another possible risk would be a blackout, which does not have to be a problem in an electricity producing facility, provided that appropriate measures are taken. The control room needs to be connected to the transformer inside the system itself and it should be possible to open the flow of brine (and energy) to the turbine by hand. Electricity is provided to the transformer and therefore the control room.

TABLE 72 - SUBSYSTEM 2 FAULT APPROXIMATIONS

Fault	Chance	Source
Sensor malfunction	$3 \cdot 10^{-5}$	(TAW, 2003)
Connection malfunction	$8 \cdot 10^{-4}$	(TAW, 2003)
Control room malfunction	$2 \cdot 10^{-4}$	(TAW, 2003)
Control system malfunction	$1.0 \cdot 10^{-3}$	

Subsystem 3: Grid connection malfunction

The advantage of the third subsystem is the low number of components. However, the components involve a very specialized construction in the form of the transformer. The transmission tower is easier to design, as it is a very common construction.

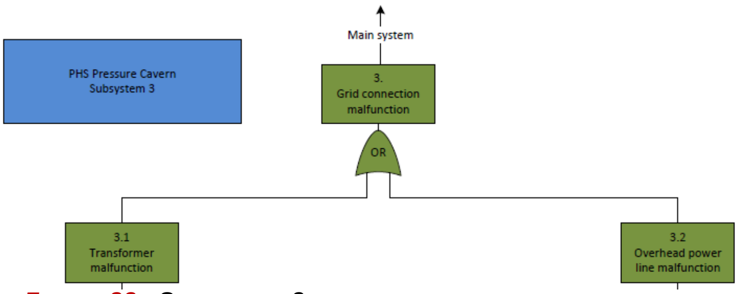

FIGURE 82 - SUBSYSTEM 3 MAIN COMPONENTS

The transformer has a lot of small components which can fail individually. However, the construction and design is proven technology and the chance that these small components fail should be small. The transmission tower can fail in a number of ways, because this large structure is placed in the open air. However, also this technology is known as well as the possible effects of the weather on the transmission tower.

TABLE 73 - SUBSYSTEM 3 FAULT APPROXIMATIONS

Fault	Chance	Source
Transformer malfunction	$3 \cdot 10^{-3}$	(TAW, 2003)
Transmission tower malfunction	$7 \cdot 10^{-4}$	(TAW, 2003)
Grid connection malfunction	$3.7 \cdot 10^{-3}$	

Subsystem 4: Reservoir malfunction

The last subsystem is that of the reservoir. This has the large complication that it is a large structure directly accessible in the open air and from the road. It will have to withstand all weather and problems that nature and humans may cause. The brine should not be able to flow into the ground water because of the extreme salinity.

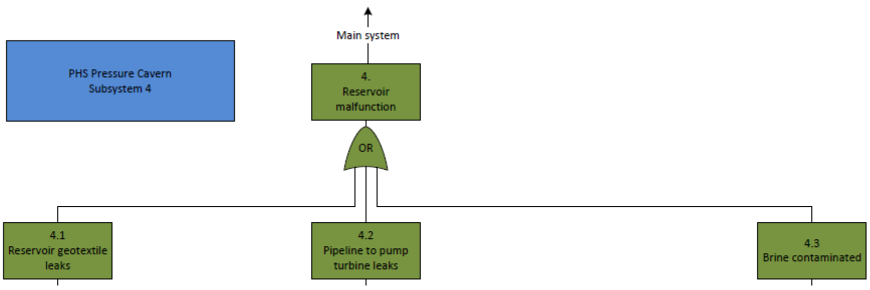

FIGURE 83 - SUBSYSTEM 4 MAIN COMPONENTS

The first risk is related to the geotextile in the reservoir. The brine level will change rapidly every day, which will result in an aggressive and changing environment for the geotextile. Nonetheless, it should be able to keep the brine out of the groundwater for the entire lifetime of the project. High quality geotextile can provide a sufficient amount of security. Regular checks of the geotextile should show when the geotextile needs to be replaced. A second form of failure could occur when the concrete pipeline between the pump turbine and the reservoir is not designed well enough to handle the changing conditions in which it needs to function. The third possibility, where the brine can be contaminated, can have human and natural causes. Regular checks of the chemical compound of the brine have to show if the system has to work with unexpected chemical substances.

TABLE 74 - SUBSYSTEM 4 FAULT APPROXIMATIONS

Fault	Chance	Source
Reservoir geotextile leaks	$1 \cdot 10^{-4}$	Design requirement for producer
Pipeline to pump turbine leaks	$6 \cdot 10^{-5}$	(TAW, 2003)
Brine contaminated	$2 \cdot 10^{-4}$	Assumption
Reservoir malfunction	$3.6 \cdot 10^{-4}$	

Main system: PHS Pressure Cavern FTA

When all chances are entered into the fault tree itself, it is possible to make a first estimate of the overall system risks and the chance of failure. The main system fault chances can be seen in the following figure.

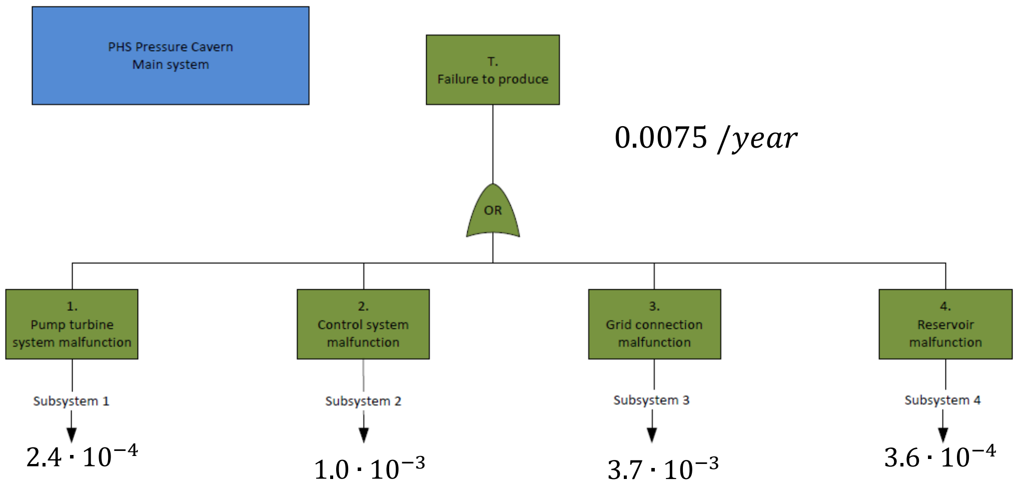

FIGURE 84 - MAIN SYSTEM FAULT TREE ANALYSIS

The figure shows that the chance of failure of the system is rather small. The chance is shown as a yearly figure. The increase in failure chance due to wear and operation over the years has not been taken into account, because the individual lifetimes of the components are unknown. Especially for intensively used components, regular maintenance checks are needed. Important, risky components might need replacement during the lifetime of the system.

These figures also show how the system risk depends on the separate subsystems and the components of the system. A division of the total risk, divided over the subsystems can be seen below. It clearly shows the dependence on the grid and the pump turbine. A possible explanation is the single transformer and the single pump turbine, which increases the risk. Although the control system consists of a much more complicated and extensive network, the cheap and easy possibility of implementing all wires and sensors in twofold decreases the risk significantly.

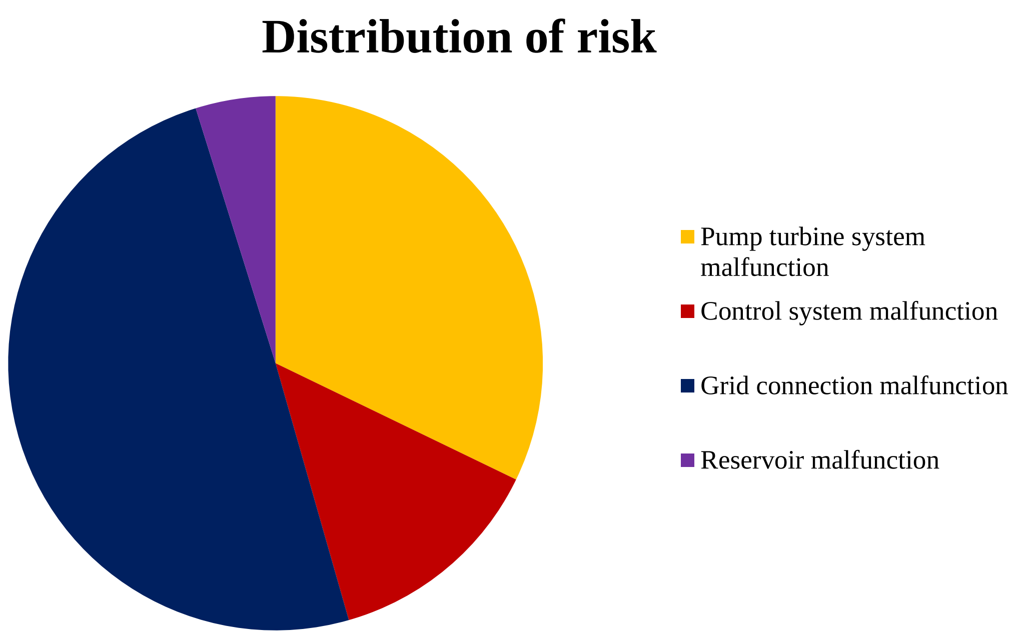

FIGURE 85 - DIVISION OF THE RISK OVER THE DIFFERENT SUBSYSTEMS AS A PART OF THE TOTAL RISK

The same solution is more problematic when it comes to the pump turbine and the transformer, because of the individual costs of the units. Especially the pump turbine, which accounts for half of the total costs, cannot afford to have a spare pump turbine ready to take over when malfunctioning.

The transformer on the other hand can have a spare unit ready, although it does lower the profitability of the system. Further investigation to the risk and the effect that a spare transformer could have on the total risk compared to the additional costs should point out whether an additional transformer is needed.

The pump turbine has two options. The first of which is to have two working pump turbines instead of one, while the power output of both pump turbines is half of the original output. This does actually increase the risk that the pump turbine will not work on full power, because of the increase in system components. Besides that the pump turbine parts will become smaller and therefore harder to clean. On the other side, the chance that the total production fails is much smaller. The other option would be increase the amount of maintenance moments, because of the importance of the pump turbine for the profitability of the system. Because the pump turbine is only used on full capacity for a small amount of time per day, it should be able to plan regular checks of the pump turbine.

The three largest risks are:

TABLE 75 - LARGEST RISKS OF THE PHS PRESSURE CAVERN-SYSTEM

Risk	Failure chance	Control measures
Transformer malfunction	$3 \cdot 10^{-3}$	Additional transformer when needed
Obstruction of pump turbine	$2 \cdot 10^{-3}$	If necessary double pump turbines or extra maintenance
Connection malfunction	$8 \cdot 10^{-4}$	Additional wires for most risky connections

Discussion

The risk analysis needs to be considered with the right perspective to be able to draw the right conclusions. The failure chances themselves are generalized estimates, on which no detailed design should be based. It can however help to show the relative differences and can therefore help to identify the most significant risks. From the analysis could be concluded that the transformer and the pump turbine are the most risky parts of the design and that the project risk could therefore be improved the most when these components are complemented with a back-up. Whether this is actually advised should depend on whether the chance of failure is acceptable and how much the reliability would improve compared to the additional costs of back-ups.

The total project risk seems rather low, but is calculated as a yearly chance to fail to produce, without taking factors like wear into account. Therefore, these numbers should in the first place be interpreted relatively to each other to find the most risky components or actions. A first step to clarify the meaning of the failure chance could be to compare the failure chance of the system and the components with the chances of failure of other facilities.

I.4.2. Risk table

The risk table shows the main risks that can cause delay or additional costs throughout the entire project. Different levels of severity are distinguished for risks that cause minor, moderate or severe problems.

The difference with the fault tree analysis is the broader picture that the risk table portraits. Besides the structural errors and the possible operational flaws it also shows the faults that can occur during construction or maintenance. Further, the consequences are more prominently represented. For this phase of the project, the fault tree analysis might have more direct value. It shows the weak points in the structural design and quantifies possible risks. The risk table on the other side shows the project as a whole, with all problems that can rise between stakeholders, during design, construction, operation and maintenance and financing.

The risk table itself is a large, constantly updated document, of which an example can be seen below in I.4.2. The most important risks can be found in Table 76.

TABLE 76 - MOST IMPORTANT PROJECT RISKS FROM THE RISK TABLE

Event	Sort	Consequence	Control measure
Change is subsidies for renewables/ energy storage	Political	Change in financial incentive	Early and regular appointments with government.
shaft leak	Technical	Loss of brine and pressure, pollution of groundwater	Controlled construction, regular measurements
Investing party quits (un)willingly	Organisational	Financial problems	Early and regularly updated agreements between parties
Protests from surrounding inhabitants	Social	Delay, negative publicity	Information appointments with inhabitants

As can be seen from Table 76, the largest risks are very spread across the project. Although most attention will go to the technical part of the project at this phase, one must keep in mind that the total project is much bigger than just the construction.

This can also have an effect on the choices made at this point already. One constructional method or used material could have a positive or negative effect on the way other people look towards the project, affecting the social and political acceptance in such an early stage. Another example of its influence is the large importance of creating financial incentive for the investors. Keeping politics involved and lowering risks could have a large positive effect on the financial outcome later on.

Below the extended risk table is shown, which has to be kept in mind and has to be updated along the whole lifetime of the project.

J7.2.1 Extended Risk table

Event	Chance	Consequence	Impact	Control measure
Political				
Change in subsidies for renewable energy/ energy storage	Large	Change in financial incentive	Large	Early agreements with government and regular appointments to adjust to future developments
Change in governmental view on underground activities	Average	Longer period needed for permits	Small	Request in time, keep government informed
Financial/ Economic				
Financing stops	Low	Project halts	Large	Keep investors informed
Price differences decrease	Average	Lower profits	Average	Focus on additional income
Legal				
Permit delay	Large	Project delay	Small	Request in time, regular checks
Legal charge	Large	Additional costs	Small	Keep clear idea of stakeholders and their incentives
Technical				
shaft leak	Average	Loss of brine and pressure	Large	Controlled construction and tests
Pressure too high for soil around casing shoe	Small	Crack along shaft casing, blowout	Large	Multiple pressure sensors, soil investigation
Leak in surface reservoir	Small	Loss of brine, groundwater contamination	Large	Regular maintenance and checks
Leak in casing	Small	Blowout	Large	Controlled construction, sensors

Unexpected salt layer reaction	Average	Lower roundtrip efficiency, decreased lifespan	Average	Extensive geotechnical investigation and tests
Soil characteristics problematic	Small	Project delay	Small	Extensive geotechnical research
Pump turbine malfunction	Small	Temporary loss of operation	Average	Regular maintenance and checks
Organisational				
Investing party quits (un)willingly	Average	Financing problems, additional funding needed	Large	Early and regularly updated agreements between parties.
Subcontractor breaks contract terms	Average	Delay, additional costs, loss in quality	Average	Use known subcontractors, quality checks
Geographic				
No appropriate location available	Average	Longer buyout period, design changes	Small	Search for locations early in design phase
unacceptable subsidence	Small	Damage to surroundings	Average	Regular measurements
Social				
Protests from surrounding inhabitants	Average	Delay, negative publicity	Average	Informing appointments with inhabitants

I.5. Preliminary Cost-Benefit analysis

By using the new insights from the previous parts of the preliminary design, it is possible to improve the cost-benefit analysis. The construction and the used techniques are clearer, which means that the costs of the system can be estimated more exact.

A special attention will be given to the possible revenues for energy storage systems. In the conceptual design two kinds of revenues were considered: arbitrage and production deferral. In this phase the sources of revenues will be investigated more precise with use of reference projects.

The use of energy storage has advantages for different parties. Besides the direct revenue from the difference between day- and night-tariff, also benefits can be found when cheap coal or renewable energy can be used instead of expensive natural gas. Thirdly, the almost instant reaction capabilities of the pump turbine reveal the possibility of using PHS for so-called ‘secondary services’. When both the costs and benefits are elaborated upon, a new Net Present Value can be calculated.

I.5.1. System costs

A big step towards a more detailed costs analysis is possible now that the construction methods and the needed dimensions are clear. As a starting point, the costs analysis from the conceptual phase is used. This divided the project into five different parts:

- PTC-station
- Shaft
- Surface reservoir
- Preparation
- Additional costs

The first three categories can be united to form the direct construction costs. The last two are not instantly linked to the construction site and are therefore indirect costs. In this stage of the project, the indirect costs are still largely unknown, but can be assumed fairly accurate as a percentage of the direct construction costs or the subtotal costs. The five categories will be covered below:

PTC-Station

The station is the heart of the system and will the most costly piece of the puzzle at the same time. It houses the reversible variable speed Francis pump turbine and the control room. Also the connection with the grid has to start from here. This results in the PTC-Station accounting for 60% of the subtotal costs. The division of the costs of the PTC-station between the different components can be seen below.

TABLE 77 - PRELIMINARY COST ESTIMATE FOR PTC-STATION

Component	Amount	Costs per unit	Component costs	Total costs
Pump turbine			16.1 million €	
Control System			0.1 million €	
Transformer System			2 million €	
Construction Station	$1000m^2$	$750\ €/m^2$	0.8 million €	
Grid connection			3 million €	
Total PTC-Station				21.9 million €

The costs of the Pump turbine stand out immediately. With a total cost of roughly 16 million euro, this is by far the most expensive component of the system. Therefore, a detailed assumption of the cost of the pump turbine is needed.

As a starting point, the construction costs of a similar pump turbine project, as conducted by Royal HaskoningDHV, is used. A multi-stage reversible Francis Turbine was used in this project for an average of 115 €/kW (2009). The construction of the Pump turbine needed for the Pressure Cavern is therefore assumed to be 130 €/kW, compensated for a lower head difference and a few years of development in design and price level. This results in a total Pump turbine construction cost of 8.5 million euro.

The cost of the Pump turbine doesn't stop with the construction. It also needs to be transported and installed. This can be a special problem considering the size of the Pump turbine itself. Common practice to incorporate these actions, as claimed by the OPAC- reference project, is to use the construction costs of the Pump turbine and multiply these with a factor. A common installation costs factor varies between 1.6 and 2.0, which includes construction. A factor of 0.1-0.25 is used for transportation. The current project has a reasonably easy installation, as the Pump turbine station is placed on ground level and is easy accessible. The Pump turbine itself needs to be installed underground, to make sure that the Pump turbine is always under pressure at the pumping stage. Because the north and the east of the Netherlands is easy accessible by road and water, transportation should also not pose critical problems. The weight and size of the Pump turbine can only cause minor issues when it comes to corners and bridges. Therefore an installation factor of 1.7 and a transportation factor of 0.2 are chosen. When accounting for the installation and the transportation as well as the construction, the cost for the total Pump turbine adds up to 16.1 million euro.

Other important costs are the Transformer System and the grid connection. The transformer has been assumed to be 2 million euro, which is a very conservative assumption based on transformers used in reference projects like OPAC. The costs of the grid connection mostly depend on the distance between the facility and the nearest high voltage grid. Because the location is unknown for the time being, this figure is also largely unknown. Therefore, a very conservative figure based on reference projects has been chosen.

Shaft

The second part of the direct construction costs is the underground part, the shaft. The borehole used for salt solution mining is not sufficient and therefore needs to be replaced by a larger diameter well. The costs can be seen below.

TABLE 78 - PRELIMINARY COST ESTIMATE FOR SHAFT

Component	Amount	Costs per unit	Component costs	Total costs
Removing salt mining well	1060 m depth	200 €/m depth	0.21 million €	
Micro Tunnelling	900 m depth	4000 €/m depth	3.6 million €	
Bentonite	2600 m^3	75 €/m^3	0.20 million €	
Casing material	1590 ton	500 €/ton	0.79 million €	
Placement Casing	1060 m depth	400 €/m depth	0.42 million €	
Total Shaft costs				5.2 million €

The shaft requires more actions that the PTC-Station, but because of the absence of highly specialized components like the Pump Turbine or the transformer, it is relatively limited in costs. The highest costs are related to the widening of the borehole. This has to be done with Micro tunnelling, because of the unusual diameter.

A second large component is the casing steel. To cope with the large pressures from in- and outside of the casing, a thick layer of steel is needed. This layer is used all along the 1060 meters in the brine inside the cavern.

Surface reservoir

The third and last direct construction component is the surface reservoir. This only refers to the constructional side of the reservoir, as the acquiring of the land is part of the preparation phase. Soil needs to be moved from the centre of the project site towards the dike location. The inside of the dike and the bottom the reservoir needs to be covered in watertight foil.

TABLE 79 - PRELIMINARY COST ESTIMATE FOR SURFACE RESERVOIR

Component	Amount	Costs per unit	Component costs	Total costs
Ground removal	160,000 m^3	4 $€/m^3$	0.64 million €	
Dike construction	50,000 m^3	10 $€/m^3$	0.50 million €	
Watertight foil	54,000 m^2	0.5 $€/m^2$	0.03 million €	
Ballast stone	9,200 m^3	75 $€/ton$	0.69 million €	
Construction reservoir			0.20 million €	
Connection PTC-station			0.50 million €	
Total Surface station				2.6 million €

The surface station is the easiest part of the construction process, because it is a straightforward and commonly executed part of construction. Reservoirs like this have been built numerous times, which means that no special and expensive material or construction method has to be used for the construction of the surface reservoir. From the figures above can be seen that the largest costs are associated with the ground repositioning and the acquiring of the ballast stone. Some changes in the costs can be made by using cheaper material or decreasing the amount of ballast or the height of the dike, but this change will only have a minor effect on the total project costs.

Preparation

The fourth part of the project is harder to quantify as it is not directly linked to the construction activities themselves. Because these activities are a part of every project however, it is common to make an assumption based on rule of thumb numbers. This is done for the costs of design and the acquiring of permits, as well as an additional part for risk.

TABLE 80 - PRELIMINARY COST ESTIMATE FOR PROJECT PREPARATION

Component	Amount	€/unit	Component costs	Total costs
Design	5% of subtotal costs		1.6 million €	
Acquiring permits	0.5% of subtotal costs		0.2 million €	
Acquiring land	50,000 m^2	50 $€/m^2$	2.5 million €	
Risk	6% of subtotal costs		2.0 million €	
Total Preparation				6.3 million €

These are mainly commonly used figures for all kinds of construction projects. In a more detailed design phase, the figures have to be specified to the special nature of the project. A large part of the costs depends on the acquiring of the land. Although land prices are low in this part of the Netherlands, this still accounts for 2.5 million euro.

Additional costs

When all the costs above are added, the *subtotal costs* can be calculated. This is the price of the project as calculated with all the components of its design and construction. According to the numbers and components used, the subtotal costs add up to 36.0 million euro.

However, it is common to incorporate several provisions, to prepare for errors made in the calculation. Because these provisions are naturally hard to quantify, they are usually taken as a certain percentage of the subtotal costs. The following provisions are made:

TABLE 81 - PRELIMINARY COST ESTIMATE FOR ADDITIONAL PROJECT COSTS

Component	Amount	Component costs	Total costs
To be designed	10% of the subtotal costs	3.6 million €	
Indirect costs	14% of the subtotal costs	5.0 million €	
Unforeseen	10% of the subtotal costs	3.6 million €	
Total Additional			12.2 million €

This table shows that a large sum of money is incorporated inside the projects total costs without a clear purpose. However, experience with previous projects show that use of these figures will lead to a fairly accurate project cost amount when used in this phase of the project. Later in the design, when a more detailed cost analysis will be made, these provisions can be made smaller.

Project costs

When all these different categories are added, the total project costs are calculated. This is the assumption of the total cost of designing and building an energy storage facility in the north of the Netherlands:

TABLE 82 - PRELIMINARY COST ESTIMATE FOR TOTAL PHS PRESSURE CAVERN-FACILITY

Component	Component costs	Total costs
PTC-Station	21.9 million €	
Shaft	5.2 million €	
Surface reservoir	2.6 million €	
Preparation	6.3 million €	
Subtotal costs		36.0 million €
Additional costs		12.2 million €
Total costs		**48.2 million €**

This is a slight difference with the costs that were estimated in the conceptual design. Comparison shows that the costs of the shaft have gone up significantly, while the Pump turbine has become cheaper. Whether the project is profitable, depends on the revenues which are explained further in the next chapter.

I.5.2. System benefits

The energy storage facility is able to provide benefits in a variety of ways. The difficult part is to redirect the revenues to the investing companies. The main benefits are:

- Arbitrage, the difference between off-peak and peak prices
- Fuel costs, using cheap coal or renewables instead of expensive gas
- Production deferral, less production capacity needed as peaks are lower
- Secondary services, where the facility is paid to help maintain the stability of the grid

Which forms of revenues apply, depend on the investing and operating companies. Two forms of revenue, arbitrage and secondary services will result in direct revenues. This means that they will provide benefits independent of the investing company. Fuel costs will only benefit energy producing companies, which would have to buy expensive gas if energy storage would not have been available. Production deferral also benefits the production companies as well as grid operator TenneT, which are responsible for the certainty of electric energy on the grid. The four ways of producing benefits will be described below briefly.

Arbitrage

This obvious form of revenue has already been described earlier. It refers to the price variation of electric energy along the night and day. Because of the low demand and the inability of a large portion of the production capacity to rapidly turn down production, prices drop during the night. On the other side due to high demand and the necessary expensive additional peak production, prices rise during the day. This difference will continue to exist as long as no significant energy storage is in place to compensate both the demand and supply during the day and the night.

From (Services, 2014) and data from powerhouse.nl[34] the price range of off-peak and peak load electricity can be approximated. These prices are an indication of the average price during the off-peak period (at night) and the peak period (during the day).

Table 83 - Peak and Off-peak prices for electricity in the Netherlands per MWh, as monitored by Energy Services (Services, 2014)

Date	Peak price (7-20h) €/MWh	Off-peak price (20-7h) €/MWh	Price difference €/MWh
January ‘13	58	43	15
July ‘13	53	38	15
January ‘14	53	36	17
July ‘14	50	33	17

A point of notice is the times in which the peak and off-peak prices are defined. These prices are the averages of the hours between 7.00-20.00 and 20.00-7.00 respectively. This means that the real momentary peaks are weakened by the rest of the hours-long period. When looking at the hourly prices at powerhouse.nl, the highest and lowest value can easily lie more than €20/MWh apart.

[34] http://www.powerhouse.nl/forecastenprijzen.html#onbalans. Accessed on 4-8-2014

Another factor that has to be taken into account is that a portion of the electricity can be used in the Unbalance Market instead of the daily market. This increases the potential revenue per MWh further. Because the energy storage facility is planned to charge and discharge in three hours, an initial price difference of €30/MWh is chosen for further calculations. The value for the price difference is significantly lower than earlier assumed. A price difference of €40/MWh was assumed in the concept design. The more detailed cost-benefit analysis will try to show whether this will greatly affect the profitability.

The development of this difference over time is still unknown, although the difference has been increasing over the past years. Based on political choices, like those on wind energy in the Netherlands (NWEA, 2011), this is most likely not going to change. Current plans are to increase the part of Dutch energy products capacity by wind energy from 10% (2015) to 30% in 2020 and 50% in 2050. This leads to the design assumption that the difference will grow over time, which has also been assumed by reference projects. Therefore, the revenues from arbitrage are assumed to grow from €30/MWh at the start of the operation to €45/MWh at the end of the project period 50 years later.

Fuel costs

A second way of producing benefits is by comparing the way of producing peak electricity with the way off-peak electricity is produced. This benefit has not been considered in the previous design step because it only benefits the producing company, which may or may not be one of the investing companies. However, in this phase it should be named that this could greatly benefit production.

Instead of expensive natural gas production, cheap coal or even renewable energy can be used to produce the electricity needed to handle the daily peak. Because it is unsure whether coal or renewables will be used, the more expensive coal will be assumed.

The prices used here are an indication made by the (ECN, 2013), that predicted the price changes over the coming years. It stated that coal will costs around €3.5/GJ, which is about €12.5/MWh. Also the gas price is predicted as $€0.30/m^3$ gas, which relates to about €30.0/MWh. These prices are momentarily far apart. This is the result of the American coal market shifting towards Europe, because several American coal plants are closing down. This lowered the coal price. Also the pollution tax on coal is still rather low. This is expected to change in the future, which is implemented into the calculation by decreasing the price difference by half in 50 years. Important to consider is whether this benefit applies for the investing parties. Especially in combination with other benefits like arbitrage or production capacity deferral. This will shortly be discussed when all benefits have been mentioned.

Production deferral

The third possible benefit has already been mentioned in the previous phase. By using the PHS Pressure Cavern-facility for peak shaving, less peak capacity is needed. In the previous phase, the amount of peak capacity needed less was estimated to be 70% of the installed energy storage capacity. However when Royal Haskoning designed the OPAC-facility in 2006, a percentage of 125% was used. A percentage higher than 100% is possible due to the faster reaction time of a hydropower turbine over a natural gas facility. Although this might be true, also the commitment of energy producers is needed and at this phase of this energy storage-facility it seems unlikely that these companies will do just that. Therefore, a percentage of 80% will be chosen. This line of thoughts also indicates that this percentage might rise along the way. The electricity producers will experience the abilities of energy storage and the impact on the amount of peak production capacity needed. As a result of the lowering risk as experience grows, the willingness of the companies to increase this percentage will grow and the percentage of 125% might be more realistic. The benefit analysis will allow a small rise, but will stay conservative by using a percentage of 80% at the start of the project up to 90% after 50 years.

Secondary services

Another direct form of income for an energy storage facility is to provide secondary services. The grid is a dynamic network, where supply and demand needs to be matched at all times. The grid has several stations that are able to regulate the amount of electricity and the quality of the grid, in the form of frequency control, to avoid problematic situations. This is needed, because traditional coal- and gas plants are not able to scale up or down quick enough to be able to regulate the grid. A hydropower turbine however is able to change production in a matter of seconds.

If a portion of the power output would not be used for storage of energy, but of the regulating of the grid, network operator TenneT will be willing to pay for that service. Reference project OPAC valued this service for €120 - €160 per kW back in 2006. When taking the average value and applying an interest rate of 4%, a price of around €190 per kW is found appropriate. However, a choice has to be made how much of the power output is used for this secondary services and how much is used for energy storage itself. For this calculation the amount of power output used for secondary services will amount up to 15 MW, which leaves 50 MW for energy storage.

Total revenues

When all possible revenues are considered with the values mentioned above, this will result in the following revenues:

TABLE 84 - YEARLY REVENUES FOR THE POSSIBLE WAYS OF PROVIDING BENEFITS FOR THE PHS - PRESSURE CAVERN

Revenue	Year 0	Year 50
Yearly arbitrage revenues	€1.6 million	€2.4 million
Yearly fuel revenues	€0.9 million	€0.5 million
Yearly production deferral revenues	€1.4 million	€1.6 million
Yearly secondary services revenues	€2.9 million	€2.9 million

These revenues do consider some change over time, but mostly do not incorporate inflation in order to keep on the conservative side. When it is possible to benefit from all these revenues, it would be possible to generate a total of €6.8 million euros the first years of operation up to €7.4 million euros towards the end of the lifetime.

Optimal benefits

The question however is: is it possible to benefit on all the ways described? In other words, will all these advantages and revenues find their way to the investing companies? If not so, the revenue should not be accounted for in the cost-benefit analysis.

First consider the energy producing companies. They have the choice between building a natural gas facility and investing in energy storage. Only they will therefore benefit from the production deferral. Investing in energy storage will result in less investment needed in natural gas facilities or at least a significant postponement of replacement. Also, they buy the needed fuel materials to produce electricity. The producing companies will therefore also benefit from the change in fuel.

The secondary services will benefit the network operator, as they are responsible for the stability of the grid. On the other side, there is already a way to redirect these benefits from the network operator to the investing company in the form of fees per kW regulating power. Arbitrage is a direct source of income (it generates actual money) and is therefore easy to benefit from as an investing company.

In order to make optimal use of the revenues stated, the electricity producing companies and the network operator need to be involved in the investing plan for the facility. Otherwise, a different way has to be found to transfer the benefits from the producers to the investors.

This could be done in the form of usage fees. However, producers supply the grid and the energy storage facility buys and sells from and to the grid as well. No clear connection between one coal plant or wind farm with the energy storage facility can be made without large costs. A different option would be for network operator TenneT to monitor the usage rates of the energy storage facility and charge the producers accordingly. This would be a fair distribution as the entire grid benefits from the increased stability and storage capacity available.

The all-important question who has to invest and how the benefits have to be obtained for the investors will be elaborated upon in a later stage. It will be assumed for this cost-benefit analysis that it is possible for all the mentioned benefits to find their way to the investors.

I.5.3. Net Present Value of the PHS Pressure Cavern-facility

The new knowledge about the costs and benefits of the project allows for a more accurate calculation to find out whether the project will be profitable. The main concept of Net Present Value has already been explained and used in the conceptual phase.

Next to the total costs and the different forms of benefits, a couple of other notions are important in order to describe the cash flows over the years as accurate as possible. These notions have already been described earlier in the conceptual phase and have been kept the same during the preliminary design:

TABLE 85 - IMPORTANT NOTIONS FOR THE PRELIMINARY NPV-CALCULATION OF THE PHS PRESSURE CAVERN-FACILITY

Variable	Description	Value
Risk-free rate	The interest percentage that can be achieved without risk. Usually based on the interest rate of government bonds or interbank loans.	3%
Risk premium	The amount of additional interest that is demanded to offset the additional risk compared to the risk-free rate. Also incorporated is opportunity cost, which is the additional interest that can be achieved by investing in projects with comparable risks.	5%
Facility lifetime	The length of time in which the project is projected to generate revenues	50 years
Construction time	The amount of time the construction takes, after which the first benefits can be made.	1.75 years
Unit running price	The amount of money it costs to run the energy storage plant for 1 MWh.	€0,50
Construction costs distribution	The distribution of costs over the construction period, divided over the 1st/2nd year in percentage of the total construction cost.	40/60

These numbers can be added to the Net Present Value calculation. Figure 86 shows the costs and benefits for every year of the project. A few things stand out, of which the constant decrease is the most explicit one. This is due to the discounting factor, which incorporates the idea of ‘a euro today is worth more than a euro tomorrow’ into the calculation. This shows how important it is to start creating benefits as soon as possible and as much as possible.

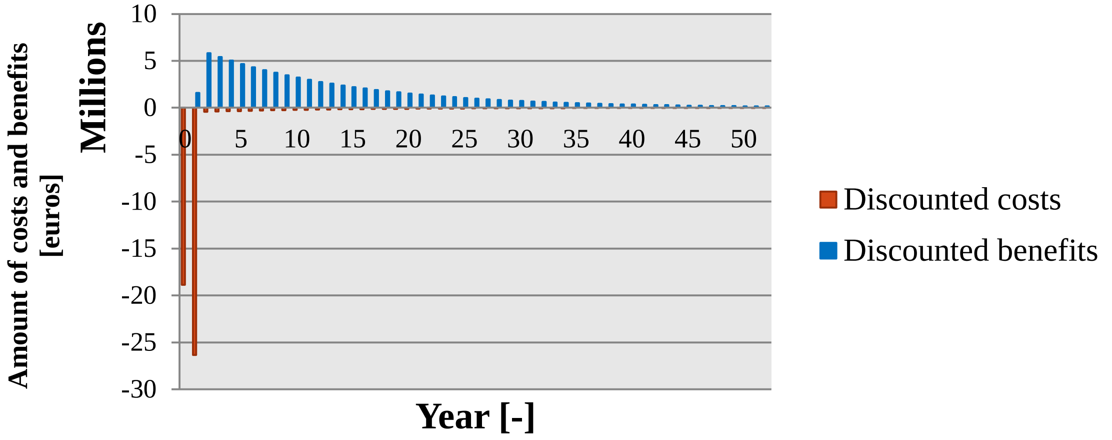

FIGURE 86 - YEARLY DISCOUNTED COSTS AND BENEFITS FOR THE PHS PRESSURE CAVERN-FACILITY

This figure shows when the highest costs are made and when the highest benefits can be expected. If the separate figures are added, the change in the Net Present Value over time can be found. This is shown in Figure 87. An important comment here is that this incorporated all of the possible benefits, which makes it a best-case scenario when it comes to investments.

In the case of this scenario, where all the benefits are exploited, the project shows a large potential.

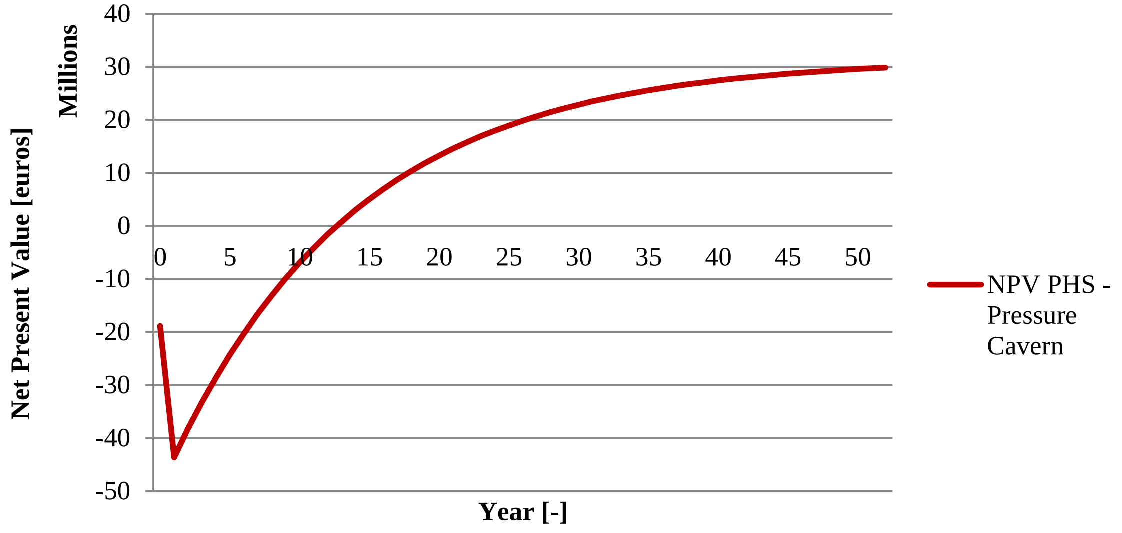

FIGURE 87 - NPV-CALCULATION DURING THE PROJECT TIME OF THE PHS PRESSURE CAVERN-FAC.

The Net Present Value starts negative because of the construction costs, but quickly changes into a profitable project. The total Net Present Value of the project is projected at **29.9 million euros**.

The next step is to test the sensitivity of this calculation. As said before, it might be possible that not all benefits can be used or accounted for. This risk could have a large impact on the profitability of the profitability of the system.

In the subchapter dealing with the system benefits, four different forms of revenues were described. Of these four possibilities, the secondary services are the most certain form of income. The biggest chance of missing out on some of the revenues is the possibility that either the fuel revenues or the production capacity deferral revenues cannot be accounted for in total. This can change the overall Net Present Value and the payback period. This is further explained with the use of Table 86.

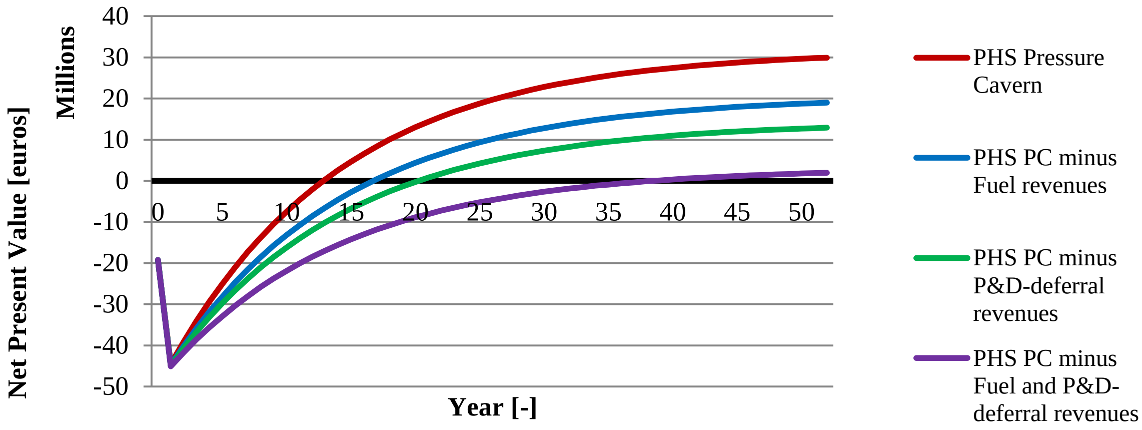

FIGURE 88 - NET PRESENT VALUE CALCULATION FOR DIFFERENT SCENARIOS OF POSSIBLE REVENUE FOR PHS PRESSURE CAVERN-FACILITY

This figure shows decline of the profitability with the declining revenues. The projected situations show the Net Present Value calculations when the revenues from fuel revenues (blue) or revenues from P&D-deferral (green) or both (purple) would not be accounted for. A small summary of the results is shown below in Table 86.

TABLE 86 - NET PRESENT VALUES AND PAYBACK PERIODS FOR DIFFERENT REVENUE SCENARIOS

Scenario	Net Present Value	Payback Period
All revenues	€ 29.9 million	7 years
All minus fuel revenues	€ 18.9 million	8 years
All minus P&D-deferral revenues	€ 12.9 million	10 years
Only arbitrage and secondary services revenues	€ 1.9 million	12 years

This table shows that the loss of one form of revenue would still result in a profitable project. However, the profit would decline significantly and the payback period would increase from 7 years to 8 or 10. An economically desirable project would therefore require the facility to capitalize on at least three of the four forms of revenue in order for the project to remain profitable.

Concluding, the project is technically and economically feasible, given that the right revenues can be generated. This shifts the main focus of the feasibility study from the technical challenges towards the right investment planning. With the preliminary design above, it has been proven that it should be possible to build a 65 MW, 156 MWh energy storage facility with a price tag of roughly 48 million euros, which means that it is able to generate profits. The remaining problem is to find investing companies with the right incentives and the ability to benefit from the possible revenue sources.