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Master of Science

Master thesis - Pumped Hydroelectric Storage at Niingen Power Plant

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Abstract

This document is a master thesis that attempts to assess the plan of pumping water from the nearby lakes of Djupåvatnet (435 m), Buvatnet (465 m), and Strandvatnet (5 m above sea level) up to the lake of Niingensvatnet (510-494 m above sea level) to store energy for later use and increase energy generation. The assessment process proved that pumping water from Strandvatnet and Djupåvatnet to Niingensvatnet is not financially feasible, while the case of Buvatnet-Niingensvatnet pumped storage is cost-efficient and has many benefits in terms of increasing stability and profitability.

Foreword

The Paris Agreement is an international climate change treaty adopted by 196 countries, including Norway, in 2015. The goal of the Paris Agreement is to limit global warming to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1,5 degrees Celsius. Norway is committed to reducing its greenhouse gas emissions by at least 50% by 2030 compared to 1990 levels. Norway has also pledged to become carbon neutral by 2030 and to achieve net-zero emissions by 2050[1], [2]. To achieve these results, advanced means of generating and storing clean energy must be utilized, pumped storage is among the most relevant, efficient, and reliable clean energy production projects that will contribute to achieving the mentioned results.

This master thesis assesses and designs systems and components of a pumped storage project in the Niingen hydroelectric power plant in Evenes municipality, Norway.

Acknowledgments

I would like to thank my supervisors, Guy Mauseth and Per Johan Nicklasson from The Arctic University of Norway (UiT) for their guidance, comments, and suggestions throughout this master thesis. Their expertise, insightful feedback, and constant encouragement played a crucial role in shaping the quality and depth of my research. I am truly grateful for their help and mentorship, as well as to my supervisor Matthew Homola at Nordkraft for answering all my questions and providing me with charts and technical drawings for the Niingen power plant during the semester and also offering a field trip to the Niingen power plant which was vital to gain insights into its components, infrastructure, and operations in details.

Main task text

Title: “Niingen pump”

Text: “The thesis will assess and evaluate pumps from Buvatnet and Djupåvatnet to Niingsvatnet (reservoir for Niingen power plant). Watersheds, potential regulation height, dimensions of pipes, pumps, power lines, and profitability should be included. Alternatively, pumping from the outlet water to Niingen can be considered.”

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List of mathematical and hydraulic symbols

V	Volume, Velocity	g	Gravitational acceleration
d	Diameter	Sg	Specific gravity
z	Elevation	p	Pressure
A	Area	H, h	head
Q	Flow	h_f	Head loss due to friction
ω	Rotational speed in rad/s	η	Efficiency
ω_P	Pump's specific speed	η_p	Pump efficiency
N	Rotational speed in rpm	η_t	Turbine efficiency
L	Length	P	Power
m	Mass	$P.E.$	Potential energy
w	Weight		
ρ	Density		
v	Kinematic viscosity		

Table 1 List of mathematical symbols

Pump			
Open valve			
Closed valve			
Pipe			
Turbine			
Motor			
Reservoir			

Table 2 List of hydraulic symbols

1. Introduction

This chapter aims to give an introductory study to the main topic, assessing the pumped storage plan at the Niingen power plant. Background data about the power plant, its location, layout, watershed data, state-of-the-art, and challenges will be included in this introduction to give a clearer vision of how to understand this topic and its specification.

1.1 Purposes

Many purposes can be for pumped storage projects, among them, in terms of the Niingen power plant:

Load balancing

One of the main purposes of pumped storage schemes is to help balance the supply and demand of electricity on the grid. By storing excess energy during low-demand periods and releasing it during high-demand periods, pumped storage schemes can help smooth out grid fluctuations and reduce the need for other, less flexible forms of energy generation.

A reliable power grid is crucial for a smoothly running society - if electricity demand outstrips supply, this can lead to power shortages or overloads. [3] To achieve this result, batteries can be used to provide energy at high-demand times and store energy at low-demand times. However, the contemporary types of batteries are often small and store only a few hours of charge. [3] Thus, a better alternative had to be found, which works similarly to a battery.

"It's called pumped hydro energy storage. It involves pumping water uphill from one reservoir to another at a higher elevation for storage, then, when power is needed, releasing the water to flow downhill through turbines, generating electricity on its way to the lower reservoir."[3]

Power shortages are caused by the higher demand, usually in the winter, and the lack of a power plant for supply. It causes mainly damage to customers' electric devices, possible decreases in the company's energy prices due to unstable production, and higher prices/profit for competitors.

On the other hand, power overload is caused by the higher supply against demand in the summer and the power plant's inability to manage the extra potential energy. And results also in damaging customers' devices, reduced or even negative prices due to the plenty of potential energy, and again higher profits for competitors.

This leads to the conclusion that a better energy-management mechanism is the best way to manage production properly. Which is the main purpose of this project. Other purposes are also aimed for in this project such as:

Increasing profitability

By pumping water from a lower reservoir to the upper reservoir at low power prices and converting this hydraulic potential energy to electric energy at high electricity prices, profits of the operation will increase as a result. In addition to higher profit stability, and lower losses during low energy prices. I.e., completely avoiding or lowering the damage of negative prices.

Energy storage

Water at high elevations is considered potential energy that can be converted to electrical power. However, the availability and prosperity of this water are not the same all year long, in times the reservoirs for water can overflow with water to seep into the soil, evaporate or flow into irrelevant lakes or the sea. In this case, useful energy that could have been used to benefit the lives of people is wasted. Other times, water levels in the reservoirs will be low, making them unsuitable for power production. Pumped storage projects offer the service of transferring this valuable energy from one reservoir to another when needed.

Ancillary services

Finally, pumped storage schemes can provide a range of ancillary services to the grid, such as voltage support, frequency regulation, and spinning reserves. These services can help to maintain the stability and reliability of the grid and ensure that electricity is delivered to customers safely and efficiently.

1.2 Background

1.2.1 Niingen power plant

Figure 1 Niingen Power Plant [4]

Niingen power plant in Evenes municipality, Nordland County, is located at the lake of Strandvatnet in Bogen in Ofoten. It was extensively rehabilitated in 1990 but started working as early as 1954. The unit was replaced in 2008, and the intake was renewed in 2009.

The Niingen power plant utilizes a drop of 495 meters from the lake of Niingsvatnet to Strandvatnet (3 m above sea level). The power plant is equipped with a 5-beam vertical Pelton turbine, and the unit has an output of 18,511 MVA.

Maximum suction capacity [m^3/s]	4.1
RPM [rpm]	750
Generator output [MVA]	18,511
Generator voltage [V]	6600
Head [m]	501,7
Length of the penstock [m][5, Tit. Tegning013]	1056,127
Length of the head race tunnel [m]	3300
Installed capacity [MW]	16,7
Annual energy output [GWh]	79
Turbine type	Pelton

Table 3 Specifications of Niingen power plant [4]

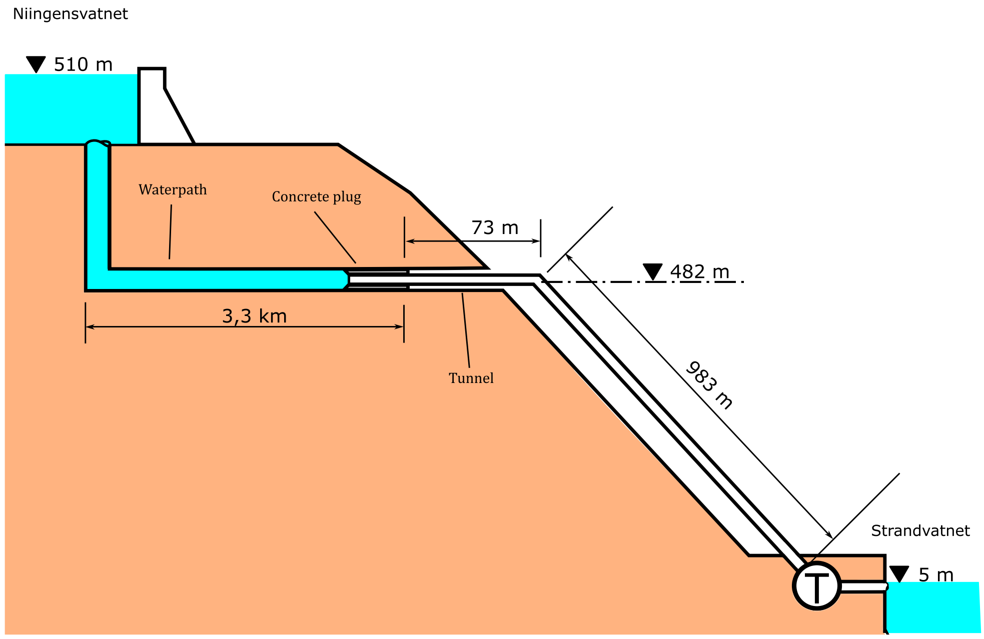


Figure 2 A side view sketch depicting the layout of the Niingen power plant

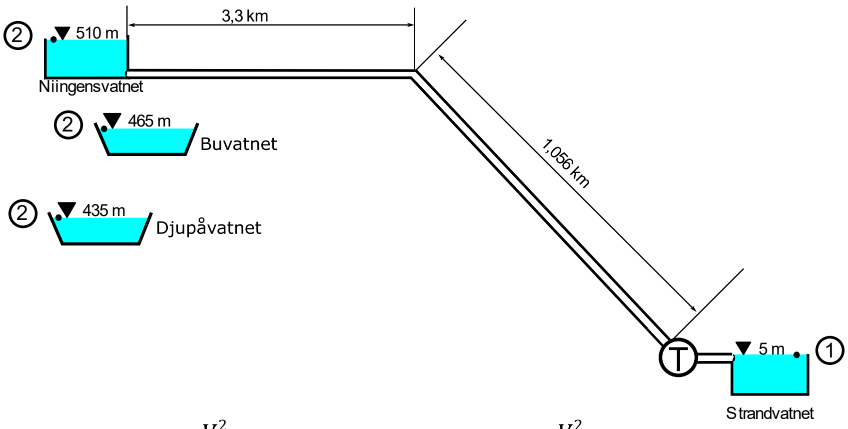
Figure 2 depicts the layout, main components, and geometry of the Niingen power station. The main components are in the following table.

	Elevation [m]	Length [m]
Niingensvatnet	510-494	-
Water path	482	3300
Penstock's tunnel	482	73
Penstock's pipe after the tunnel	482 -5	983
Turbine chamber	5	-
Tail race tunnel	5	-
Strandvatnet	5-0	-

Table 4 Specifications of Niingen power plant

The water path is not a pipe; but is a channel that draws the water of Niingensvatnet of a cross-section of 4,5 m^2 [6]

However, the use of such a complex model in Figure 2 can pose challenges in terms of analytical calculations and interpretation of results. To overcome these challenges, model simplification can be employed to reduce the complexity of the model while maintaining its essential features as in Figure 3.



$$\left(\frac{p_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1\right) + h_t + h_p = \left(\frac{p_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2\right) + \sum hl$$

Figure 3 Simplification of the Niingen power plant mode and other lower reservoirs which allows a direct approach to the energy equation

1.2.2 Niingensvatnet

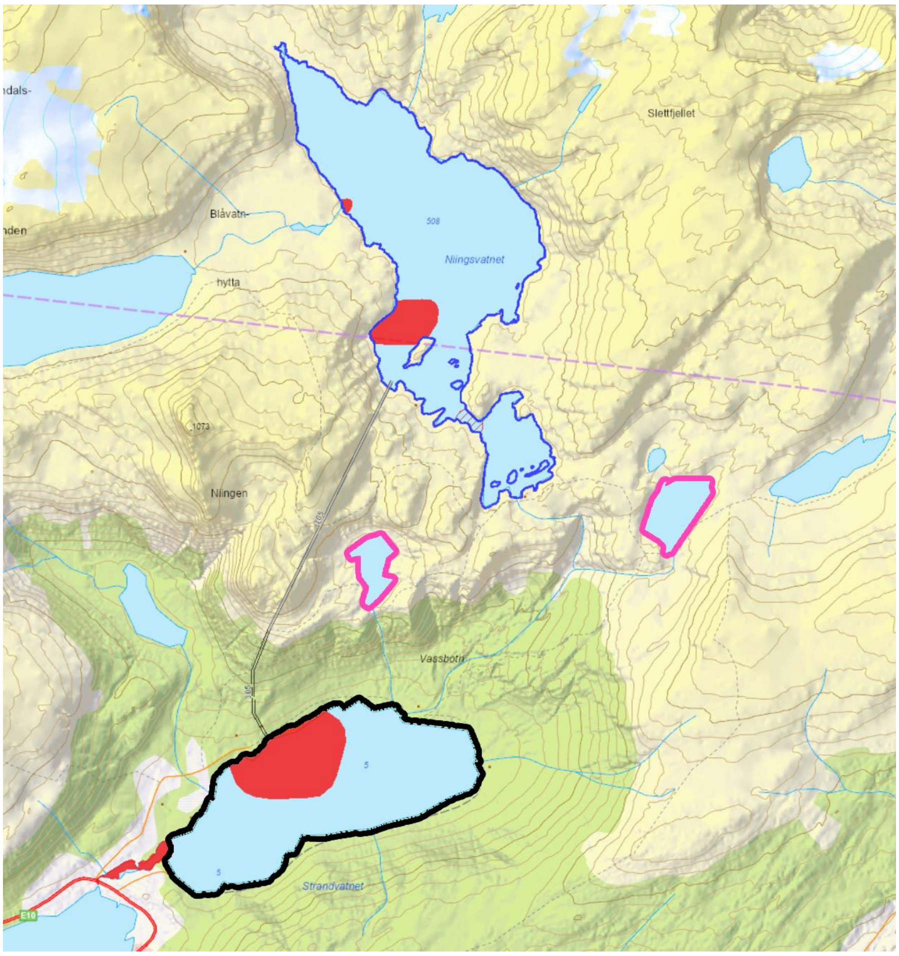


Figure 4 A map that shows the location of Niingensvatnet, pipes that lead the flow to the Niingen powerplant (double lines), weakened ice (red regions), Buvatnet (right, marked in pink), and Djupåvatnet (left, marked in pink) and Strandvatnet (marked in black) [7]

Maximum height at water surface [5, Tit. Tegning013] [m]	510 (Above this level dam overflow will occur.)

Minimum height at water surface [5, Tit. tegning013] [m]	483,12 (Below this level is the top point of the penstock.)
Yearly precipitation [mm]	1100,23
Area [km^2]	3,04

Table 5 Relevant specifications of Niingensvatnet[8]

Figure 5 Aerial photos showing the locations of the four lakes and the dam at Niingensvatnet[9]

1.2.1 Strandvatnet

Maximum height at the water surface [m]	5
Minimum height at the water surface [m]	0 (Sea level)
Yearly precipitation [mm]	1033
Area [km^2]	1,95

Table 6 Specifications of Strandvatnet

1.2.2 Buvatnet

Maximum height at the water surface [m]	465
Minimum height at water surface	N/A
Yearly precipitation [mm]	1055
Area [km^2]	0,18

Table 7 Data and specifications for Buvatnet[8]

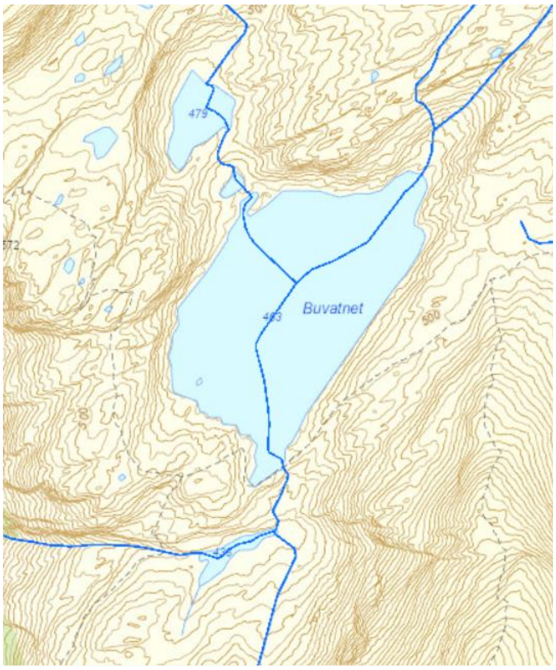


Figure 6 Map for Buvatnet [8]

Figure 7 A map that shows the location of Djupåvatnet[8]

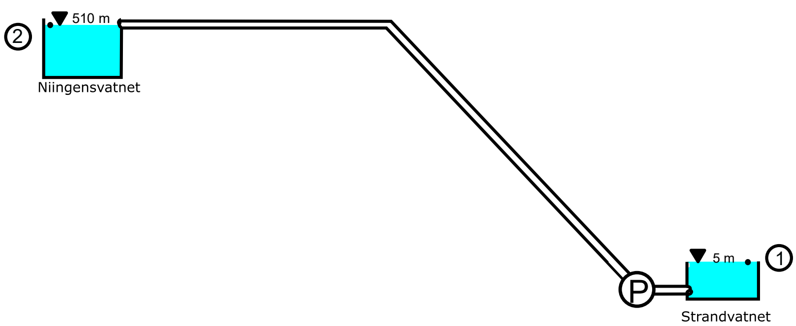
1.2.3 Djupåvatnet

Maximum height at water surface [m]	438
Minimum height at water surface [m]	N/A
Yearly precipitation [mm]	1055
Area [km^2]	0,10

Table 8 Data and specifications for Djupåvatnet [8]

1.2.4 Strandvatnet-Niingensvatnet pumping station

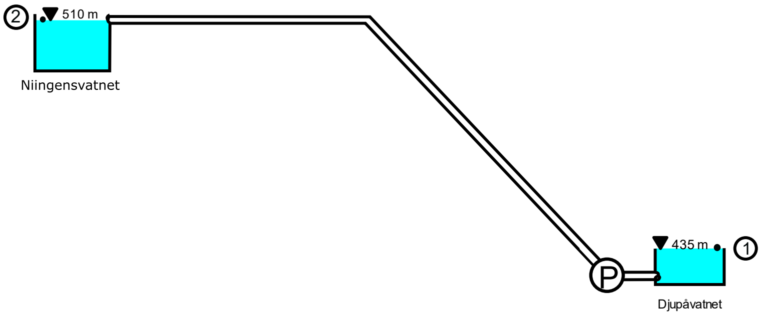
In this thesis, the pumping station of Strandvatnet-Niingensvatnet will be studied in detail including lengths of the pipes, sizes, and choice of pumps. As an initial overview, the pumping station will look like the following figure.



$$\left(\frac{p_1}{\gamma}+\alpha_1\frac{V_1^2}{2g}+z_1\right)+h_t+h_p=\left(\frac{p_2}{\gamma}+\alpha_2\frac{V_2^2}{2g}+z_2\right)+\sum hl$$

Figure 8 Simplified model of Strandvatnet-Niingensvatnet pumping plan with the energy equation

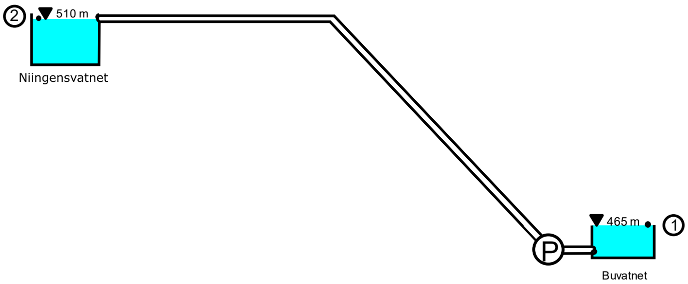
1.2.5 Djupåvatnet-Niingensvatnet pumping station



$$\left(\frac{p_1}{\gamma} + \alpha_1\frac{V_1^2}{2g} + z_1\right) + h_t + h_p = \left(\frac{p_2}{\gamma} + \alpha_2\frac{V_2^2}{2g} + z_2\right) + \sum hl$$

Figure 9 Simplified model of Djupåvatnet-Niingensvatnet pumping plan with the energy equation

1.2.6 Buvatnet-Niingensvatnet pumping station



$$\left(\frac{p_1}{\gamma} + \alpha_1\frac{V_1^2}{2g} + z_1\right) + h_t + h_p = \left(\frac{p_2}{\gamma} + \alpha_2\frac{V_2^2}{2g} + z_2\right) + \sum hl$$

Figure 10 Simplified model of Buvatnet-Niingensvatnet pumping plan with the energy equation

1.2.1 Definitions

1.2.2 Pumped storage

Also called pumped hydroelectric energy storage, is a type of hydroelectric energy storage. It is a arrangement of two reservoirs at different altitudes that can generate power as water flows down from one to the other (discharge), rotating a turbine. The arrangement also requires energy as it pumps water back into the higher reservoir (recharge). Pumped storage behaves similarly to a massive battery because it can deposit energy and then discharge it when required[10]. Its main components are:

- Higher reservoir
- Dam
- Head race tunnel (also called feeder pipe or a supply pipe)
- Penstock
- Lower reservoir
- Turbine
- Tailrace tunnel
- Pump
- Pipeline

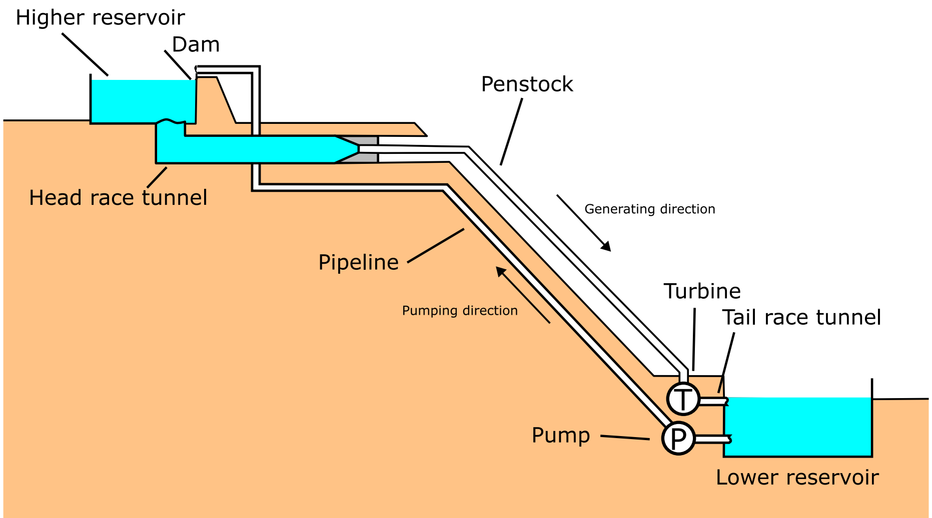


Figure 11 Layout of pumped storage project in Niingen power plant as planned in this report in the case of Strandvatnet-Niingensvatnet

1.2.3 Head

In terms of water pumping, the head refers to the head of water, also called meters of head. In simple terms, the head is the height of an object in Equation 1.1. Even though it is measured in meters and represents a height, it can be meant as the energy-to-weight ratio of a particle that is passing in a cross-section, because it's related to potential energy [11, p. 278].

$$P.E = mgh \tag{1.1}$$

$$h = \frac{P.E.\,[\mathrm{J}]}{m.\,[\mathrm{kg}]g[\frac{\mathrm{m}}{\mathrm{s}^2}]} = \frac{P.E.\,[\mathrm{J}]}{w[\mathrm{N}]} = \frac{P.E.\,[\mathrm{kg}\cdot\frac{\mathrm{m}^2}{\mathrm{s}^2}]}{w[\mathrm{kg}\cdot\frac{\mathrm{m}}{\mathrm{s}^2}]} = \frac{P.E.}{w}[\mathrm{m}]$$

In short, the head is a representation of a certain height level of the respective component and can be understood or interpreted as:

- A representation of fluid elevation, then is called elevation head and uses meters as unit [m].
- A representation of fluid pressure in meters of head.
- A representation of the energy per unit weight [m].

1.2.4 Elevation head (or static head) h_s

"The difference between two heights is referred to as the static head when a liquid needs to be elevated from one level to another."[12]

1.2.5 Head race

In a hydroelectric power plant, the term "head race" refers to the section of the plant where water is channeled from the reservoir or intake to the turbine, where it is used to generate electricity.

1.2.6 Tail race

Once the water has passed through the head race and has been used to generate electricity, it is discharged into the tail race at the penstock, which is another channel or tunnel that carries the water away from the turbine and back into the river or other body of water.

1.3 Notation

- In this document, a comma is used before the decimal digits. For example, the fraction $\frac{1}{100}$ is written 0,01 as a decimal number.

- Citation form in this document is made according to the IEEE citation system, which uses square brackets. However, that might interfere with the square brackets that are used frequently for units. One can easily differentiate between the two by the square bracket content; if it contains letter/letters, it refers to a unit, if it contained a number (can be followed by additional information about citation after the reference number), it is a citation.

1.4 Translation

The word "vatn" in Norwegian is a dialectal word for "vann" [13] which translates in this context to "body of water"[14] or "lake". For ease of writing and reading in this document, the original names of "Niingensvatnet", "Strandvatnet", "Buvatnet" and "Djupåvatnet" are preserved, but explained in this section for understanding and clarification.

1.5 Objectives

Studying and assessing the cases of pumping water:

- From the lake of Buvatnet to Niingensvatnet.
- From the lake of Djupåvatnet to Niingensvatnet.
- From the lake of Strandvatnet to Niingensvatnet.

The thesis will assess the process of pumping water from Strandvatnet, Buvatnet, and Djupåvatnet to Niingensvatnet through:

- Pumping system engineering.
  - Identification of project requirements for pumping.
  - System design and regulations.
  - Studying data for lakes' watersheds as well as water quotations.
- Studying system components.
  - Selection of pumps, pipe dimensions, specifications, and data preparation.
  - Studying fluid behavior and performing an analytical examination of the concept.
- Evaluating and assessing the project.
  - Studying the profitability, economic feasibility, and efficiency of the project.

1.6 Limitations

- The scope of this thesis project is focused on the mechanical engineering perspective and thus, is restricted to the listed project objectives. Consequently, the project does not encompass studies related to electrical engineering, such as analyzing power lines or determining the requirements of electrical equipment. Additionally, studies relating to installation, operation, and maintenance are also excluded.
- This thesis does not go into detail about the studies of hydrology, topology, geology, or meteorology, which are critical for achieving precise results. Such factors as watersheds, precipitation, liquid losses due to soil absorption and evaporation, volume, and depth of lakes, and exact locations for pumps and pipes are all related to the aforementioned areas of study.
- While the local environment, wildlife, and ecosystems are briefly addressed, these topics are outside the scope of this thesis and require the expertise of specialists in their respective fields of knowledge.
- The Integration of other power generation sources such as solar and wind energy with the pumped storage scheme in the Niingen power plant will be not included in this study.

1.7 State-of-the-art

Pumped storage projects are well-known and globally used solutions for storing hydro-energy.

"As of 2021, the US had 43 operating pumped storage plants, collectively qualified of creating about 22 gigawatts of power and storing 553 gigawatt-hours of energy. These stations constitute 93% of

heavy power storage in the country. On a global ratio, pumped hydro storage reports for an even larger share of energy storing, comprising about 99% of the total energy storage volume." [3]

"Pumped storage is the largest-capacity form of grid energy storage available as of March 2012."

The Electric Power Research Institute (EPRI) reported that pumped storage accounts for more than 99% of bulk storage capacity worldwide, representing around 127 GW. [15]

North America	Canada	0.2	United States	22.2
Central & South America	Argentina			1
Europe	Austria	4.4	Luxembourg	1.1
	Belgium	1.3	Norway	1.4
	Bulgaria	0.9	Poland	1.4
	Croatia	0.3	Portugal	1.0
	Czech Republic	1.1	Serbia	0.6
	France	4.3	Slovakia	0.9
	Germany	6.7	Spain	5.3
	Greece	0.6	Sweden	0.1
	Ireland	0.3	Switzerland	1.8
	Italy	7.5	United Kingdom	2.7
Eurasia	Lithuania	0.8	Russia	1.2
Africa	Morocco	0.5	South Africa	1
Asia & Oceania	Austria	1	Korea, South	4
	Japan	25	Taiwan	3
World				104

Table 9 Summary of pumped storage installed capacities in the world and different countries at the end of the year 2009 in Gigawatts [9] Source: US Energy Information Administration 2012

International Hydropower Association provides an online Pumped Storage Tracking Tool that we can investigate to get an overview of the present projects in this domain.

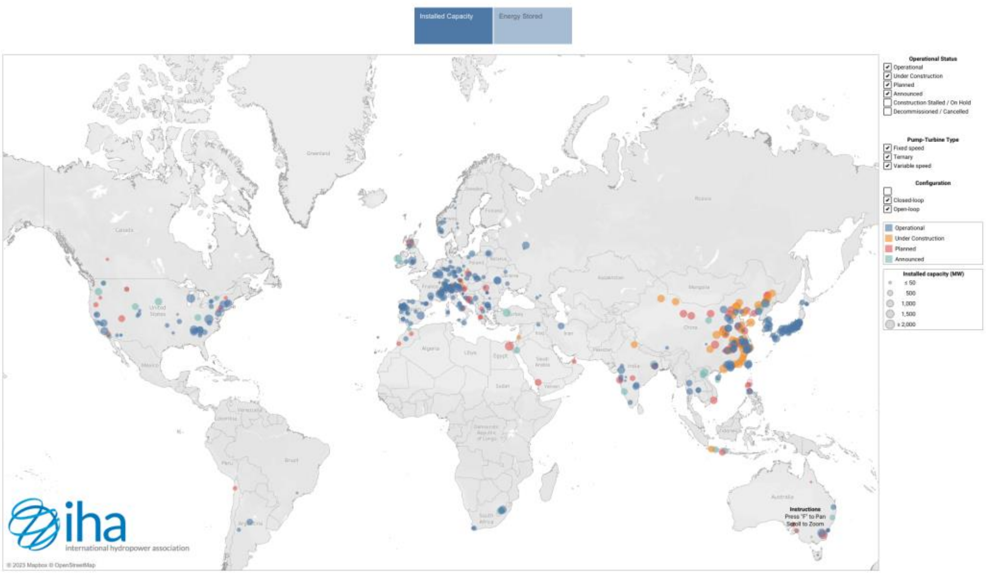


Figure 12 A world map listing all operational, under construction, and planned pumped-hydro storage plants by installed capacity[16]

In the Norwegian market, Norway has a long history of using hydropower as a source of renewable energy, and pumped storage is an important component of the country's energy infrastructure. Norway has several large pumped storage projects in operation, with several more in the planning or construction phase. The following tables show the most important aspects of the most prominent pumped storage project.

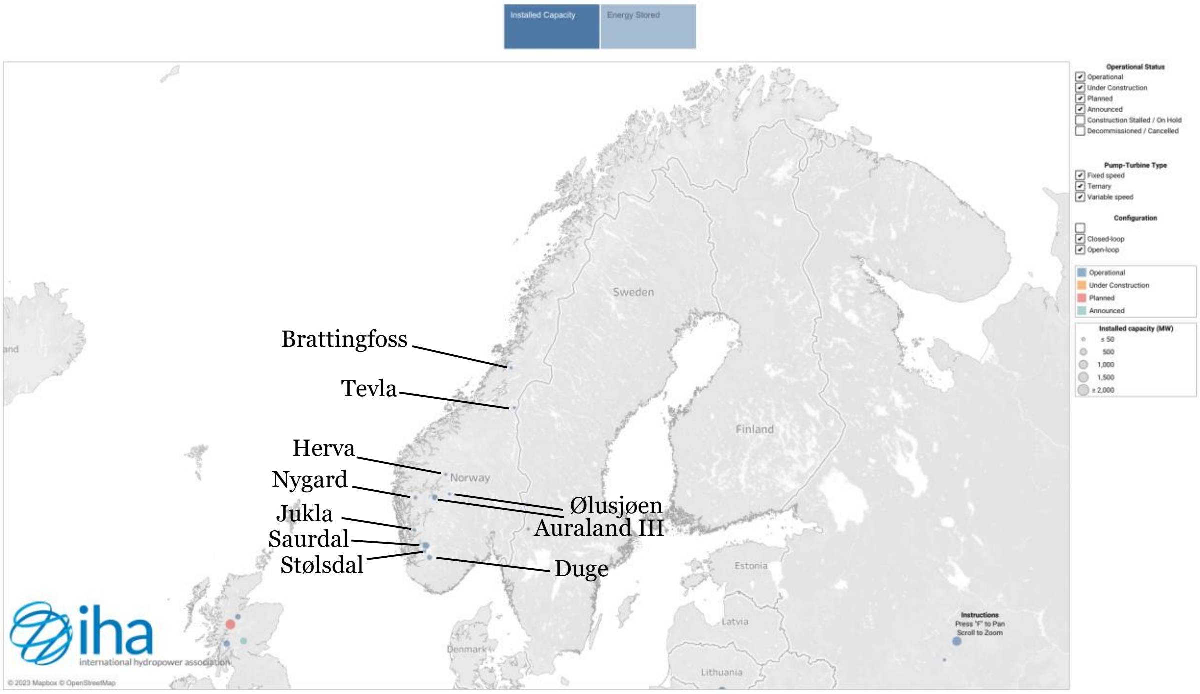


Figure 13 iha's map of pumped storage projects in Norway[16]

Name	Turbine Capacity [MW]	Pump Capacity [MW]	Gross Annual Production [GWh]	Pump Consumption [GWh]	Net Annual Production [GWh]	Gross Head [m]	Commissioning Year
Aurland III	270	258	350	280	70	400	1979
Brattingfoss	11	11	33	3	30	118	1955
Duge	200	170	303	55	248	220	1979
Herva	35	31	142	24	118	257	1962
Jukla	40	41	76	22	54	230	1974
Nygard	57.5	52	138	49	89	450	2005
Saurdal	640	320	1285	333	952	465	1985
Stølsdal	17	6	61	10	51	103	1986
Tevla	50	42	125	18	107	164	1994
Øljusjøen	49	39	78	50	421	212	1974
Sum	1369	997	2591	844	1761	-	-

Table 10 Pumped storage projects in Norway[17]

	Upper Reservoir			Lower Reservoir		
Name	$10^6[m^3]$	[GWh]	$10^3[\frac{GWh}{MW}]$	$10^6[m^3]$	[GWh]	$10^3[\frac{GWh}{MW}]$
Aurland III	44s	440	1556	10	10	36
Brattingfoss	107	31	2480	8	2	218
Duge	1398	755	3879	926	500	2570
Herva	109	69	1747	22	14	389
Jukla	236	116	2124	31	15	272
Nygard	103	114	1715	43	47	761
Saurdal	3105	3331	4978	230	247	737
Stølsdal	24	1	31	1	0.5	37

Tevla	204	82	1650	5	2	43
Øljusjøen	161	84	1518	7	14	328
Sum	5873	5023	21,678	1303	851	5391

Table 11 Energy reservoirs in Norwegian pumped storage projects[17]

Name	Construction Costs 10^6 [€]	Specific Cost per kW [€/kW]	Specific Cost per kWh [€/kWh]
Aurland III	212	787	0.51
Brattingfoss	30	2844	1.14
Duge	300	1501	0.39
Herva	60	1721	0.99
Jukla	146	3654	1.72
Nygard	41	739	0.43
Saurdal	995	1555	0.31
Stølsdal	64	3760	121.6
Tevla	103	2079	1.25
Øljusjøen	79	1612	1.06

Table 12 Construction costs in Norwegian pumped storage projects[17]

Name	Generator Output		Motor Consumption		Speed of Rotation	Transformer
	[MVA]	[MW]	[MVA]	[MW]	[rpm]	[kV/kV]
Aurland III	2x 150	2x 135	2x 150	2x 126	500	420/15.5
Brattingfoss	14	11	14	10.6	428	66/6.3
Duge	2x 120	2x 100	2 106	2x 85	375	320/13
Herva	45	35	32	31	500	132/8
Jukla	4	40	48	41	500/375	67/12
Nygard	65	57.5	65	52.3	750	300/11.4
Saurdal	4x 185	4x 160	2x 185	2x 160	428	324/18.5
Stølsdal	2	17	N.A.	2x3	375	300/6.6
Tevla	2x 30	2x 24.8	2x 3	2x 21.1	500	132/8.8/4.4
Øljusjøen	55	49	50)	38.6	428	WO/7

Table 13 Generators and pumps used in Norwegian pumped storage projects and their characteristics[17]

1.8 Challenges that might face pumped storage project at Niingensvatnet

Regulatory treatment and licensing

Any major construction project requires numerous permits and approvals from regulatory bodies. In Norway, this process can be particularly complex, with multiple layers of government involved. Obtaining a license for this type of project is a challenging process that takes a long time and requires getting many permits and approvals to initiate a pumped storage project before the developer attains the authority to begin[18].

High capital costs

Pumped storage projects require significant investment in infrastructure, including dams, tunnels, and power stations. The remote location of Niingensvatnet can also increase construction costs and logistical challenges.

Public opposition

Large-scale development projects can often face opposition from local communities and environmental groups. In Norway, where there is a strong cultural and environmental identity, concerns over the impact of pumped storage facilities on the natural landscape and traditional lifestyles could result in significant opposition to proposed projects.

Time spent in building the pumping stations

Case studies show that building hydroelectric facilities for power plants takes many years to be completed, ranging from 5 years in small-scale plans and up to 20 years for larger-scale projects.

"The establishment of Niingen power station launched in 1950 and ended in 1954"[6]

This long time in establishing without gaining income makes the investment in such projects less encouraging, even though the expected profits and efficiency are high. In addition, this waiting time has to be longer knowing that the region of the plan is challenging topographically, geologically, and climate-wise.

Technical difficulties

The harsh weather conditions in the arctic circle can pose significant technical challenges to the design, construction, and operation of pumped storage facilities. For example, extreme temperatures can affect the performance of equipment, and ice formation can cause structural damage.

2. Regulations, components and system design

2.1 General regulations

2.1.1 Suggested cycles for generating/pumping

2.1.1.1 Energy supply/demand curve at different times

In electricity grids, the supply of electricity is designed to match the demand as closely as possible. This result can be accomplished thanks to many strategies:

- The grid in the EU region is interconnected. Interconnecting power grids can help balance supply and demand by allowing surplus electricity from one area to be used in another area experiencing a shortage. For example, Nordpool operates in the physical electricity market across several European countries, including Norway, Sweden, Denmark, Finland, Estonia, Latvia, Lithuania, Germany, and the UK. It provides a platform for trading in wholesale electricity and offers services related to price risk management, market analysis, and settlement. Nord Pool is one of the largest power exchanges in Europe and plays an important role in the integration of renewable energy sources into the grid. Nordpool has many power suppliers who can provide energy when it's needed to cover market needs and a bidding system for whole-selling energy for retailers allowing them to deliver exactly what their customers want»[19].
- When the demand is high, power prices will rise and this leads to a reduction in the consumption(demand), and vice versa.
- Other strategies can be used when the demand is too high vs. supply such as rationing.
- Energy storage technologies such as batteries pumped hydro, and compressed air energy storage can be used to store excess energy during times of low demand and release it during periods of high demand.
- Renewable energy integration: Renewable energy sources such as wind and solar can be integrated into the grid to reduce reliance on fossil fuel generation. However, their variable nature requires careful management to ensure matching needs for supply and demand.

While every effort is made to match supply with demand, certain factors can lead to temporary imbalances. Those circumstances can be, among others:

- Unexpected equipment failures
- Seasonal changes and weather circumstances that change the water availability (high precipitation, snow/ice melting, heat waves, and water evaporation).
- Seasonal changes and weather circumstances that affect the customers' usage habits (cold days, heat waves, etc.)
- Times of the day, week, or year (weekends, holidays, vacations).

Since all the mentioned reasons for the change in power supply and demand will have to result in a price change, it is safe to assume that the most essential factor that controls the process of pumping/generating energy is the energy prices.

Other factors such as times for precipitation, snow melting, etc., will not be considered in this report due to limitations. But it is highly recommended to further study these circumstances to get a more detailed and customized plan of pumping water depending on the change of those factors.

2.1.1.2 Classification of production/pumping cycles based on timing

Timing-based production/pumping cycles can be classified using the following table[20]

Pumping/ production method	Mode	Circumstances of the mode	Examples
Hourly	Custom times of pumping and generation	Maintenance and repairs services, removing the harmonics from the net, better control of frequency, backup energy support at times of supply fluctuation.	
Daily	Custom patterns of pumping and generation	Pumping in the day/producing in the night (or vice versa) depending on power prices change, supply-demand during the day, availability of solar or wind energy, etc.	- Ghatghar Pumped storage plant, India, which operates 6 hours a day for generating, and 7 for pumping.[21] - Genex Kidston pumped hydro storage, Australia, which pumps in the night and generates in the day[22]
Weekly	Pumping	During weekends as demand reduces. Or on windy/sunny days when the energy supply increases.	Kyushu, Japan's three power plants combine solar and hydroelectric generation; pumping the times of less sunny days[23]
	Generation	During weekdays as demand increases. Or on not windy or cloudy days when the energy supply decreases.	
Seasonally	Pumping	During times of negative prices, ice melting, and high precipitation. Or in the summer when high solar energy production and low power consumption, etc.	- The Forona del Viento hybrid power plant, in Spain, pumps water at times of surplus in wind energy generation to generate hydroelectric energy in times of less windy seasons[23] - Hunt et al. proposed a seasonal pumped storage and generation plan for exploiting hydraulic energy in Brazil, where generating occurs in dry seasons, and pumping in wet seasons[24]
	Generation	Dry period or freezing weather. Low solar and wind power generation.	
Annually	Pumping	During times of negative prices, an annual surplus of hydroelectric generation.	
	Generation	Years of high-power deficit and higher energy demand.	

Table 14 Pumping/generation cycles systems

2.1.1.3 Classification of pumping/production cycles based on energy prices in different periods

Energy prices change constantly, even during the day, for many reasons including changes in supply and demand, changes in fuel costs, market conditions, policies, and regulations.

By referring to the different systems for production-pumping systems and crossing those systems with data for energy prices from Nordpool, we get customized plans for energy power generating/pumping in different time intervals[1].

[1] It is assumed in Section "2.1.1.1 Energy supply/demand curve in certain periods" that the most essential factor that controls the process of pumping/generating energy is prices.

It is more relevant for the Niingen power plant to use the generation/pumping of power on an hourly, daily, monthly/seasonal basis. The other types of cycles are the weekly cycle, yearly cycle, and customized cycle. While pumping water on a weekly and/or yearly plan is not relevant as no major regular changes happen between weeks and years, the decision of of pumping water following the third cycle has to be taken during those irregular circumstances, such as heat or cold waves, unforeseen trends in prices, unpredicted events, sudden change in supply or demand, etc.

- ❖ **Hourly**

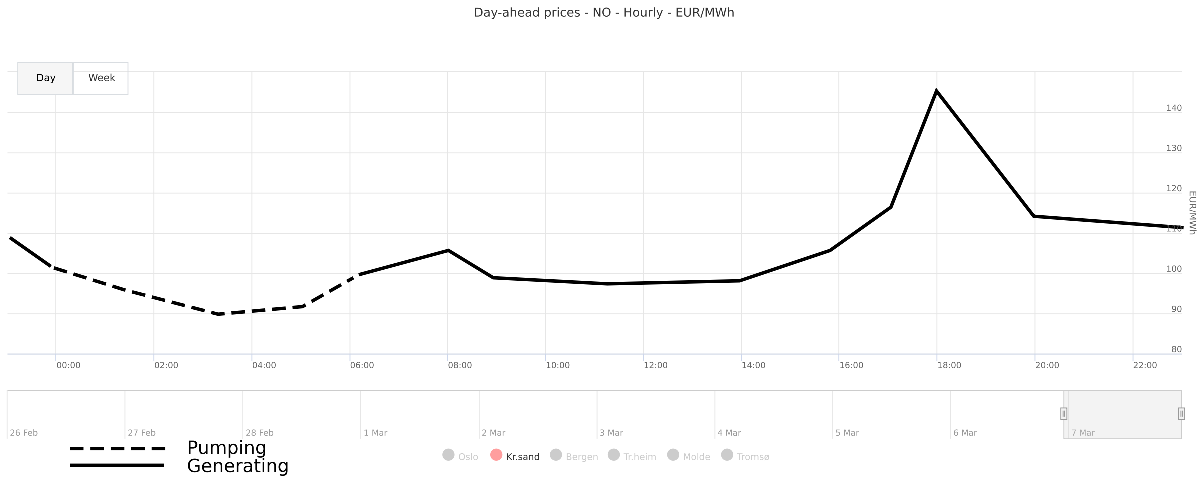


Figure 14 Suggested plan for pumping and generating hourly.

- ❖ **Daily**

The 3rd, 4th, and 5th of March in the respective year happen to be on the weekend, which explains why prices drop, and this drop can be used to pump water.

Figure 15 Suggested plan for pumping and generating daily

❖ Weekly

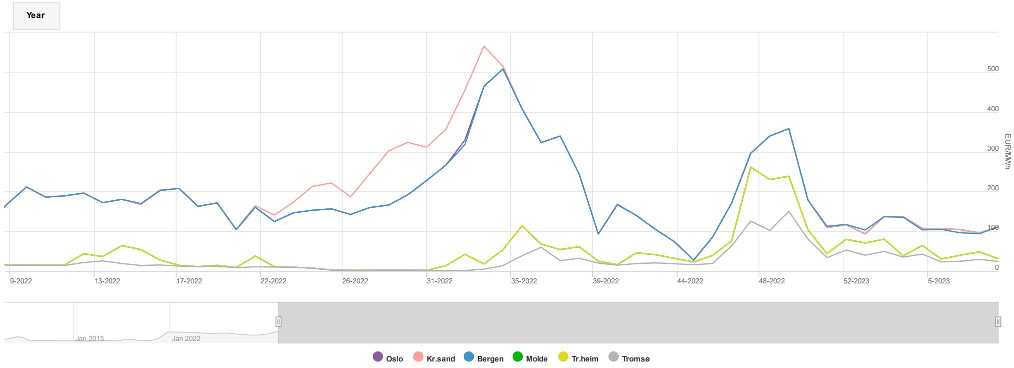


Figure 16 Energy prices change during the span of many weeks with Nord Pool

❖ Monthly/seasonally

The charts below show a drop in prices in the summer that is expected to be regular, which offers a good chance to pump water.

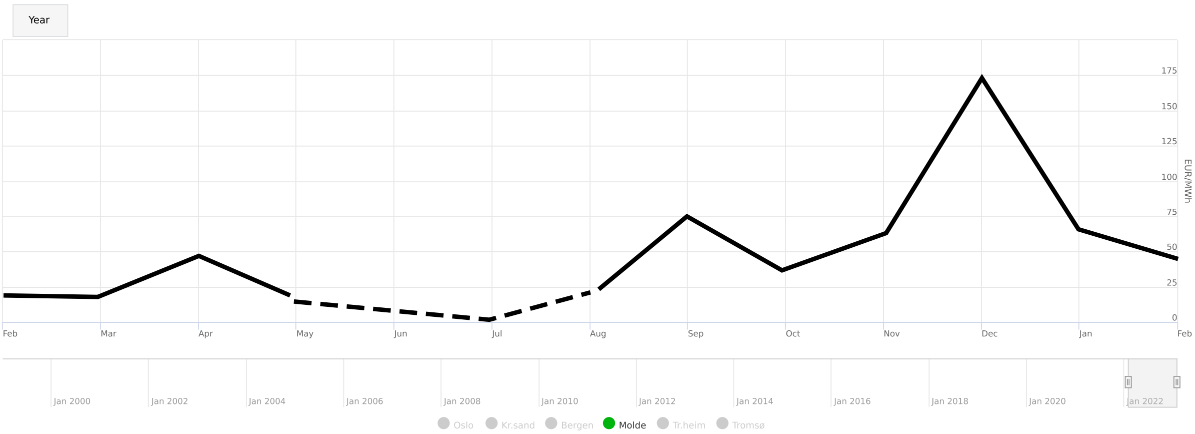


Figure 17 Suggested plan for pumping and generating monthly

❖ Yearly

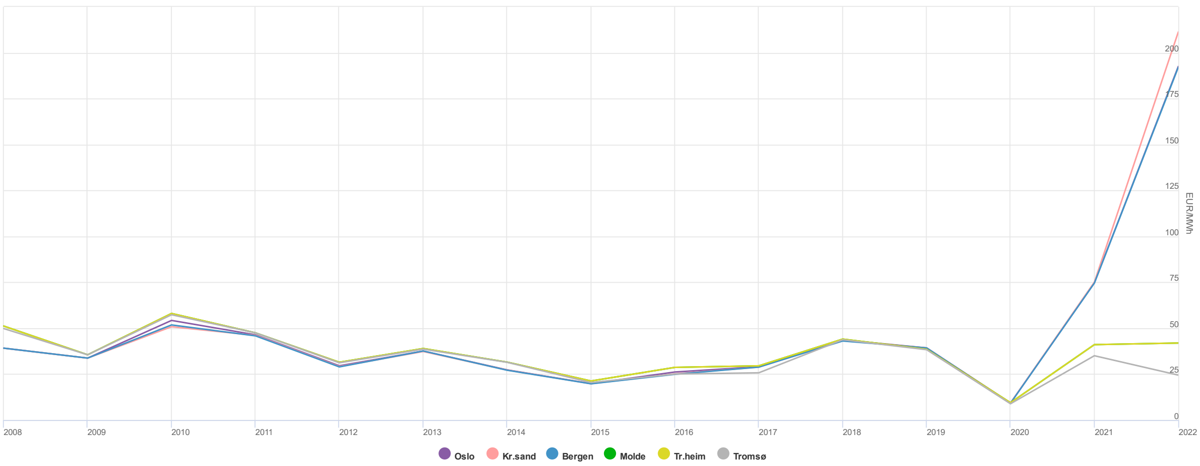


Figure 18 Energy prices change in the span of 15 years with Nordpool as

- **The phenomenon of negative prices**

Negative prices in electricity production occur when the price of electricity on the wholesale market falls below zero, meaning that producers are essentially paying buyers to take their electricity. This is a relatively rare occurrence, but it has become more common in recent years, particularly in regions with a high penetration of renewable energy.

There are several reasons why negative prices can occur in electricity markets:

1. Oversupply: Negative prices often occur when there is an oversupply of electricity on the grid. This can happen when the electricity demand is low, but wind or solar power generation is high. In this scenario, the excess electricity produced by renewable generators can flood the grid, leading to negative prices.
2. Grid constraints: In some cases, negative prices can occur when there is limited capacity to transport electricity from areas of high production to areas of high demand. This can lead to congestion on the grid, forcing generators to curtail their output and resulting in negative prices.
3. Market design: In some cases, negative prices can be the result of the design of electricity markets. For example, in some markets, generators may bid negative prices to avoid shutting down their operations when demand is low. This can lead to negative prices if the bid is accepted.

Negative prices have several damages concerning the power plant and its profit. If producers are unable to sell their energy supply and are forced to curtail their production, it can lead to significant financial losses for the producers. This is because the producers are still incurring the costs of generating the electricity but are not receiving any revenue from selling it.

In some cases, producers may be able to avoid curtailment by reducing their output or temporarily shutting down their operations. However, this can still result in lost revenue.

In addition to the financial impact on producers, curtailment of electricity supply can also have broader implications for the electricity grid and the reliability of the system. If large amounts of renewable energy are curtailed due to oversupply, it can result in wasted energy resources and may make it more difficult to meet future energy demands. Furthermore, if producers are forced to shut down their operations, it can result in job losses and other negative impacts on the local economy.

Having a pumped storage system built-in with the hydroelectric power plant will provide the producer with means of managing the supply and demand and avoiding the problem of negative prices. [25]

2.1.1.4 Automatic control of powering on/off the pumping assembly

Previously in Section 2.1.1, it has been proven that power prices change, sometimes drastically, hour to hour and day to day. To optimize the performance of the pumping system, it is suggested to use a programmed automatic controller for turning on/off the pumping system depending on the electricity prices. Further explanation about this method of optimizing the project is made in Chapter three as this procedure is related to increasing the income and optimize performance.

2.1.2 Regulation of Buvatnet and Djupåvatnet

It is necessary to regulate the lakes that water gets pumped from in pumped storage projects to ensure that there is enough water available to meet the electricity demand when needed, the water level in the lower reservoir must be carefully regulated.

Regulating the lake can involve managing the amount of water that is released from the lake, either through natural or man-made outlets, and controlling the flow of water into the lake through streams and other inflows. In some cases, it may be necessary to build dams or other structures to help control the water level and ensure that the lake remains a reliable source of water for the pumped storage project.

In similarity with Niingensvatnet, it is recommended to build dams at the waterway of outflow to control water levels at the lower reservoirs, preferably with a measurement station. The width and dimensions of the dams rely heavily on the civil engineering study and most importantly on $Y_{\max}$ the reservoir's available capacity.

- **Raising dam height to overcome the problem of low water level**

At times of low inflow to the reserves, potential energy to be produced, mainly water, will be limited. For example, at times of low water levels at all higher and lower reservoirs, no water will be available to run through the penstock to produce energy nor to be pumped to the higher reservoir.

In this case, the power plant has to shut down its operations, and the energy production is terminated, meaning lower profit than the possible high profit due to high energy prices at those times when reservoirs are drained as inflows are low.

A way to solve this problem is to design the dam heights during the civil engineering study stage to store more liquid only enough until times of high inflow in precipitation are back.

Note that this plan is beneficial for deciding the dam height when regulating Buvatnet, Djupåvatnet, and Strandvatnet, and not only Niingensvatnet.

2.1.3 Matching pumps to system design

In pumps, a pump must produce enough available head to defeat the required head, which is resistance in the system[26] [12], [27]. Therefore:

$$\text{Available head} > \text{required head}$$

$$h_a > h_r$$

$$h_a - h_r > 0$$

The available head at the pump's discharge outlet must be greater than the required head (resistance) so the fluid reaches the needed distance.

- Available head (or discharge head)

Which is the pressure produced by the pump at its outlet measured in meters of head and given by the manufacturer.

- Required head (or resistance) h_r

There are two types of resistance (required head), which are characteristics of the pipes, the piping components, and the location.

$$h_r = h_l + h_s$$

- Elevation head (static head) h_s, which is the difference between the water level at the surface of the lower reservoir and the surface of the higher reservoir

$$h_s = z_2 - z_1$$

- Head losses in pipes h_l, which are the head losses due to friction

$$h_f = \frac{f \cdot L \cdot V^2}{d \cdot 2g}$$

  And minor head losses due to fittings, bends, and other instrumentations and configurations in the pipes. See Section 2.3.2.3

The important aspect is to know that the resistance can change in the short term or the long term, it varies using different operations, changes with maintenance, or changes in design. Thus resistance is not constant[27, p. 116] For example, usage of VFD can change the resistance in the system in the short term. The resistance doubles four times easily by doubling the velocity of the fluid two times. Also, installing new instruments such as flow rate gauges into a pipe increases the resistance. Other examples are changing filter meshes, opening and closing a flow control valve, etc. In the long term, sedimentation can reduce the diameter of a pipe increasing resistance in friction and velocity.

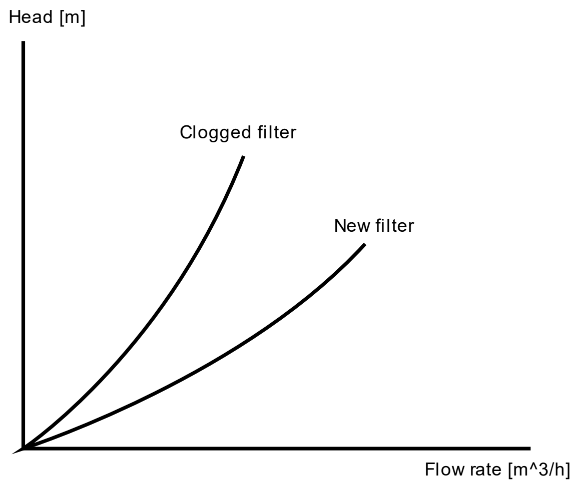


Figure 19 Change of h_r as a result of the clogged and new filter in the system

Steps for better control over the system resistance can be, among others[27]:

- Set up values for the maximum and minimum flow beforehand, those values must not be exceeded.
- Establish the flow and pressure that corresponds to a new, clean filter and the flow and resistance that signify a dirty filter requiring replacement.
- It is recommended to install pressure sensors that can send a signal to shut off the pump, trigger an alarm, or notify the operator when it is time to change the filter. Once a new filter is installed, the pump should start running again on the right side of the Best Efficiency Point (BEP) within the optimal operating range and gradually move towards the opposite end of the sweet zone over time.

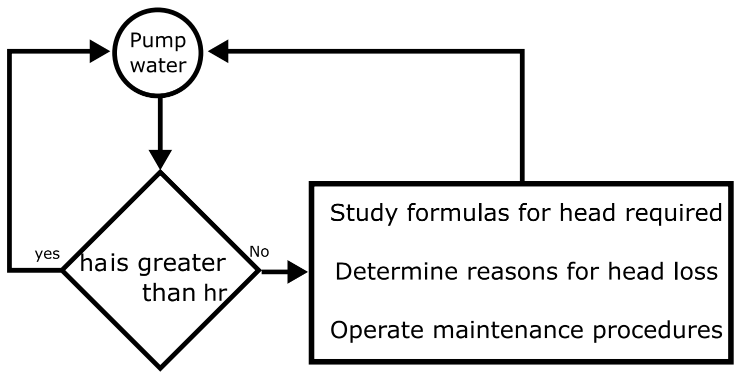


Figure 20 Representational plan for pumping system design

2.2 Calculations related to the reservoir's available capacity

2.2.1 Time needed to drain a lake

One important factor to consider when deciding time limitations for pumping water from a natural reservoir is the time to drain a lake, as it can give a clearer picture of the time needed to completely drain a lake's water. We know that the volumetric flow rate is:

$$Q = \frac{V}{t}$$

$$t = \frac{V}{Q}$$

Assuming that inflow and pumping volumes will remain constants per time,

$$\text{Time to drain lake} = \frac{\text{water volume in a lake}}{\text{Pumping capacity}} \tag{2.1}$$

2.2.2 Water level allowed to be pumped from and added to lakes

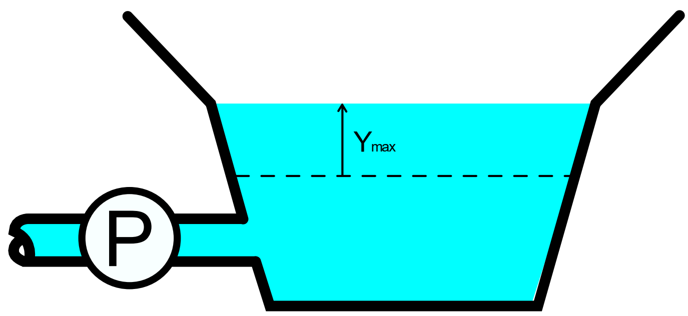


Figure 21 Visualization of a water reservoir with the value of Y_{max}

In the case of Niingensvatnet, it is relatively easy to find out the maximum and minimum allowed values of water height as the lake is regulated and exceeding the maximum allowed height (510 m) will mean that water will overflow over the dam, while exceeding the lower minimum water level (482,4 m) will lead to that water level will be lower than the headrace tunnel.

Thus, the allowed water volume to be used in the generation is:

$$\text{Water level allowed to be used} = \text{Maximum height} - \text{Minimum height}$$

$$= 510 - 482{,}4 = 27{,}6 \text{ m}$$

For the cases of Buvatnet, Djupåvatnet, and Strandvatnet, the maximum amount of water allowed to be pumped is a variable parameter and will change due to other factors such as the lake's size and depth, inflow and outflow amounts, governmental and local regulations, in addition to the pumping capacity and pump inlet placement. We define the variable $X_{\max}$, which is the amount of water allowed to be pumped. $X_{\max}$ can either take the shape of maximum water level $Y_{\max}$ or maximum water volume $V_{\max}$ allowed to be pumped. For example, $Y_{\max}$ can increase at times of snow melting in May but decrease at days of high temperature.

Inspiring by other cases studies, we see that this parameter can be assumed with different values, the following table gives an overview of two of these values and their respective reservoir volume:

Case study	Water magnitude allowed to be used $X_{\max}$	Lower reservoir volume $[\mathrm{m}^3]$
Site Louvie lake–Fionnay reservoir [28]	10%	$170 \cdot 10^3$
La Gouille des Vernays [28]	11,33%	$170 \cdot 10^3$

Table 15 Case studies of the assumed water percentages allowed to be pumped from each reservoir

2.2.3 Dimensions of a lake

Knowing the water volume in a lake and its water height can be essential to gain an overview of a lake' state and water level. Over-usage of a lake's water can have economic and ecological impacts, among others. Draining a lake can have significant influences on the local ecology and wildlife. As the water level drops, the exposed lakebed can dry out, leading to the loss of habitat for aquatic plants and animals. Therefore, reservoir dimensions must be considered when studying pumped storage projects.

2.2.3.1 Depth

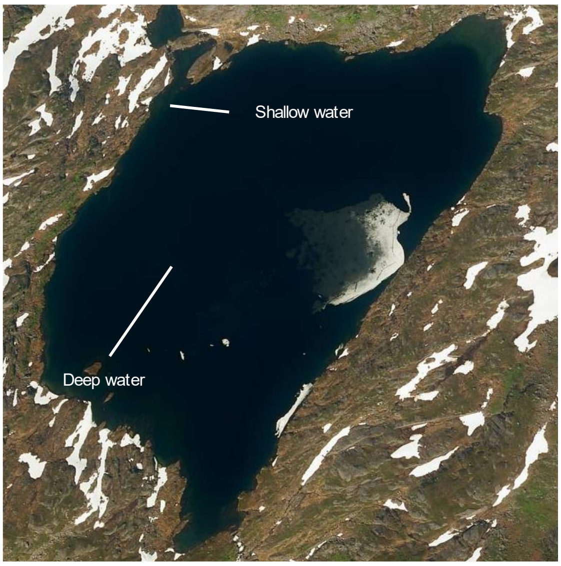


Figure 22 Aerial photo of Buvatnet showing the areas of shallow and deep water [29]

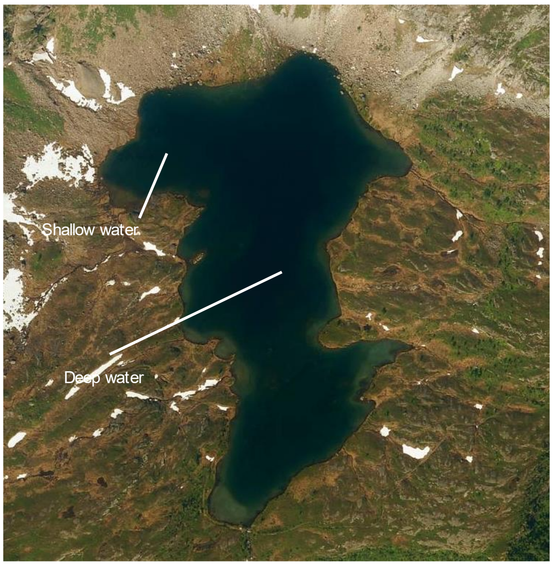


Figure 23 Aerial photo of Djupåvatnet showing the areas of shallow and deep water[29]

It is necessary to know the depth of a lake to calculate the level of water possible to be pumped without getting the lake to be drained. Although we know this information for Niingensvatnet since it is a regulated lake, we do not have information about the depth of Buvatnet and Djupåvatnet yet, as they are not regulated or controlled.

Methods for measuring a lake's depth can vary from using a fish finder sonar on a boat, a robe, and a weight[30], to echo-sounding devices. The simplest assumption one can do is, based on aerial photos and the color of a lake's surface, that if it was dark blue, it is at least 2 m deep, and shallow if it had a green/brown color.

Aerial footage shows that Djupåvatnet might not be suitable for a pumped storage scheme as it looks as if it is mostly shallow water, especially due to its relatively small area. However, the topological, and geological study will reveal more about the depth of this lake.

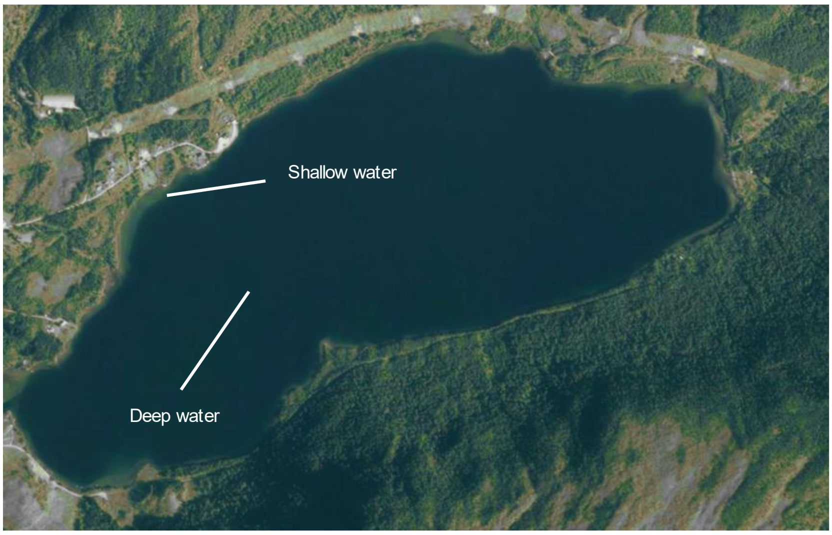


Figure 24 Aerial photo of Strandvatnet showing the areas of shallow and deep water[29]

2.2.3.2 Volume

Volume and depth are directly proportional, and knowing those values can have many advantages. It is difficult to find out the volume of a reservoir without data based on physical measurements. Some of the most typical methods for measuring water volume in a lake can be, among others:

1. Bathymetric survey: A bathymetric survey involves using specialized equipment to measure the depth of a lake at regular intervals. This information is then used to create a topographic map of the lake bottom, which can be used to calculate the lake's volume. The accuracy of this method can vary depending on the quality of the survey data.

2. Sonar measurement: Sonar is a technique that uses sound waves to determine the depth of a lake. A sonar device is typically mounted on a boat and moved around the lake to collect data. The information is then used to estimate the volume of the lake. This method is often less accurate than a bathymetric survey but can be more cost-effective.

2.3 Pumping stations calculations

For this master thesis project, we consider establishing the following three pumping stations, each with its own pump, pipes, and pumping chamber.

- Strandvatnet-Niingensvatnet
- Buvatnet-Niingensvatnet
- Djupåvatnet-Niingensvatnet

2.3.1 Pumps selection

2.3.1.1 Pump type

We can use the specific speed formula to determine the pump type based on the given parameters [26, p. 197]

$$\omega_P = \frac{\omega\sqrt{Q}}{(gh)^{\frac{3}{4}}} \tag{2.2}$$

Where

$$\omega = \frac{2\pi N}{60} \quad (2.3)$$

If

$\omega_P < 1$	radial flow pump
$\omega_P > 4$	axial flow pump
$1 < \omega_P < 4$	mixed flow pump

2.3.1.2 Pump characteristics

Characteristics of pumps are described using charts that describe their behavior in different circumstances[31]. After studying these charts, it is possible to purchase an industrial pump that fulfills the project circumstances by contacting pump suppliers who usually have pump specialists who can assist in the selection of the best pump for the project based on our specific requirements and constraints. See case studies at the end of this document for more details on doing calculations and purchasing pumps for the three pumping stations.

❖ **Head-Flowrate curve chart**

A pump is chosen based on the required flow rate and head at the pumping point. Head-flow rate charts are made for different types of pumps, which is highly required to choose the pump that suits each project best. Those charts are available usually with the pump suppliers as a necessary tool to help choose the optimal pump for each project.

The flow rates will be different in different circumstances. But a great way to start is by dividing the water volume we aim to pump at the time of pumping. See case studies in the appendices for further explanation, for example, in Appendix 1, Sub-section 1.1.4.

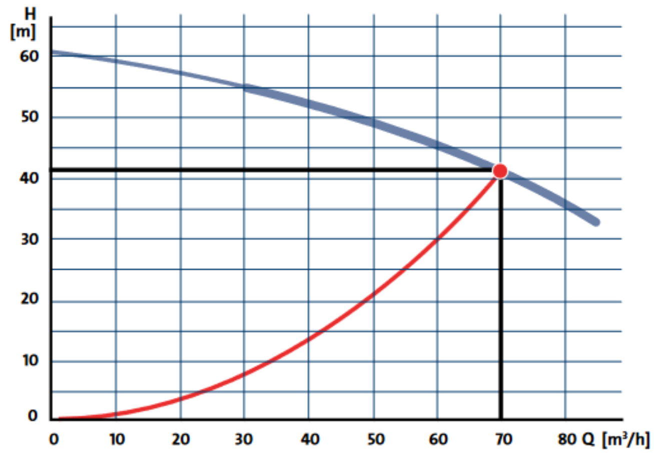


Figure 25 An example of a head-flow curve[31]

❖ **NPSH (Net Positive Suction Head) curve**

NPSH stands for Net Positive Suction Head, and it is an important concept in pump design and operation. NPSH is a measure of the available pressure at the suction inlet of a pump, and it is critical to ensure that the pressure at the inlet remains above a certain minimum value to prevent cavitation. “NPSH-values are measured in meters and depend on flow; when flow increases, the NPSH-value also increases” [31]

The reason we study NPSH is to avoid cavitation that might occur at the suction inlet of the impeller of the pump. Cavitation is a phenomenon where water bubbles form in a liquid region where liquid pressure reduces below its vapor pressure[32]. These bubbles collapse suddenly in regions of high-pressure causing cavities at the metallic surfaces as well as vibration and noise. Most importantly, it results in a reduction in head and efficiency.

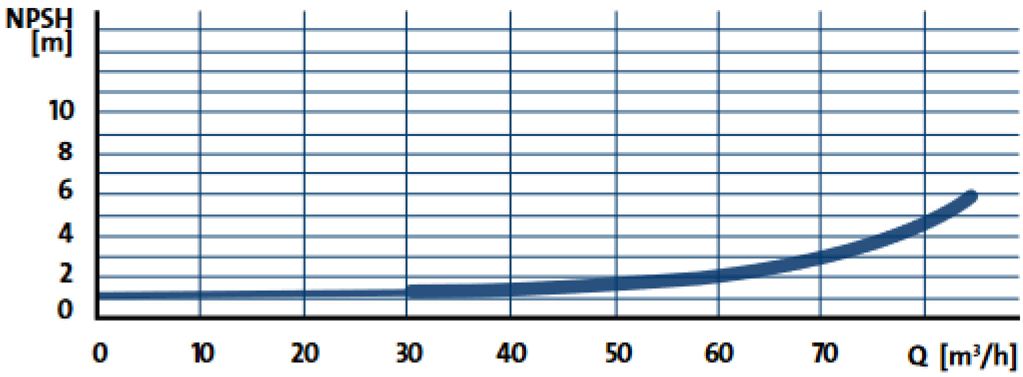


Figure 26 An example of the $NPSH$-flowrate chart[31]

Moreover, we can find two types of NPSH:

- NPSHa: «This is the amount of Net Positive Suction Head available at the pump inlet. NPSHa demonstrates the amount of pressure acting on a fluid as it enters the pump. This measures the amount of pressure between the liquid staying in its current state and forming vapor bubbles (beginning to boil). »[33] We get the value of NPSHa using two methods:
  - Physically, by installing a Gauge at the suction pipe in the pump, which gives a reading of pressure at the respective point.
  - Analytically, by using the following formula:

$$\text{NPSHa} = H_s + H_a - H_{vp} - H_f \tag{2.4}$$

Where:

H_s is the head at the studied point

H_a is the atmospheric pressure (for closed reservoir pressure at the surface of the reservoir)

H_{vp} is the vapor pressure

H_f is the friction losses

Alternatively, we can use the following formula for NPSHa [26, Eq. 8.17]

$$NPSHa = \frac{P_{atm}}{\gamma} - z_1 - \sum h_l - \frac{P_v}{\gamma} \tag{2.5}$$

Where

h_l is the head losses

P_v is the vapor pressure

Another method to calculate NPSHa is by calculating the difference between pump inlet pressure and vapor pressure and using the energy equation. [11, Ch. 14.5]

- NPSHr: is the required Net Positive Suction Head from the pump to function without cavitation. Typically listed in the pump curve.

In simple words, NPSHa is the pressure that the inlet pipe in the pump has at the time of operating, and is a property of the pump, while NPSHr is the pressure that should be at that moment at the pump inlet, it is a property of the location, and directly proportional to pump elevation compared to the higher reservoir surface, and head losses due to friction, but inversely proportional to vapor pressure and atmospheric pressure.[34]

To avoid cavitation, it is important to ensure that the NPSH available (NPSHa) at the pump inlet is greater than the NPSH required (NPSHr) by the pump. [34] [35]

$$\mathrm{NPSHa} > \mathrm{NPSHr} \quad (2.6)$$

It is required to study NPSH for the pumps as well as in the provided charts to know the value of the required pressure at the pump inlet for cavitation not to happen.

❖ **Power consumption curve**

Power consumption and flow rate relation are necessary to consider when buying a pump, as different pumps can deliver the same flow rate but with different values for power consumption. The following equation gives the formula for power consumption in a pump[31]

$$P_2 = P = \frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p} \quad (2.7)$$

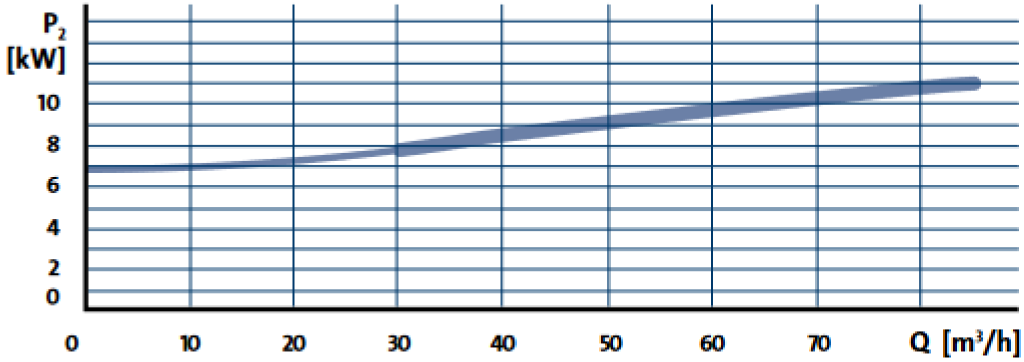


Figure 27 An example of a power-flow rate curve[31]

❖ **Other factors**

Many other areas can be studied to select the optimal pump, but that is usually done with the supplier as they have an overview of the pumps, their characteristics, features, advantages/disadvantages, and uses. Those factors can be the motor's frequency, variable frequency drive (VFD, also known as variable speed motor), voltage, self-priming pump, number of stages, etc. Also, other charts are available which can be necessary to select pumps, such as the chart for efficiency.

2.3.1.3 Locations and layouts of pumping stations and pipes

It is highly recommended to have the pump located in an assigned construction that isolates it from the external weather and low temperatures and provides it with sufficient space for maintenance and possible repair or regulation. The pump inlet is also recommended to be under the lower reservoir's level, such that it does not experience the damaging impacts of cavitation that cause a large reduction in pump performance. See case studies in this document to see more details of recommended locations of pumping stations. It is particularly necessary to study NPSH with this section as it is directly proportional to the pump's elevation compared to the reservoir.

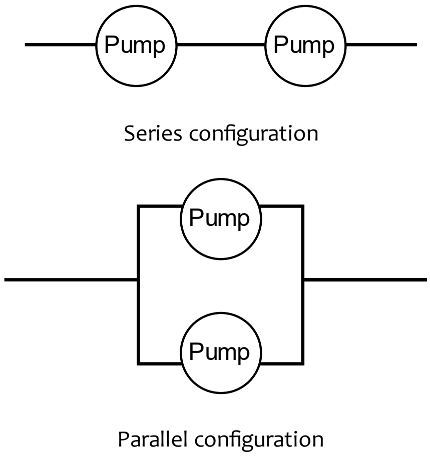
❖ **Location**

The position of the pump near its suction source is crucial for ensuring its overall dependability. Ideally, the pump should be situated near its suction source, as this minimizes the impact of friction losses on the NPSH available, but the pump must also be far enough away from the suction source to allow for proper piping practices to be implemented[35].

❖ **Multiple pumps: Parallel and series pumps**

It is possible to use many pumps to achieve the required values for flow rate and head, for instance when the elevation head is too high. Pumps can be connected in series or parallel connection.

The overall flow rate or the total head is not simply added to the specific flow rates and heads of each pump. Pumps that are connected parallelly provide twice the flow at the same head, while pumps that are in series offer twice the head at the same flow rate [12] [36].



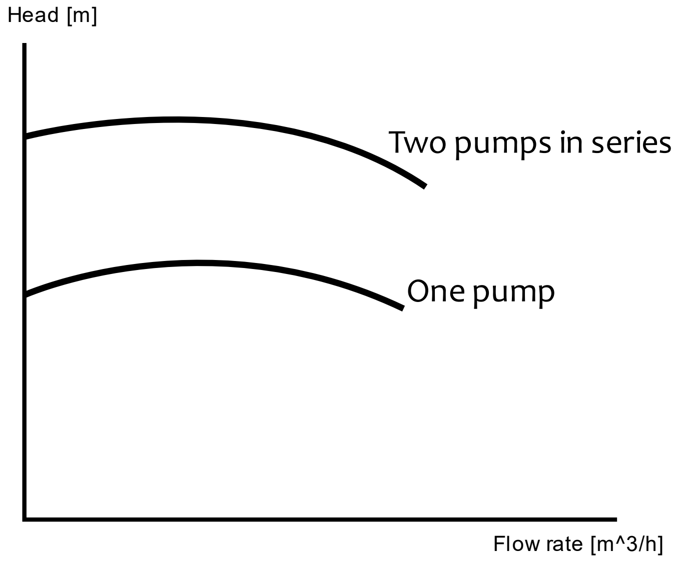


Figure 28 Visualizing series and parallel configuration of pumps

Figure 29 Chart of change of head using one pump and two pumps in series

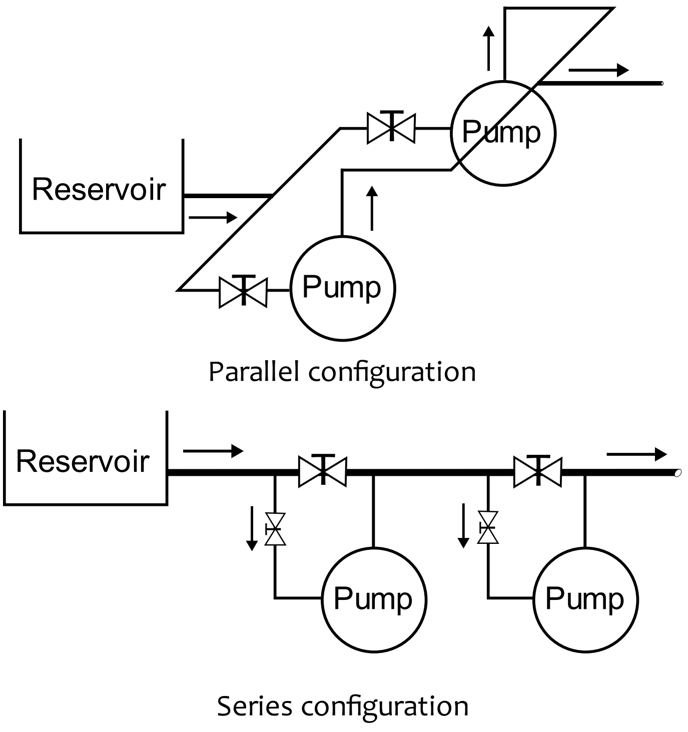


Figure 30 Visualizing series and parallel configuration of pumps

Connecting pumps in series adds the head from different pumps to offer total head H_T

$$H_T = H_1 + H_2$$

2.3.2 Pipes selection

2.3.2.1 Pipe layout

❖ **Overground and underground pipelines**

Typically, buried lines consist of drainage systems and water or gas supply lines. In regions with prolonged cold winters, burying these lines beneath the frost line can prevent the freezing of water and solutions, which can save the cost of tracing lengthy horizontal sections of the lines[37, Ch. 6] [38, Ch. 10].

When it comes to installing underground pipes, there are many main methods: trenching, tunneling, and burying. Trenching involves digging a trench in the ground, laying the pipe in the trench, and then laying a concrete or grating cover. Tunneling includes digging tunnels through rock or ground layers for the pipes to pass in. Buried installation, on the other hand, involves directly burying the pipe in the ground without digging a trench.

One advantage of trenching is that it allows for easier maintenance and repair, as the pipe is more accessible. Additionally, trenching may be the preferred method for deeper installations that require shoring or additional support.

However, burying the pipe directly in the ground can be a more cost-effective and faster installation method, especially for shallower depths. It also reduces the amount of disturbance to the surrounding soil and can be less disruptive to landscaping or structures.

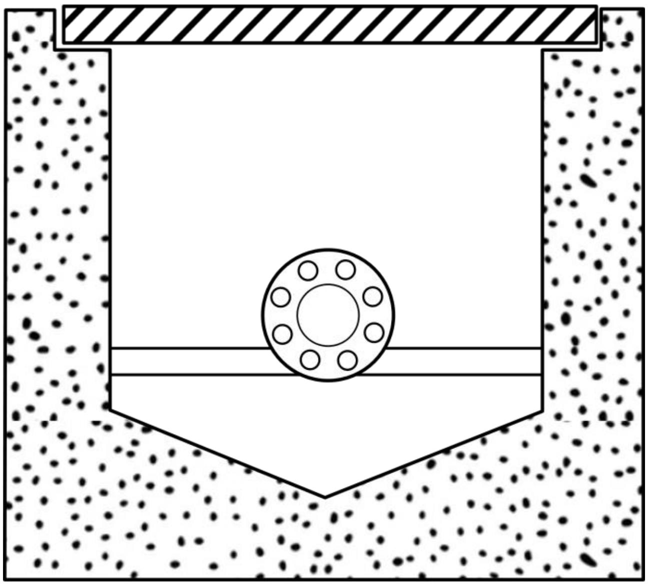


Figure 31 Trenched piping drawing

Figure 32 Trenched piping footage

"Trenches should be low and broad sufficiently to let enough clearance between the ditch wall and pipes. The smallest adequate clearance is 150 mm between the external of pipe and the internal of wall. This permits for setting up of tubing, painting, and potential repairs"[38]

Aerial footages show that the turbine penstock is partially underground from the elevation of circa 480 m and above. Below this elevation, the penstock is overground. At the top end, the penstock enters the tunnel which is also a steel pipe for the first part of the tunnel up until the blocking wall. Beyond that, the tunnel is the water path.

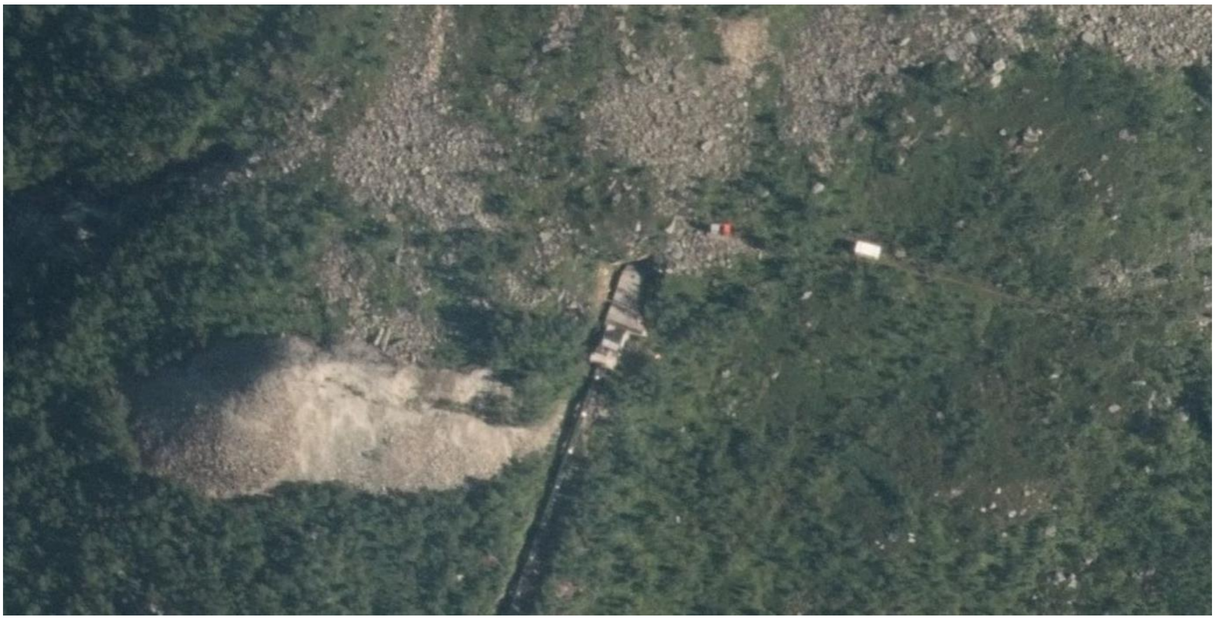


Figure 33 A screenshot aerial footage shows the area where the penstock becomes underground in Niingen mountain at coordinate (68.544481, 17.029082) [39]

Installing trenched pipes for a pumped storage system in a terrain where temperatures drop to -15 C can bring significant benefits to the overall efficiency and reliability of the system. Trenched pipes can help to protect the water in the system from freezing, which is critical for the operation of the system during the winter months. By trenching the pipes in the ground, the soil acts as an insulating layer, helping to maintain a stable temperature for the water in the pipes. This means that the system can operate at its full capacity without any interruptions caused by freezing temperatures, which could otherwise lead to costly downtime and repairs.

Furthermore, trenched pipes can also offer advantages in terms of environmental impact. By trenching the pipes, the visual impact of the system can be reduced, making it less obtrusive in the landscape. This can be particularly important in areas where preserving the natural beauty of the surroundings is a priority.

❖ **Joined, mixed, and separated pipelines**

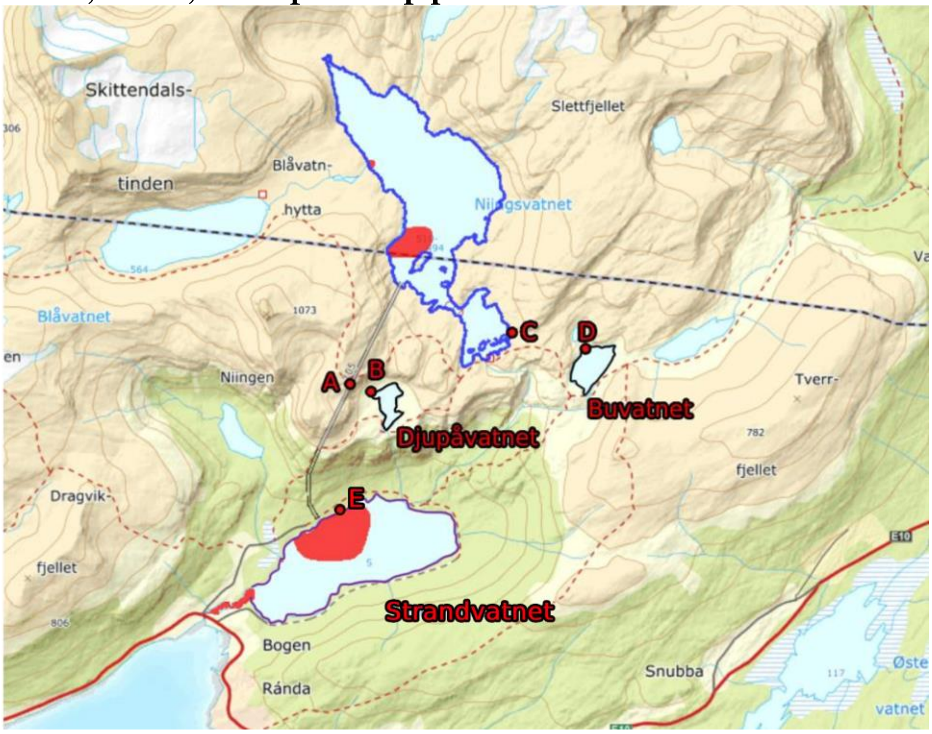


Figure 34 A map of the distribution of the four lakes showing distances between them and the main pipeline

In general, having the same pipeline and motor/generator assembly for both power production and water pumping is much more cost-effective than installing additional pipeline with its motor for pumping water, but difficulties might appear due to the turbine type used in the power plant, the layout in the already installed penstock and the locations of the pumping stations. We face three cases here: A) the pump's pipeline is completely joined with the penstock and head race tunnel (joined plan). B) pump's pipeline is partially joined with the penstock and head race tunnel (mixed plan). C) pump's pipeline is completely separate from the penstock and head race tunnel (separate plan).

➢ Strandvatnet-Niingensvatnet pumping station

This case is possibly the most relevant case for the joined or mixed plan for the pump's pipe to the turbine's penstocks since the pumping distance is the longest here. We face the following cases:

▪ Using the turbine as a pump-turbine

Pump-turbines are mechanisms that can work in both directions, generating power in one way when water that flows inside it rotates its blades causing energy to be created, and pumping water when power is induced by the electric motor. However, this case cannot apply to the Niingen power station as it uses a Pelton turbine which utilizes nozzles that jet the water on its vanes causing them to rotate, but not allowing water to flow in reverse path.

▪ Motor/generator assembly

Also called a Ternary set[40], Brattingfoss pumped storage project utilizes this method, visualized in the following figure, where the motor is used as a generator as well as that the penstock is used as a pipeline for the pump[17].

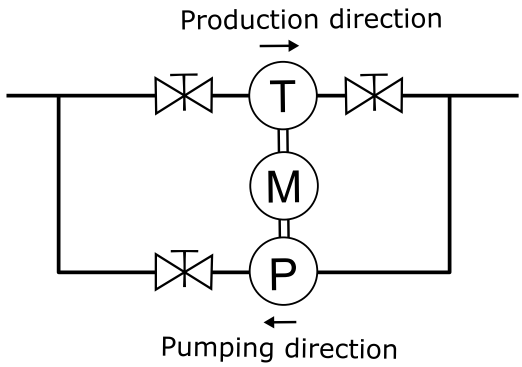


Figure 35 Ternary set plan for the motor/generator assembly at Brattingfoss power plant[17]

This method entails a significant reduction in investment costs. Its disadvantage, on the other hand, is that it is possible to pump or produce power, but not the two at the same time, causing fewer flexible cycles.

- Joining the penstock at an elevation below the turbine level

When the pumping outlet pipe joins the tailrace tunnel and the water is pumped, this will lead to driving the turbine in reverse. Driving a Pelton turbine in reverse is neither recommended nor possible as it is an impulse turbine, meaning it uses the impulse force of water by using jet nozzles to rotate the turbine blades. This means that it is impossible to force water into the nozzles to lead it back to the main reservoir.

- Joining the penstock at an elevation above the turbine level in a mixed pipeline plan

This method offers a considerable reduction in construction cost by using the same penstock as a pipeline to pump water. But obstructs the ability to pump and produce energy at the same time. Also, since the penstock starts with a water path under Niingensvatnet which is already charged with water, the joined pipeline section can be only to the elevation of 482 m where the tunnel starts and then it has to be a separate pipe to the height of 510 m.

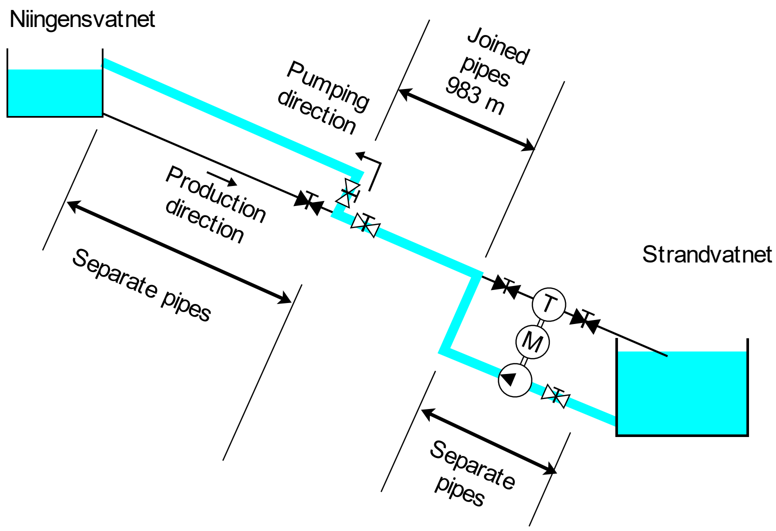


Figure 36 Water direction and plan in the discussed plan

However, this plan is also prone to many obstructions. Since the Niingen power plant keeps the water flowing during times of cold winter to not let the water freeze in pipes, see Section 4.2.1, this causes that this method has to be used also while pumping to not let icing happen, water should not stagnate in pipes or else they might freeze causing more damages. Another difficulty is the enlarged friction and minor head losses due to elongated pipe and the increased quantity of fittings, bends, and valves, which then require a more powerful pump motor. These obstacles make this idea less economically feasible than separate pipelines. For the mentioned reasons, joined pipelines will not be considered an interesting plan in this thesis.

- Djupåvatnet-Niingensvatnet pumping station

Measured straight-line distance (does not consider elevation change) using aerial footage, Figure 34, shows that the closest distance between Djupåvatnet and the penstock (between points A and B) is 220 m. However, at the elevation of approximately 482 m, the penstock becomes underground in the tunnel that meets the water path of length 2,3 km which starts at the blocking wall and ends under the Niingensvatnet. See Figure 2. The water path is not a pipe; but is a channel of a cross-section of 4,5 m^2. Therefore, the pump's outlet can be joined to the turbine's penstock only between the elevations 435 m and 480 m before entering the tunnel at 482 m, but not at the water path since it is not a pipe. Joining the penstock at this plan means joining it only for a distance of less than 90 m. Which does not offer a significant reduction in investment expense and has the disadvantage of losing the ability to produce energy and pump water at the same due to sharing one pipeline.

Therefore, the pumping outlet for Djupåvatnet must be separate from the penstock.

- Buvatnet-Niingensvatnet pumping station

Figure 34 shows that the distance between Buvatnet and Niingensvatnet (between points D and C) is about 950 m in straight-line length, which makes it irrelevant to connect Buvatnet to the main pipeline. Thus, this pipeline has to be separate.

- Considerations for joining pump pipeline with penstock

The main problems that need to be addresses when using the technique of joining pipelines are, among others,

- Obstructing the ability to pump water and produce electricity at the same time, meaning less flexible pumping/production cycles.
- Head losses at the fittings, bends, changes in diameters, etc will add. Also, it is acceptable that the penstock's diameter decreases downhill to increase both pressure and velocity, while the pump's discharge pipe to decrease slightly uphill to decrease friction losses. However, a study of the pressure drops and losses due to friction and fittings, bends, and decrease/increase in the tunnel's diameter must be done to ensure the safety of the system.
- The reservoir outlets and inlets for water production and pumping should not be the same.
    - In the higher reservoir, the pump's discharge pipe must have no additional pressure other than atmospheric, or else this will cause more resistance in the system. Thus, the outlet of the pump should be at the surface of the higher reservoir, or else a tremendous amount of pressure (resistance) will be added to the system and for the pumps to defeat. While the penstock's inlet should be at the deepest point of the higher reservoir where potential energy is maxed. Refer back to the previous figure which shows the potential plan for pumping using this method of joined pipeline/penstock.
    - In the lower reservoir, the opposite applies. The pump needs maximum pressure at its inlet to overcome the NPSHr, therefore must have its inlet at an adequate depth below the water surface. While the turbine's tail race tunnel must be free and put at the surface of Strandvatnet.

2.3.2.2 Pipe geometry

The following factors must be considered when designin pipes geometry in a pumped storage project:

- **Standards**

Industry standards and guidelines, such as those developed by the American Society of Mechanical Engineers (ASME) or the International Organization for Standardization (ISO), provide detailed recommendations and guidelines for selecting appropriate wall thicknesses, diameters, pressures, materials, and fittings for different types of structures and applications.

- ❖ **Suction pipe length**

It is recommended to have a straight pipe length of approximately 5 to 10 times the diameter of the inlet pipe before encountering any obstructions in the suction line such as valves, tees, or other components.[35], [41].

Also, it is recommended to avoid using elbows or other fittings that change flow direction before the pump's inlet.

- ❖ **Diameter**

The pipeline diameter in pumped storage projects may remain constant or may be increased in certain sections. The diameter of the pipeline may need to be increased in certain sections to reduce friction losses and ensure efficient flow of water, especially if the pipeline is very long or if there are significant elevation changes between the reservoirs. But a larger diameter in the pipe means fewer losses in pressure due to friction but also higher cost, so we should maintain a balance between cost and friction loss.

The Practical pumping handbook suggests that the pipe size before the inlet and after the discharge outlet is at least one size larger than the nozzle diameter itself. In addition to using an eccentric decrease to the pump inlet and and an increaser after its outlet [35] [41]."

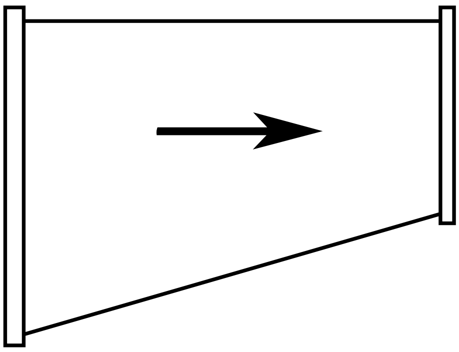


Figure 37 Diameter eccentric reducer for a pump inlet as proposed by The Pumping Handbook

- ❖ **Wall thickness**

ASME-B31.1 describes that the size of the same pipe comes with different wall thicknesses. The selection of wall thickness depends on the pressure the pipe is carrying.

- ❖ **Pipe material, coating, and lining**

Different materials can be chosen in piping depending on the substance being transported, as well as factors such as temperature, pressure, and corrosiveness. However, the choice of either steel materials or ductile iron pipe is the clearest choice for pumping stations.

"Either steel or DIP (ductile iron pipe) should be chosen for the piping applications in hydroelectric power plants due to their strength and characteristics that make them resist water hammer impacts, in addition to that they can have variation of sizes and diameters."[42, Ch. 4.1.1]

- ❖ **Other pipe selection factors**

Fittings such as elbows, tees, and couplings are used to connect pipes and change the direction of flow. Fittings, valves, and supports of pipes will not be studied in this master thesis as they will certainly change depending on the topology and geology of the Niingen mountain and therefore difficult to decide before a study of the region's geology is made.

The cost of the pipe and fittings should be considered, as well as any installation and maintenance costs associated with the system.

2.3.2.3 Losses of energy in pipes h_l

Losses of energy in pipes can be divided into two groups [32]:

- **Major losses of energy (friction head h_f)**

Friction head is the loss of a fluid's energy when flowing in pipes due to friction[43]

h_f is given by the Darcy-Weisbach equation:

$$h_f = \frac{f \cdot L \cdot V^2}{d \cdot 2g} \quad 2.8$$

In which h_f is the friction head (loss in the head due to friction in the pipe or penstock)

V= Velocity of flow in the penstock

L= Length of penstock

d= Diameter of penstock

f= friction coefficient, inversely proportional to Reynolds number R_e

$=\frac{16}{R_e}$ for $R_e < 2000$, viscous flow case

$=\frac{0{,}079}{R_e^{1/4}}$ for $4000 < R_e < 10^6$

R_e is given by

$$R_e = \frac{V \cdot d}{v} \quad 2.9$$

- **Minor energy losses**

These types of losses occur due to an expansion or contraction of pipe that occurs suddenly or having fittings, obstruction or bending in pipes, etc.

- Head loss at the entrance of a pipe h_i

This type of head loss occurs as the fluid enters the pipe and experiences a change in direction.

$$h_i = 0{,}5\frac{V^2}{2g} \quad 2.10$$

- Head loss due to sudden enlargement h_e

When the diameter of the pipe suddenly increases, the fluid undergoes a sudden expansion, causing a reduction in pressure and an increase in velocity.

$$h_e = \frac{(V_1 - V_2)^2}{2g} \quad 2.11$$

- Head loss due to sudden contraction h_c

When the diameter of the pipe suddenly decreases, the fluid undergoes a sudden contraction, causing an increase in pressure and a reduction in velocity.

$$h_c = 0{,}5\frac{V_2^2}{2g} \quad 2.12$$

➢ Head loss due to an obstruction in a pipe

If there is any obstruction, in the pipe, it can cause a reduction in the energy due to the reduction of the pipe's cross-section at that point, followed by a sudden enlargement of the area of flow beyond the obstruction.

➢ Head loss due to bend in a pipe h_b

When the fluid flows through a bend or a curved section of the pipe, it experiences centrifugal forces that cause a pressure drop and an increase in velocity.

$$h_b = \frac{kV^2}{2g} \tag{2.13}$$

Where k is the coefficient of bend, its value depends on the angle of bend, the radius of curvature of bend, and the diameter of the pipe. A table of k values is available in the book "Engineering Fluid Mechanics", in table 10.5.

➢ Head loss due to various pipe fittings

Pipe fittings, such as elbows, tees, and reducers, can cause head losses due to changes in velocity, turbulence, and pressure drop. The amount of head loss depends on the type of fitting and the flow rate of the fluid.

$$Head\ loss\ due\ to\ various\ pipe\ fittings = \frac{kV^2}{2g} \tag{2.14}$$

Where k is the coefficient of pipe fitting

➢ Head loss at the exit of a pipe

This type of head loss occurs as the fluid exits the pipe and experiences a change in direction. The amount of head loss depends on the velocity of the fluid, the diameter of the pipe, and the shape of the exit.

$$h_o = 0{,}5\frac{V^2}{2g} \tag{2.15}$$

2.3.2.4 Water hammer

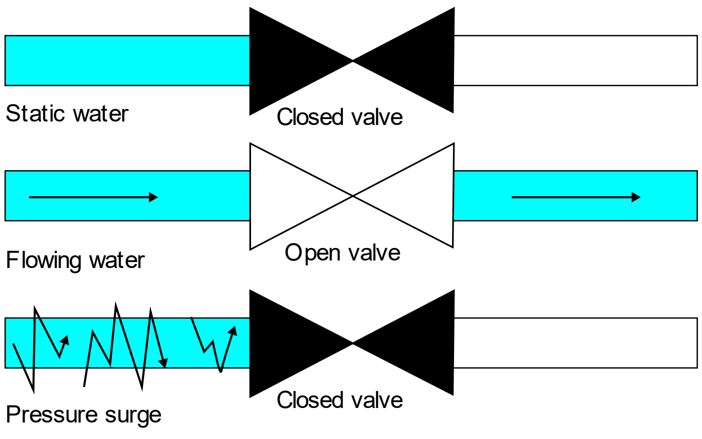


Figure 38 An illustration of Water hammer

A water hammer is an abrupt pressure surge that is created by a sudden stop or redirection in a fluid[44]. The reasons for the water hammer can be attributed to inadequate valve operation, abrupt cessation of pumps, or a power outage. [45]

Water hammer can happen in many scenarios. For example, having the pump at the first end of the pipe, followed by a valve that closes after an amount of water has been pumped towards Niingensvatnet.

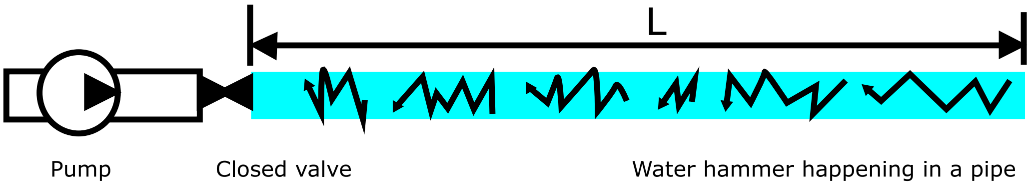


Figure 39 A water hammer case in terms of the Niingen power plant

Another example is a power outage while pumping water, the water that was already running in a pipe at high elevations will be receding backward towards the pipe at high velocity, causing major damage to the pipes and other components.

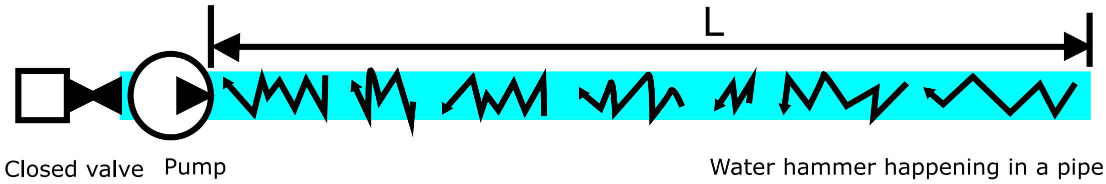


Figure 40 A water hammer case in terms of the Niingen power plant

- **Calculating pressure surge due to water hammer**

One can use one or more of the following ways to calculate the pressure surge in a pipe as a result of a water hammer. Using more than one way is advised, the answers of the used methods should converge so we consider it true.

- Analytically

Many methods can be used to estimate the value of a pressure rise in a water hammer. One of which is Joukowsky (Water hammer) Equation [44]–[46], in addition to PDE equations of motion and continuity, finite elements methods, and more, depending on the specific application and the level of accuracy required.

Dr. R. K. Bansal provides a practical method to calculate pressure raise due to a water hammer[32].

- Gradual closure of the valve

$$P = \frac{LV}{gT} \tag{2.16}$$

- Sudden closure of the valve

$$P = \rho VC \tag{2.17}$$

We consider the valve closure to be gradual if

$$T > \frac{2L}{C} \tag{2.18}$$

We consider the valve closure to be sudden if

$$T < \frac{2L}{C} \tag{2.19}$$

Where

C is velocity of pressure wave

$$C = \sqrt{\frac{K}{\rho}} \tag{2.20}$$

K bulk modulus

T is time in seconds

- Numerically

Many software packages are available to provide water hammer analysis using different methods and offer analysis of piping networks[47].

- Physically

This practical method is based on physical testing and experimenting on the same or a minimized scale of the original case. It involves the use of pressure gauges, analogs, pipelines, and different valves to understand the behavior of water hammers in the same or similar circumstances to the original situation.

3. Economy and profitability

3.1 Data about the costs of other pumped storage projects

3.1.1 Norwegian pumped storage projects

Recalling Table 12, Section 1.7 where data on costs for Norwegian projects are accumulated.

Name	Construction Costs 10^6 [€]	Specific Cost per kW [€/kW]	Specific Cost per kWh [€/kWh]
Aurland III	212	787	0.51
Brattingfoss	30	2844	1.14
Duge	300	1501	0.39
Herva	60	1721	0.99
Jukla	146	3654	1.72
Nygard	41	739	0.43
Saurdal	995	1555	0.31
Stølsdal	64	3760	121.6
Tevla	103	2079	1.25
Øljusjøen	79	1612	1.06

Table 16 Construction costs in Norwegian pumped storage projects[17]

3.1.2 International pumped storage projects

Case study		Site Louvie lake–Fionnay reservoir [28]	La Gouille des Vernays [28]
Energy storage capacity [MWh]		33,4	47
Lower reservoir volume [m^3]		$170 \cdot 10^3$	$170 \cdot 10^3$
Costs	Reservoirs [€]	0	0
	Piping [€]	2271897,2	4627073,6
	Civil engineering [€]	2051512	2063699,2
	Hydro and Electric Equipment [€]	2261741,2	5381664,4
	Electrical connection [€]	127965,6	489519,2
	Study [€]	707873,2	1342623,2
	Miscellaneous [€]	495612,8	940445,6
	Total [€]	8285264,8	15712347,6
	Total [€/w]	1,92964	1,92964

Table 17 Costs comparison in two different international pumped storage plants

3.2 Energy storage in a reservoir

Based on its available water volume and static head, one can develop an equation for energy storage [kWh] a reservoir has. It is possible to estimate the expected return from a water volume that is available in a water container, as this volume is mainly potential hydraulic energy that can be converted to electrical energy at times of high prices.

The formula for energy available in a container of water:

$$E\ [J] = \eta_t \rho g h V$$

We can convert the previous equation to give energy in kWh instead of Joules by multiplying by $2{,}77 \cdot 10^{-7}$[48]:

$$E = 2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g h V [kWh] \qquad 3.1$$

For example, the case study for Site Louvie Lake–Fionnay reservoir in Switzerland [28] its energy storage is given by:

$$E = 2{,}78 \cdot 10^{-7} \rho g V h$$

In terms of pumped storage, it is the pumped water that will serve as stored potential energy in the higher reservoir for later conversion.

3.3 Price per potential energy unit

The value of this potential energy can be converted to Megawatt-hours and multiplied by the electricity prices at the respective time to have its value in currency.

$$\text{Expected revenue} = E \cdot \text{high power prices} \qquad 3.2$$

3.4 Cost models of pumped storage project and its estimation

Pumped storage systems are complicated engineering works and therefore difficult to describe using one cost model's calculations and parameters[49, Sec. 3.2] One of the cost models that can be found to estimate the costs of these projects is the ANU (Australian National University) cost model. In their book "Closed-Loop Pumped Storage Hydropower Resource Assessment for the United States"; the U.S. Department of Energy followed this cost model to give an estimated number of the costs of pumped storage[49]. Moreover, the "Encyclopedia of Energy Storage" had an article in its 2022 edition called "Cost Models for Pumped Hydro Storage Systems" that has significant information. However, another significant cost model, especially in terms of Norwegian hydroelectric power plants, is the costs model released annually by NVE The Norwegian Water Resources and Energy Directorate, which will be employed in this document.

The costs of a pumped storage project can vary widely depending on several factors, including the size and capacity of the project, the complexity of the site, and the local regulatory environment. The major costs associated with pumped storage projects are civil and electro-mechanical costs[50] which are capital investment costs. Also, operating costs should be included as they are recurring costs to keep the project running as it should. But the following costs will not be included as they are related to factors out of the scope of this study and not included in NVE's guidelines either:

- Taxes and fees.
- Transport and shipping costs.
- Valves, fittings, seals, supports.
- Administration, construction management, and quality control.
- Builders cost and land acquisitions.

3.4.1 Capital investment costs

3.4.1.1 Mechanical and electrical equipment costs

Pumped storage projects typically require devices that will be utilized to pump water and transmit power to these pumps. For example, pumps, pipes, fittings, valves, supports, seals, power cables' lines, etc.

As for the pumps and pipes, their prices C_{pump} and C_{pipes} respectively, are already set and known by the supplier. However, for C_{pipes}, the official cost index that is released annually by NVE which is adapted for small-scale hydropower plants will be used as it gives reliable data about pipe costs.

For power lines costs C_{line}, as the pumps that can be used in this project are medium voltage pumps, NVE provides a guidelines book for the choice and cost analysis of high voltage cables only, and therefore, this value must be assumed based on market research.

3.4.1.2 Civil engineering costs

Civil engineering costs include the design and construction of the civil works, such as the dams, tunnels, trenches, underground pumping chambers, site access infrastructure, developer/owner costs (including planning, feasibility, permitting), and land acquisition. Dam costs, C_{dam} are described in NVE's guidelines in all of their editions. The same applies to tunnel costs C_{tun}, trench cost C_{tre} and pumping chamber costs C_{ch}. Those costs will be studied in detail later in the cases studies in the appendices.

3.4.2 Operating costs

Once the project is up and running, there are ongoing costs associated with operating and maintaining the system, including the cost of electricity to power the pumps' motors, as well as the cost of personnel, maintenance, and repairs. As for maintenance C_{ma} And operating personnel C_{per}, hydropower establishes demand for little repairs, and operations costs will be minimal after commission. International Renewable Energy Agency (IRENA) refers to that operation and maintenance costs range from 1 to maximumly 4% of the total capital cost[50]. The only cost left that will add up to operating costs is the pump power consumption, which is given by the law (see Section 2.3.1.2, Power consumption Subsection):

$$P = \frac{Q \cdot h \cdot g \cdot \rho}{3600 \cdot \eta_p} \tag{3.3}$$

$$C_{\text{power}} = P \cdot \text{low power price} \tag{3.4}$$

3.4.3 Total costs

$$\begin{aligned} &\text{Total costs of pumped storage} \\ &\qquad = \text{mechanical and electrical equipment costs} + \text{civil engineering costs} \\ &\qquad + \text{operating costs} \end{aligned}$$

3.5 Expected profit

$$\text{Expected profit} = \text{Expected revenue} - \text{Total cost of pumped storage}$$

3.6 Automatic control of powering on/off the pumping assembly

In Section 2.1.1.5, a programmed controller was suggested to be used to turn on or shut down the pumping procedure depending on electricity prices. This proposition is explained in detail here as it is related to rising profitability.

The governing equation for this case will be derived as follows:

Turn on the pumping system if the pump's power consumption is less than the expected revenue, from Equations 3.1, 3.2, 3.3, 3.4 we get:

$$C_{\text{power}} < \text{Expected revenue}$$

$$P \cdot \text{low power price} < E \cdot \text{high power prices}$$

$$\frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p} \cdot \text{low power price} < 2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g h V \cdot \text{high } power\ prices$$

$$\text{low power price} < \frac{2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g V \cdot 3600 \cdot \eta_p}{Q \cdot g \cdot \rho} \cdot \text{high power prices}$$

$$\text{low power price} < 9{,}972 \cdot 10^{-4} \eta_t \eta_p \cdot \frac{V \cdot \text{high power prices}}{Q}$$

The values of η_t and η_p are constants. Since that $V = Q \cdot t$, and the value of Q has to be known and planned for beforehand, therefore is constant. We get:

$$\text{low power price} < 9{,}972 \cdot 10^{-4} \eta_t \eta_p \cdot t \cdot \text{high power prices} \qquad 3.5$$

Where the value of t can be predicted by studying patterns of time changes in Section 2.1.1.3 Cycles based on energy prices in different periods. For example:

- $t = 6$ hours in the hourly plan which starts at 00:00 and ends at 06:00 on workdays.
- $t = 72$ hours in the daily plan which starts at 00:00 o'clock on Fridays and ends at 00:00 on Mondays.

Higher power prices can be obtained from the last surge in power price and assumed that production will occur at a similar price. Knowing these values limits the computations to only low power prices and higher prices, which makes it practical to implement Equation 3.5 on the mentioned programmed controller that turns on the pumping system only if Equation 3.5 was true. Making the pumping procedure autonomous and more profitable.

4. Environmental effects

4.1 Possible hazards and environmental considerations

4.1.1 Weather factors

Severe environments, such as Niingen Mountain, can have several effects on components in a hydroelectric power plant, such as frozen clogging, ice load on gates, and thermal expansion and contraction.

- One of the main concerns is the potential for the pipes to freeze, which can cause them to crack or rupture. This is especially true for pipes that are not designed to withstand low temperatures, or that are not properly insulated. Freezing can also cause blockages in the pipes, which can reduce the flow of water and affect the efficiency of the power plant.

One method to overcome this issue is to keep water running in the penstock as it only can freeze if it was standing still. So, in very cold weather the power station is kept in operation with a small amount of water flow. Note that pipes must either have an active flow or empty, but not have stationary fluid as this will be a reason for internal icing.

- Another concern is the potential for thermal expansion and contraction of the pipes. When exposed to low temperatures, the pipes can contract, which can cause stress on the joints and fittings, leading to leaks or damage. Conversely, when the pipes are exposed to higher temperatures, they can expand, which can also cause stress and damage.

To prevent these issues, pipes in a hydroelectric power plant are typically designed with appropriate materials and thickness to withstand low temperatures. They are also often insulated with materials such as foam or fiberglass to help maintain a consistent temperature and prevent freezing. In addition, temperature sensors and heating systems may be installed to monitor and regulate the temperature of the pipes.

- Outer corrosion of the pipes

Outer corrosion is dealt with by paint coating and regular sandblasting and repainting. Maintenance and inspections are also important to ensure that the pipes are in good condition and to address any issues that may arise.

- Avalanches: Snowy mountains are often prone to avalanches, which can pose a serious risk to human life and property. Building a pumped station in such a location could increase the risk of avalanches and would require extensive measures to be taken to mitigate this risk.

"On January 21, 1952, a significant avalanche occurred during building, causing the construction station to be swept 500 meters up the mountainside, resulting in the unfortunate passing away of five workers."[6]

- Landslides: Mountainous regions are also prone to landslides, especially in areas with steep slopes and loose soil or rock. Construction activities associated with building a pumped station could destabilize the soil or rock and increase the risk of landslides.

4.1.2 Dam failure

The case of "Taum Sauk Pump Storage Plant" in Missouri, USA shows that the dam on the upper reservoir failed when it was overflowing with water and this incident caused estimated damage and property destruction reaching up to $1 billion.[51]

An email from the plant operator to supervisors; on September 27, 2005, reads:

"Allowing the upper reservoir to overflow is strictly prohibited. It would lead to severe erosion and eventual failure of the dam. If water keeps spilling over the top of the wall, it could result in a collapse of a section, leading to a cascading failure."

Therefore, it is highly recommended that dikes in dams get regularly maintained and inspected to detect possible cracks and prevent any possible failures.

4.1.3 Other hazards

Different hazards can be considered when studying pumped storage schemes. Risks associated with pumped storage projects may include, but are not restricted to, adverse effects on the hydrology of the basin, droughts, soil erosion due to hydropower generation, destruction of fish habitats, accumulation of sediment in the reservoir, emissions of CO_2, degradation of water quality, transportation issues, impacts from climate change, induced earthquakes, flood control challenges, thinning ice layer, noise pollution, vegetation flooding, and environmental consequences, among other potential hazards.[52]

5. Conclusions and suggestions

5.1 Assessment

Assessment is the act of judging or concluding the condition, quality, revenue, or importance of something[53]. Comparing results gained from case studies that are reported later in the appendices with criteria for assessment including requirements for pumped storage will be the main tool to check the viability of this project. Based on the assumptions made in the case studies, we find the following results:

- Pumping water from Strandvatnet to Niingensvatnet is uninteresting and is not cost-effective, because the long distance from Strandvatnet to Niingensvatnet which increases the capital investment costs, especially in pipes, and the high head that increases the operational costs, especially in pumps power consumption.
- Pumping water from Buvatnet is the most interesting case, it achieves all the expected rewards and is cost-effective, especially after precise studies. However, as in all hydropower projects, large investment capital has to be put in to gain the benefits.
- Pumping from Djupåvatnet to Niingensvatnet might be uninteresting, but this is not a final assessment. Careful examination of the reservoir has to be done as it can be shallow and has less available capacity.
- An alternative reservoir to Djupåvatnet, the nearby lake Blåvatnet can be considered for this task as it has more water capacity and at a higher elevation than Niingensvatnet which causes less operational expenses.
- The most relevant factors to judge the economic feasibility of a pumped storage project at a lake are
    - The height difference between lower and higher reservoirs (in other words, the required head at the pump's outlet), which is reversely proportional to profit and affects it severely. The smaller the elevation difference between the lower and the higher reservoir, the more feasible the project is.
    - Distance between the lower reservoir and higher reservoir which is also reversely proportional to profit.
    - The lower reservoir's available capacity V_{max} which is directly proportional to flow rate and therefore to profit (V_{max} is directly proportional to reservoirs area and depth).
- The uncertainty in power prices and costs for pumped storage surfaces undoubtedly when calculating its values, especially for financial feasibility, because power prices vary during the day and the year as well, in addition to that the costs change from year to year. To deal with this uncertainty, an Excel document named "Financial calculations table" was made and attached to this thesis which contains all the important parameters that lead to possible changes in revenue and costs, graphs and charts were made to point out the problem of uncertain costs and prices changes in different examples and how they could affect these projects procedures. See case studies in the appendices for further explanation.
- The factor of low power price (the power price during pumping water) is much less relevant than the high power price (during generation) which plays a significant role in the equation of cost-effectiveness in this project. See the conclusion of case study B for instance.

5.2 Future work

5.2.1 Description of remaining work

- The most essential future work will be the topological, environmental, and geological studies for knowing the lakes' sizes and values for available capacity.
- Doing the previously mentioned studies can allow more decisions taking regarding the exact locations of the pipes and pumping stations in Niingen Mountain.
- Electrical engineering studies to optimize the motor's performance including studying voltages, frequencies, velocity control, cables, transformers, and costs.
- Practices for erection, operation, and maintenance of the piping system.

- This thesis aims to assess the case of pumped storage in the Niingen power plant, but not to design this project. Thus, detailed calculations for pipes including thermal expansion, fittings, supports, bends, enlargements, and contraction were not included and must be studied further.

5.2.2 Suggestions for future work

- This is an individual project, which provokes the need for a team of more engineers and specialists to discuss the concepts from many points of view and eliminates the risk of individual thinking.
- Hydropower projects take a long time, ranging from 4 to 20 years, to be prepared for and implemented using excessive studies and research, more time and resources will be required for this project so it achieves its most favorable findings.
- This study proposed plans for pumping/generating energy only from the perspective of power prices. Other factors such as times for precipitation, snow melting, etc., was not considered in this report due to limitations. But it is highly recommended to further study these circumstances to get a more detailed and customized plans of pumping water depending on the change of those factors.
- The aerial footage and maps show reservoirs that can be more promising around Niingensvatnet such as Villdalsvatnet (652 m) and Blåvatnet (564 m) with bigger capacities and higher elevations than Buvatnet and Djupåvatnet. Which makes the pumped storage schemes in these two lakes more feasible. Those two lakes are proposed to be studied in the future and considered as sources of potential energy.
- If regulated and a dam was built on it, Blåvatnet can work as an instant source of energy that requires little to no power consumed to refill Niingensvatnet, especially because it is located higher than Niingensvatnet and is walled by mountains from three sides. Building a dam on the fourth side will assure making it a resource of potential power and therefore increased profitability.

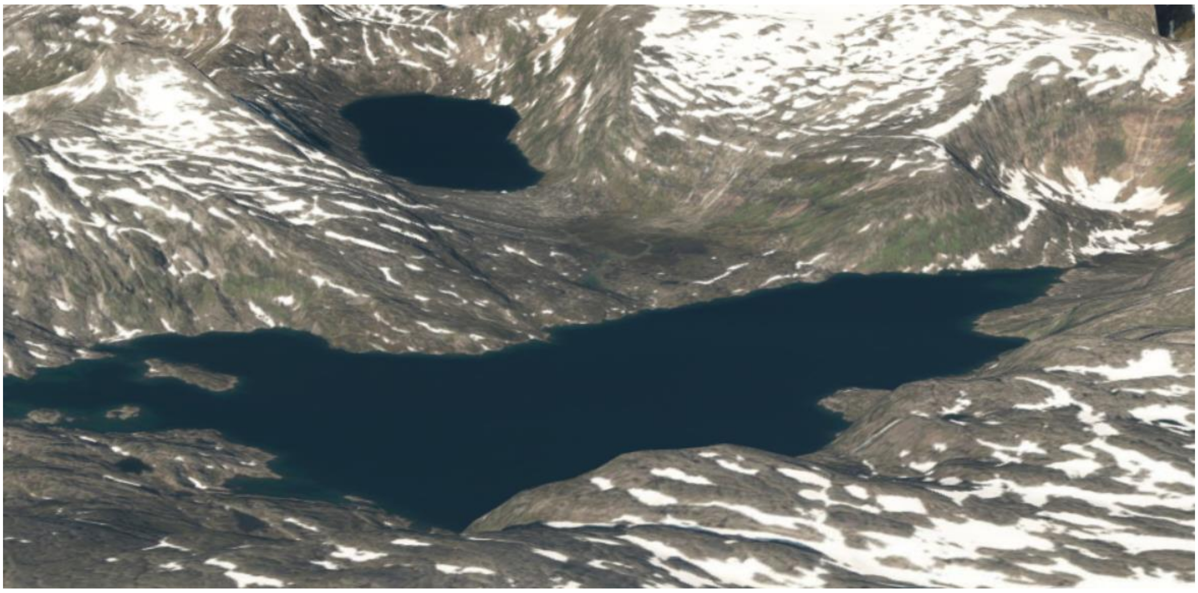


Figure 41 A 3D map of Blåvatnet (above) and Niingensvatnet (below) [39]

5.3 Conclusion

An extensive assessment of plans for pumped hydroelectric energy storage in the lakes that surround the Niingen power plant is conducted in this document, focusing on the system design of the possible projects, practices, regulations, and components selection to give a clarifying review of the worthiness and practicability of these plans. This made the answer to the question of whether pumped storage schemes from Strandvatnet, Buvatnet, and Djupåvatnet to Niingensvatnet are practical to be exploited clearer.

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Appendices

1 Case Studies

1.1 Case study A: Pumping from Strandvatnet

1.1.1 Circumstances of this case study

Water temperature [°C]	0
Weather temperature [°C]	-5
Kinematic viscosity $[\mathrm{m}^2/\mathrm{s}]$	$1.789 \cdot 10^{-6}$
The specific weight of water γ $[\mathrm{kg/m} * \mathrm{s}^2]$	9810
Vapor pressure of water P_v [kPa]	0,652
Atmospheric pressure [Pa]	101260,47
Density $[\mathrm{kg/m}^3]$	1000
Gravitational acceleration $[\mathrm{m/s}^2]$	9,81
Specific gravity, dimensionless	1
Bulk modulus $[\mathrm{N/m}^3]$	$2{,}1 \cdot 10^9$
The velocity of pressure wave [m/s]	1449,13

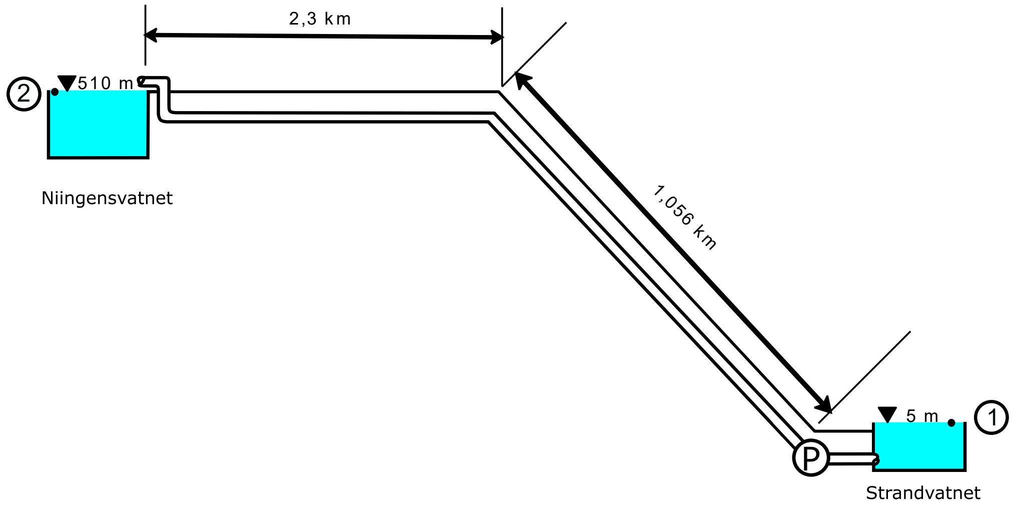
Table 18 Circumstances of this case study (assumed to be constant in different elevations)

1.1.2 Assumptions of this case study

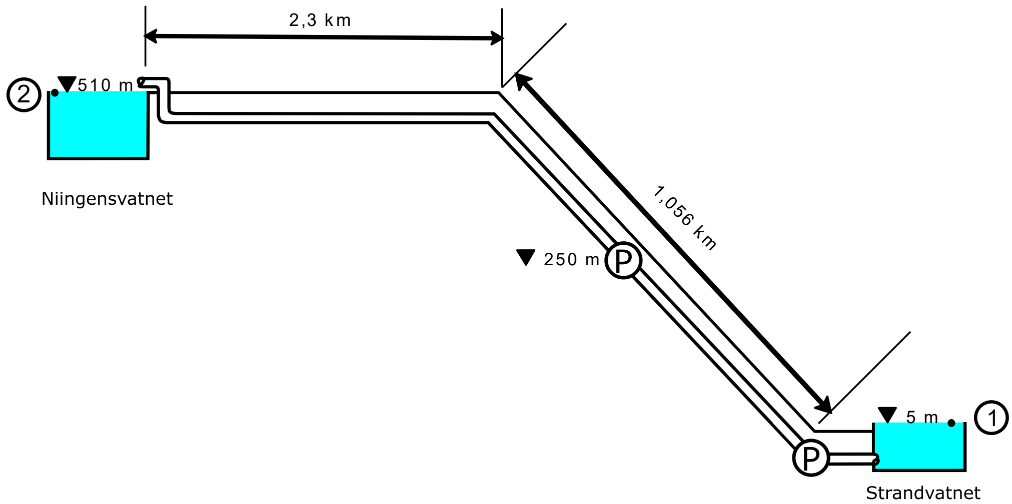
Depth of Strandvatnet [m]	10
Volume of Strandvatnet $[\mathrm{m}^3]$ assuming it is a container with a constant rectangular profile	$195 \cdot 10^5$
Water percentage allowed to be pumped off Strandvatnet	10%
Pump's suction percentage per hour of the allowed water volume V_{max}	0,004%
Pump efficiency η_p	95%
Turbine efficiency η_t	95%
High power price [Nok/MWh]	1000
Low power price [Nok/MWh]	500
Price of power line (5000-8000 [kV]) [NOK/km]	$4 \cdot 10^4$
Velocity at the surface of the water in an open reservoir is negligible	
Head losses due to bends, fittings, and other minor losses are not included in this study as they depend on different changes in the layout that result from the area's topology. Therefore, assumed to be zero.	

Table 19 Table of assumptions in case study A

1.1.3 Location and layout



Layout and dimensions using one pump



Layout and dimensions using two pumps

Figure 42 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Strandvatnet to Niingensvatnet using one and two pumps as it will be studied in this case study

Two circumstances were examined in this case study, one with only one pump, and another with two pumps due to the high elevation. For this case study, the location for the lower pumping station, i.e. at Strandvatnet is chosen near the powerhouse at the lake's shore. While the exact location for the higher pump is left a variable depending on geological and topological studies. The lengths of the pipes are chosen to be similar in length and parallel to the penstock and tunnel plan before 2003. Pipes are recommended to be trenched, and pumping chambers are suggested to be underground as we will see later in this case study.

1.1.4 Reservoirs geology

For the volume of water to be pumped, in Section 2.2.2 "Water levels allowed to be pumped from and added to lakes"; we defined the variable $X_{\max}$, which is the maximum amount of water we can pump. And this variable can either describe the volume allowed to be pumped $V_{\max}$, or the water level allowed to be pumped $Y_{\max}$.

- Lake's volume

Assuming the depth of Strandvatnet is 10 m, then its volume will be the following:

$$V_{\text{Strandvatnet}} = \text{Depth} \cdot \text{area} \tag{1.1}$$

$$= 10[\text{m}] \cdot 1{,}95 \text{ km}^2$$

$$= 10[\text{m}] \cdot 195 \cdot 10^4[\text{ m}^2] = 195 \cdot 10^5 \text{ m}^3$$

Note that the volume calculation assumes that Strandvatnet is container with a constant rectangular profile.

- Deciding the allowed water magnitudes to be pumped

Assume that:

$$V_{\text{max}} = 10\% \cdot V_{\text{Strandvatnet}} \tag{1.2}$$

Then:

$$V_{max} = 0{,}10 \cdot 195 \cdot 10^5 = 195 \cdot 10^4 \text{ m}^3$$

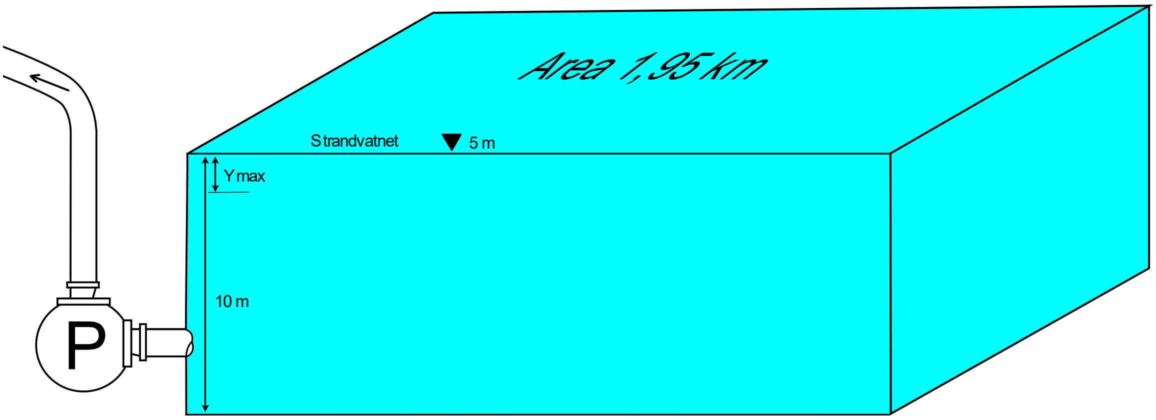


Figure 43 The reservoir at Strandvatnet assuming it is a container with a constant rectangular profile

- Deciding the flow rate

As a preliminary step for choosing a pump, we need to know the flow rate and the head at the pumping station.

Finding the flow rate is necessary, as different pumps can deliver water to the required destination at different speeds. And knowing this value will help later in calculating pipe diameters. One can find the flow rate by dividing the water volume needed to be pumped by the time that will be consumed in pumping.

As for time, studying energy prices and considering the suggested timelines for generating/pumping in Section 2.1.1 as well as volumes of the lakes, the time needed to drain lakes, and water levels allowed to be pumped from Section 2.2.2, we find that the plan that requires the fastest pumping is the hourly plan, as it has 6 hours during the 24 hours of the day for pumping. We assume[2] that the pumping pipeline has to be parallel and similar in layout, location, and plan to the turbine's penstock and headrace tunnel before moving its location in 2003, time needed for water to start reaching the elevation of 510 m flowing through the pipeline, which is of length 3356 m, starting to be pumped from Strandvatnet is one hour. Meaning that we specified an hour for the water to be pumped from Strandvatnet to start reaching the height of 510 m cutting approximately 1056,127 m, then it will flow horizontally for 2300 m until it reaches Niingensvatnet.

[2] Nordkraft does not have to do the assumptions for time, volume, and depth, as it can have the precise numbers for those parameters.

Assuming that the pump will draw a volume of 0,004% of $V_{\max}$ per hour

$$\text{Flow rate volume} = 0{,}004\% \cdot V_{\max}$$

$$= 0{,}004 \cdot 0{,}01 \cdot 195 \cdot 10^4 = 78 \text{ m}^3$$

$$Q = \frac{\text{Flow rate volume}}{\text{time}} =$$

$$= \frac{78}{1} = 78 \frac{[\text{ m}^3]}{[\text{h}]}$$

- Time taken to pump water volume from a lake

Recalling Equation 2.1:

$$\text{Time to drain lake } = \frac{\text{water volume in a lake}}{\text{Pumping capacity}}$$

$$= \frac{V_{\text{Strandvatnet}}}{Q} = \frac{195 \cdot 10^5}{78} = 2500 \text{ h}$$

- Following the daily plan

For this case study, the daily pumping cycle is proposed. In Section 2.1.1.3, the daily plan explained that three days of pumping is the optimal pumping time. In each cycle of three days (72 hours), the amount of pumped water is:

$$V = Q \cdot t = 78 \cdot 72 = 5616 \text{ m}^3$$

- Time taken to fully pump $V_{\max}$

$$\text{Time to pump an allowed water volume of a lake } = \frac{\text{water volume allowed to be pumped } V_{\max}}{\text{Pumping capacity}}$$

$$= \frac{V_{\max}}{Q} = \frac{195 \cdot 10^4}{78} = 250 \text{ h} = \frac{250}{72} = 3{,}472 \text{ cycles of daily pumping (three days a week)}$$

1.1.5 Pumps selection

1.1.5.1 Pump selection

Required flow rate [m^3]/[h]	78
Required total head [m]	506,91
Required pressure at the pump outlet [bar]	5,1

Table 20 Parameters of flow in case study A

- Deciding on pump type

Recalling Equations 2.2 and 2.3 at $N = 1450$ rpm

$$\omega_P = \frac{\omega\sqrt{Q}}{(gh)^{\frac{3}{4}}}$$

$$= \frac{151{,}84\sqrt{0{,}021}}{(9{,}81 \cdot 510)^{3/4}} = 0{,}036$$

Where:

$$\omega = \frac{2\pi N}{60}$$

$$= \frac{2\pi \cdot 1450}{60} = 151{,}84 \text{ rad/s}$$

And:

$$Q = 78 \frac{\text{m}^3}{\text{h}} = \frac{78}{3600} = 0{,}021 \frac{\text{m}^3}{\text{s}}$$

If:

$$\omega_P < 1 \qquad \text{radial flow pump}$$

After this stage, it became possible to compare different pumps available with pump suppliers.

Browsing different catalogs of industrial suppliers, we find a variety of pumps that can deliver as high pressure and flow rate as is needed for this project.

- Using one pump

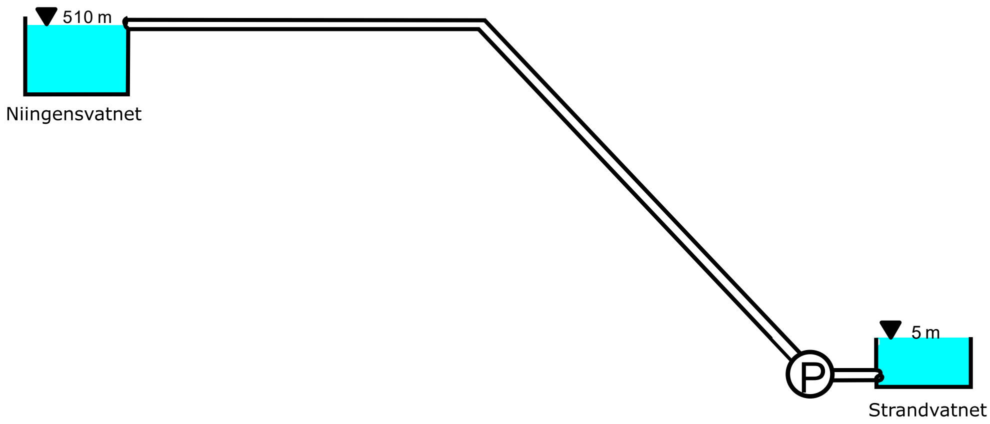


Figure 44 Pumping plan using one pump

Studying pumps that "North Ridge Pumps" provide as an example, after studying the head-flow rate curves, we find that their pump series "North Ridge SKM-E End Suction Horizontal Centrifugal Multistage Pump" fulfills the requirements of this project. Choosing the pump "SKM-K 150/10"[33] in this case study, we get the following data for this pump:

Max flow rate [m^3]/[h]	350
Max head [m]	510
Number of stages	10
Pump materials	AISI304, AISI316, AISI316L, Bronze, Cast Iron, Cast Steel, Ductile Iron, Duplex, NiAl Bronze, Super Duplex
Inlet/outlet sizes[3] d_{pump} [mm]	150
Max suction lift (max height of the suction pipe) [m]	8
Operating Temperature [°C]	-10 to +140
Estimated price [NOK]	$25 \cdot 10^4$

Table 21 Characteristics of the selected pump at 1450 rpm

- Using multiple pumps

Since the head and flow rate magnitudes are large in this case; using one pump can cause increased load on the motor and additional possible costs on the maintenance and natural wear and tear of

[3] Assumed to be ID (inner diameter)

pump components. To avoid the case of overloading the pump, one can use two pumps at different elevations on Niingen Mountain.

Factors that will change in this case compared to using one pump are

- Price difference.
- Two pumping stations must be built, meaning an increase in construction cost.
- The lower pump must be chosen to provide more pressure to the higher pump so that cavitation can be avoided in the higher pump, see NPSH Sub-section in Section 2.3.1.2.

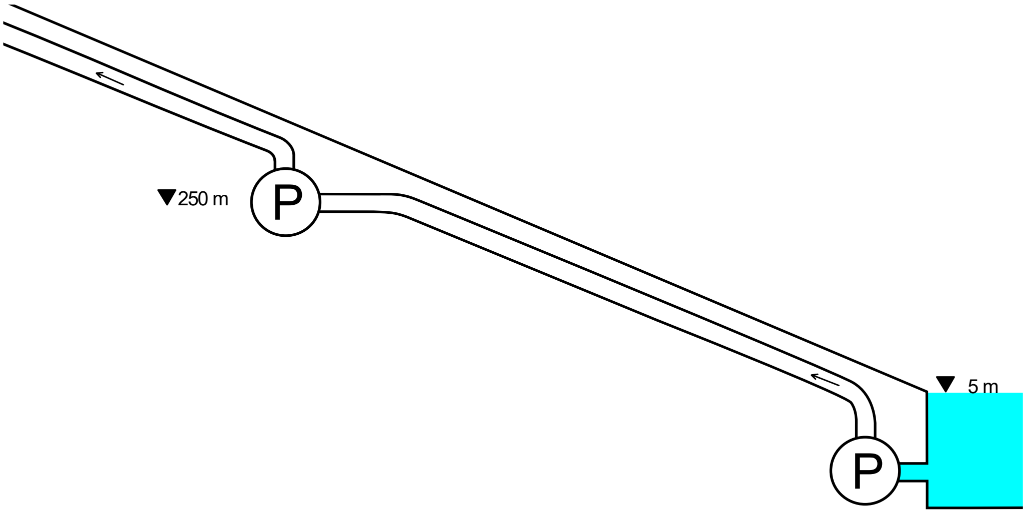


Figure 45 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Strandvatnet to Niingensvatnet using two pumps

In this case, we will be selecting two pumps, a lower one with a head of about 300 m, and a higher one at an elevation of 250 m and a pressure head of 250 m. Both pumps should deliver the same flow rate of 78 $[\mathrm{m}^3]/[\mathrm{h}]$.

Selecting from the same supplier, as they have a wide variety of industrial pumps. We can find the pump "SKM-K 100/15" provides a head of 300 m with inlet/outlet diameters of 100 mm, and "SKM-K 80/15" provides a head of 200 m with inlet/outlet diameters of 80 mm.

Lower pump SKM-K 100/15	Max flow rate $\frac{[\mathrm{m}^3]}{[\mathrm{h}]}$	160
	Max head [m]	350
	Number of stages	15
	Pump materials	AISI304, AISI316, AISI316L, Bronze, Cast Iron, Cast Steel, Ductile Iron, Duplex, NiAl Bronze, Super Duplex
	Inlet/outlet sizes[4] d_{pump}[mm]	100
	Max suction lift (max height of the suction pipe) [m]	-
	Operating Temperature [°C]	-10 to +140
	Estimated price [NOK]	$15 \cdot 10^4$
Higher pump SKM-K 80/15	Max flow rate $[\mathrm{m}^3]/[\mathrm{h}]$	80

[4] Assumed to be ID

	Max head [m]	240
	Number of stages	15
	Pump materials	AISI304, AISI316, AISI316L, Bronze, Cast Iron, Cast Steel, Ductile Iron, Duplex, NiAl Bronze, Super Duplex
	Inlet/outlet sizes[5] d_{pump}[mm]	80
	Max suction lift (max height of the suction pipe) [m]	-
	Operating Temperature [°C]	-10 to +140
	Estimated price [NOK]	$10 \cdot 10^4$

Table 22 Characteristics of the selected pump at 1450 rpm

1.1.5.2 Pumps characteristics

❖ **Power consumed**

Section 2.3.1.2 explains how power consumption varies with the flow rates of the pump. However, it is given by Equation 2.7:

$$P = \frac{Q \cdot h \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

Also, the pump's efficiency varies with flow rate and depends on the specific final choice of the pump using parameters that are not studied in this case study such as the motor phases, voltage, and frequency. Assuming $\eta_p = 95\%$ for both types of pumps.

➢ Using one pump

$$P = \frac{Q \cdot h \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

$$= \frac{78 \cdot 510 \cdot 9{,}81 \cdot 1000}{3600 \cdot 0{,}95}$$

$$= 114105{,}78 \left[\frac{\mathrm{kg} * \mathrm{m}^2}{\mathrm{s}^2}\right] \cdot \left[\frac{1}{s}\right] = 114105{,}78 \left[\frac{\mathrm{J}}{\mathrm{s}}\right] = 114105{,}78\ [\mathrm{W}] = 114{,}10\ [\mathrm{kW}]$$

Where $\left[\frac{\mathrm{kg}*\mathrm{m}^2}{\mathrm{s}^2}\right] = [\mathrm{J}]$

➢ Using two pumps

$$P = P_1 + P_2 = \frac{Q \cdot h_1 \cdot g \cdot \rho}{3600 \cdot \eta_p} + \frac{Q \cdot h_2 \cdot g \cdot \rho}{3600 \cdot \eta_p} = (h_1 + h_2)\frac{Q \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

$$= (300 + 250)\frac{78 \cdot 9{,}81 \cdot 1000}{3600 \cdot 0{,}95} = 67{,}1215\ \mathrm{kW} + 55{,}93\ \mathrm{kW} = 123{,}05\ \mathrm{kW}$$

❖ **NPSHa**

As we studied in Section 2.3.1.2, inlet pressure must be known to avoid cavitation.

▪ Using one pump

Suggesting the layout in the following figure:

[5] Assumed to be ID

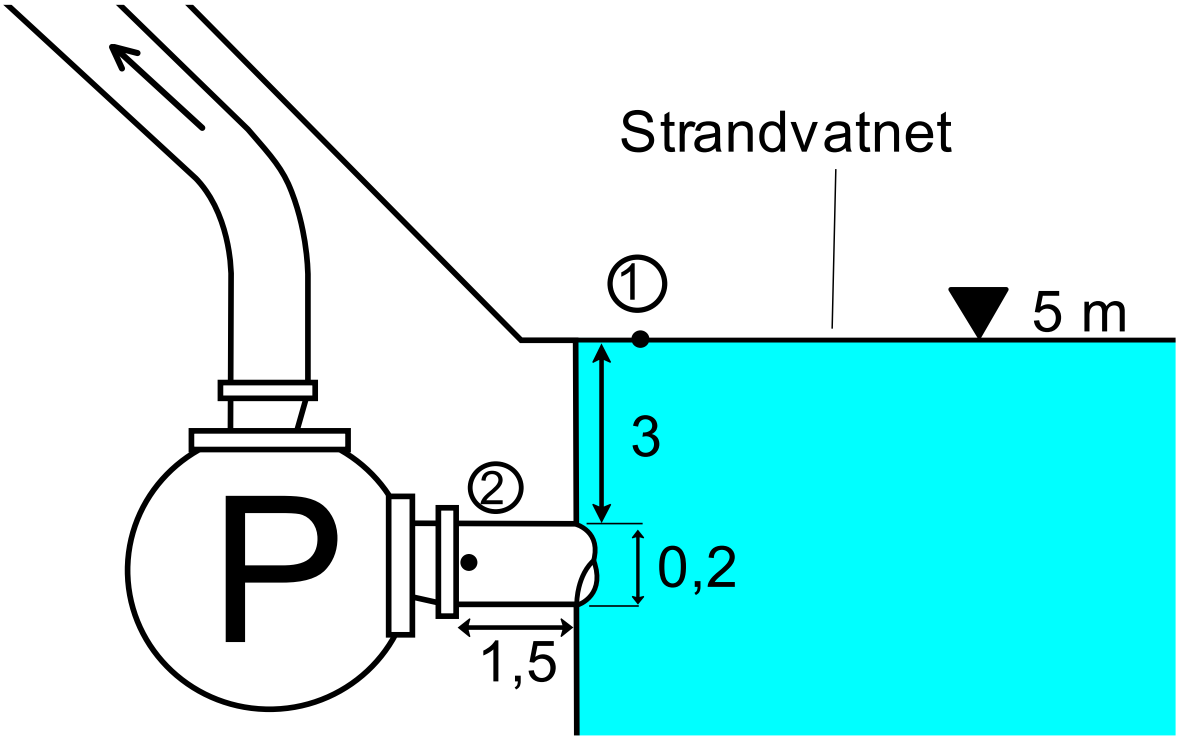


Figure 46 Proposed plan for the pumping station by considering recommendations in Chapter 2

We solve this problem by subtracting vapor pressure from pump inlet pressure and using the energy equation[11, Ch. 14.5].

- Applying the energy equation between points 1 and 2

$$\left(\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2\right)+\sum h_l$$

Where

Water velocity at the water surface is negligible $V_1 = 0$, $z_1 = 0$ m, $z_2 = -2$ m, z_2 is an assumed value that can be changed later to achieve larger NPSHa.

- Atmospheric pressure in meters of head

$$\frac{P_1}{\gamma}=\frac{101260{,}47[\mathrm{Pa}]}{9810\left[\frac{\mathrm{kg}}{\mathrm{m}*\mathrm{s}^2}\right]}=\frac{10.32[\mathrm{m}]}{1[\mathrm{m}]}=10{,}32$$

Because $[\mathrm{Pa}] = [\frac{\mathrm{kg}}{\mathrm{m}*\mathrm{s}^2}][11, \mathrm{Tbl. F.1}]$.

- Friction head in the pipe[6]

From Equation 2.8 we get the friction head:

$$h_f=\frac{f\cdot L_1\cdot {V_2}^2}{d_{pipe}\cdot 2g}$$

$$=\frac{0{,}0047\cdot 1{,}5\cdot (0{,}69)^2}{200*10^{-3}\cdot 2\cdot 9{,}81}=0{,}0008\,m$$

[6] L_1 is know from pipe length calculation later in this case study

Where:

$$f = \frac{0{,}079}{R_e^{1/4}} = \frac{0{,}079}{(77138{,}06)^{\frac{1}{4}}} = 4{,}74 \cdot 10^{-3} = 0{,}0047$$

Because:

$$R_e = \frac{V_2 \cdot d_{pipe}}{v}$$

$$= \frac{0{,}69 \cdot 200 \cdot 10^{-3}}{1.789 \cdot 10^{-6}} = 77138{,}06$$

Where:

$$V_2 = \frac{Q}{A}$$

$$= \frac{\frac{78}{3600}}{0{,}031} = 0{,}69[\frac{\mathrm{m}}{\mathrm{s}}]$$

Where:

$$A = \frac{\pi}{4} d_{\mathrm{pipe}}{}^2$$

$$= \frac{\pi}{4} \cdot (200 \cdot 10^{-3})^2 = 0{,}031\ \mathrm{m}^2$$

- Head loss due to pipe entrance

From Equation 2.10, we get the head loss at the pipe entrance

$$h_i = 0{,}5 \frac{V_2{}^2}{2g}$$

$$= 0{,}5 \frac{(0{,}69\ \ )^2}{2 \cdot 9{,}81} = 0{,}01\ \mathrm{m}$$

Putting the values into the energy equation:

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) + \sum h_l$$

$$10{,}322 + 0 + 0 = \frac{p_2}{1} + \frac{(0{,}69)^2}{2(9{,}81\ )} - 2 + 0{,}01\ + 0{,}0008$$

$$p_2 = 12{,}28\ \mathrm{m} = 1{,}2\ \mathrm{bar}$$

- Subtracting vapor pressure

Vapor pressure of water $P_v = 0{,}652\ \mathrm{kPa} = 652\ \mathrm{Pa} = 6{,}64\ \mathrm{m}$

$$\mathrm{NPSHa} = 12{,}28 - 6{,}64 = 5{,}6\ \mathrm{m} = 0{,}56\ \mathrm{bar}$$

$$\mathrm{NPSHa} > \mathrm{NPSHr}$$

$$5{,}6\ \mathrm{m} > \mathrm{NPSHr}$$

- Conclusion

To determine the NPSHr (Net Positive Suction Head Required) of the pump, one needs to consult the manufacturer to get the pump curve or datasheet provided by them. This value can change using different parameters that are outside the scope of this case study, such as frequency, voltage, number of phases, and speed of the motor. Therefore, NPSHr is left as a variable here.

Once the value of NPSHr is obtained, the comparison of Equation 2.6 must be made. If the value of NPSHr was greater than the calculated NPSHa, decreasing the value of z_2 will be the solution (manipulating the equation to increase NPSHa with other methods such as manipulating the flow rate is possible too).

- Using two pumping stations

Lower pumping station

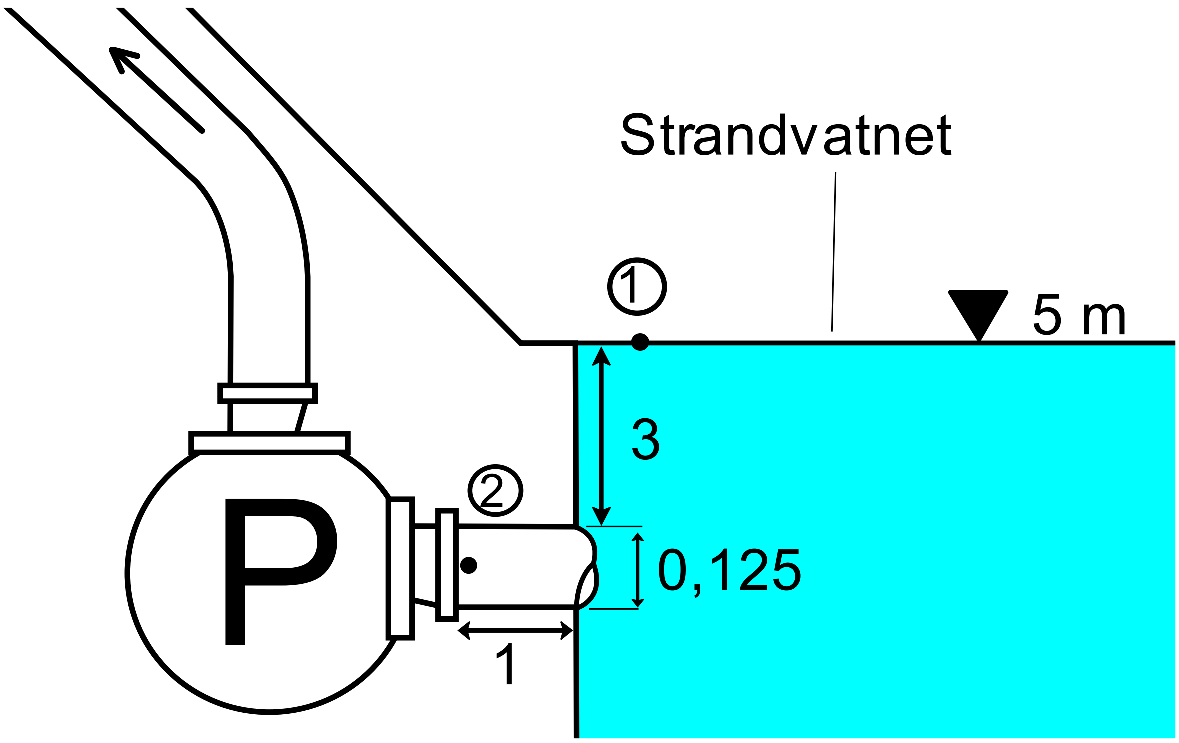


Figure 47 Detailed view of pipe's diameters at the lower pump

We solve this problem by subtracting vapor pressure from pump inlet pressure and using the energy equation[11, Ch. 14.5].

- Applying the energy equation between points 1 and 2

$$\left(\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2\right)+\sum h_l$$

Where:

Water velocity at the water surface is negligible $V_1=0$, $z_1=0$ m, $z_2=-2$ m.

- Atmospheric pressure in meters of head

$$\frac{P_1}{\gamma}=\frac{101260{,}47[\mathrm{Pa}]}{9810\left[\frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}^2}\right]}=\frac{10.32\mathrm{m}}{1\mathrm{m}}=10{,}32$$

Because $[\mathrm{Pa}]=[\frac{\mathrm{kg}}{\mathrm{ms}^2}][11,\mathrm{Tbl.\,F.\,1}]$.

- Friction head in the pipe

From Equation 2.8 we get the friction head:

$$h_f = \frac{f \cdot L_1 \cdot {V_2}^2}{d_{pipe} \cdot 2g}$$

$$= \frac{0{,}0041 \cdot 1 \cdot (1{,}8)^2}{125 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} = 0{,}0054\ m$$

Where:

$$f = \frac{0{,}079}{R_e^{1/4}} = \frac{0{,}079}{(77138{,}06)^{\frac{1}{4}}} = 4{,}19 \cdot 10^{-3} = 0{,}0041$$

Because:

$$R_e = \frac{V_2 \cdot d_{pipe}}{v}$$

$$= \frac{1{,}8 \cdot 125 \cdot 10^{-3}}{1.789\ \cdot\ 10^{-6}} = 125768{,}58$$

Where:

$$V_2 = \frac{Q}{A}$$

$$= \frac{\frac{78}{3600}}{0{,}012} = 1{,}8\ \frac{\mathrm{m}}{\mathrm{s}}$$

Where:

$$A = \frac{\pi}{4} {d_{\mathrm{pipe}}}^2$$

$$= \frac{\pi}{4} \cdot (125 \cdot 10^{-3}\mathrm{m})^2 = 0{,}012\ \mathrm{m}^2$$

- Head loss due to pipe entrance

From Equation 2.10, we get the head loss at the pipe entrance

$$h_i = 0{,}5 \frac{{V_2}^2}{2g}$$

$$= 0{,}5 \frac{(1{,}8\ )^2}{2 \cdot 9{,}81} = 0{,}08\ \mathrm{m}$$

Putting the values into the energy equation

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) + \sum h_l$$

$$10{,}322 + 0 + 0 = \frac{\mathrm{p}_2}{1} + \frac{(1{,}8)^2}{2(9{,}81\ )} - 2 + 0{,}08\ + 0{,}0054$$

$$p_2 = 12{,}07\ \mathrm{m} = 1{,}2\ \mathrm{bar}$$

- Subtracting vapor pressure

Vapor pressure of water $P_v = 0{,}652\ \mathrm{kPa} = 652\ \mathrm{Pa} = 6.64\ \mathrm{m}$

$$\mathrm{NPSHa} = 12{,}07 - 6{,}64 = 5{,}4\ \mathrm{m} = 0{,}54\ \mathrm{bar}$$

$$\mathrm{NPSHa} > \mathrm{NPSHr}$$

$$5{,}4 \text{ m} > \text{NPSHr}$$

- Conclusion

To determine the NPSHr (Net Positive Suction Head Required) of the pump, one needs to consult the manufacturer to get the pump curve or datasheet provided by them. This value can change using different parameters that are outside the scope of this case study, such as frequency, voltage, number of phases, and speed of the motor. Therefore, NPSHr is left as a variable here.

Once the value of NPSHr is obtained, the comparison of Equation 2.6 must be made. If the value of NPSHr was greater than the calculated NPSHa, decreasing the value of z_2 will be the solution (manipulating the equation to increase NPSHa with other methods such as manipulating the flow rate is possible too).

Higher pumping station

The higher pumping station can be located at varying elevations. Different elevations will require different NPSHa for the higher pump. And thus, the selection of both pumps will differentiate based on this NPSHa.

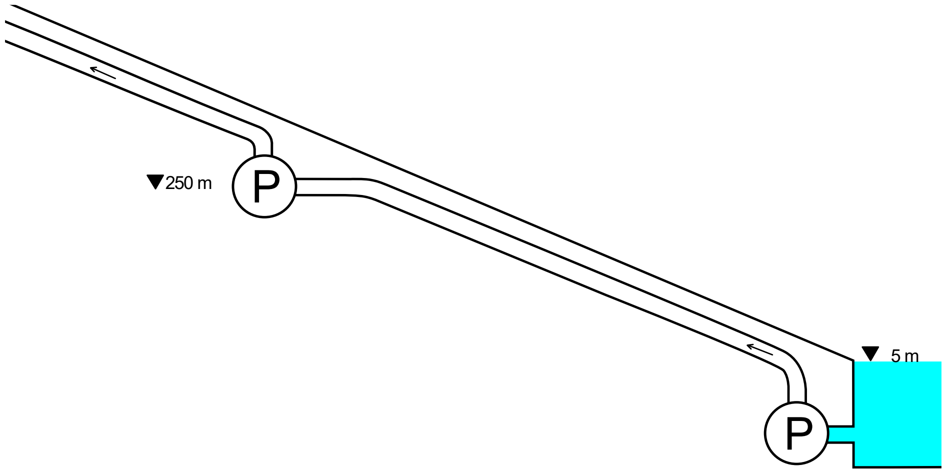


Figure 48 A simplified sketch showing layout locations and elevations of different pumping stations

Calculating NPSHa for this case is somehow different because the higher pump will draw water from the lower pump, and not from an open reservoir. To solve this issue, we simplify the model, we assume that the lower pump acts as an open reservoir that has an atmospheric pressure of 300 m. All other parameters will be taken as they were described before.

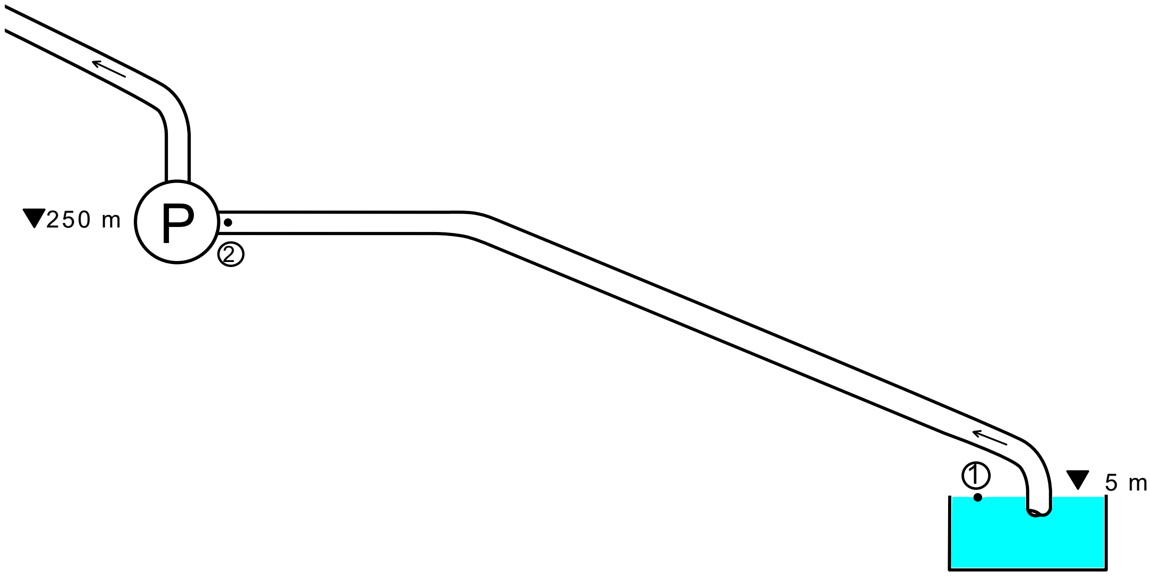


Figure 49 Assuming the lower pump as a reservoir

We solve this problem by subtracting vapor pressure from pump inlet pressure and using the energy equation[11, Ch. 14.5].

- Applying the energy equation between points 1 and 2

$$\left(\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2\right)+\sum h_l$$

Where:

Water velocity at the water surface is negligible $V_1 = 0$, $z_1 = 0$ m, $z_2 = 250 - 5 = 245$ m.

- Atmospheric pressure in meters of head

$$P_1 = 300 \text{ m}$$

- Friction head in the pipe

From Equation 2.8 we get the friction head

$$h_f = \frac{f \cdot L_1 \cdot {V_2}^2}{d_{pipe} \cdot 2g}$$

$$= \frac{0{,}0041 \cdot 567{,}368 \cdot (1{,}8)^2}{125 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} = 3{,}07\ m$$

Where:

$$f = \frac{0{,}079}{R_e^{1/4}} = \frac{0{,}079}{(77138{,}06)^{\frac{1}{4}}} = 4{,}19 \cdot 10^{-3} = 0{,}0041$$

Because:

$$R_e = \frac{V_2 \cdot d_{pipe}}{v}$$

$$= \frac{1{,}8 \cdot 125 \cdot 10^{-3}}{1{,}789 \cdot 10^{-6}} = 125768{,}58$$

Where

$$V_2 = \frac{Q}{A}$$

$$= \frac{\frac{78}{3600}}{0{,}012} = 1{,}8\ \frac{\text{m}}{\text{s}}$$

Where

$$A = \frac{\pi}{4} d_{\text{pipe}}{}^2$$

$$= \frac{\pi}{4} \cdot (125 \cdot 10^{-3})^2 = 0{,}012\ \text{m}^2$$

- Head loss due to pipe entrance

From Equation 2.10, we get the head loss at the pipe entrance:

$$h_i = 0{,}5 \frac{V_2{}^2}{2g}$$

$$= 0{,}5 \frac{(1{,}8\ )^2}{2 \cdot 9{,}81} = 0{,}08\ \text{m}$$

Putting the values into the energy equation:

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) + \sum h_l$$

$$300 + 0 + 0 = \frac{p_2}{1} + \frac{(1{,}8)^2}{2(9{,}81\ )} + 245 + 0{,}08\ + 3{,}07$$

$$p_2\ = 51{,}68\ \text{m} = 5{,}68\ \text{bar}$$

- Subtracting vapor pressure

Vapor pressure of water $P_v\ = 0{,}652\ \text{kPa} = 652\ \text{Pa} = 6.64\ \text{m}$

$$\text{NPSHa} = 51{,}68\ - 6{,}64 = 45{,}04\ \text{m} = 4{,}5\ \text{bar}$$

$$\text{NPSHa} > \text{NPSHr}$$

$$45{,}04\ \text{m} > \text{NPSHr}$$

- Conclusion

To determine the NPSHr (Net Positive Suction Head Required) of the pump, one needs to consult the manufacturer to get the pump curve or datasheet provided by them. This value can change using different parameters that are outside the scope of this case study, such as frequency, voltage, number of phases, and speed of the motor. Therefore, NPSHr is left as a variable here.

Once the value of NPSHr is obtained, the comparison of Equation 2.6 must be made. If the value of NPSHr was greater than the calculated, decreasing the value of z_2 will be the solution (manipulating the equation to increase NPSHa with other methods such as manipulating the flow rate is possible too).

1.1.6 Pipes selection

1.1.6.1 Using one pumping station

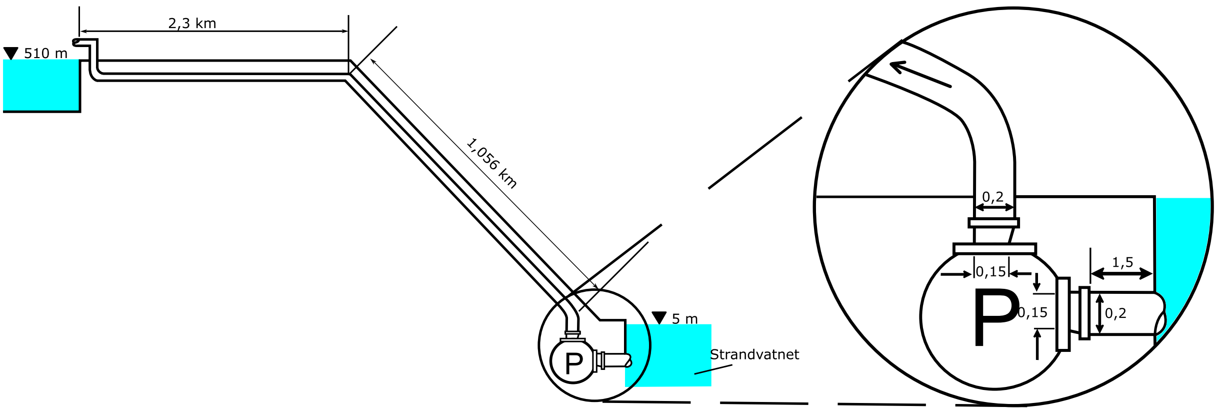


Figure 50 Dimensions for pumping station (in meters, unless otherwise stated)

- Suction pipe length

Using recommendations for pipes selection in Section 2.3.2.3, we find the length of the suction pipe:

$$L_1 = 10d_{\text{pump}} = 10 \cdot 0{,}15 \text{ m} = 1{,}5 \text{ m}$$

- Pipe diameter

Recommendations advise using a suction pipe one size larger than the inlet nozzle which is $d_{\text{pump}} = 150$ mm., then we select the pipe diameter (ID) $d_{\text{pipe}} = 200$ mm both for the suction and discharge pipe. Of course, for this change in diameter, we need to use an eccentric reducer at the pump's inlet from 200 to 150 mm and an eccentric increaser from 150 to 200 mm as discussed in Section 2.3.2.2.

- Discharge pipe length

In Section 2.3.2.2 we find that different configurations for discharge pipes can be found, the final decision of this arrangement is influenced by other factors that are not included in this case study, such as topology in the geology of the Niingen mountain. Assuming we choose that the discharge pipe length will be approximately the same as the length of the penstock and head race tunnel before the moving of the inlet in 2003.

$$L_2 = 2{,}3 + 1{,}056 = 3{,}356 \text{ km}$$

- Material

The material for pipes in Niingen Mountain should be

  - Thermal insulator
  - Not expensive

Generating a chart for price against thermal conductivity in Ansys Granta Edupack, followed by a chart for yield strength against price, filtering the prices to maximumly 8 NOK/kg, we find that steel materials offer the requirements needed. Especially since steel material is used in the penstock pipeline in the Niingen power station and recommendations in Section 2.3.2.2.

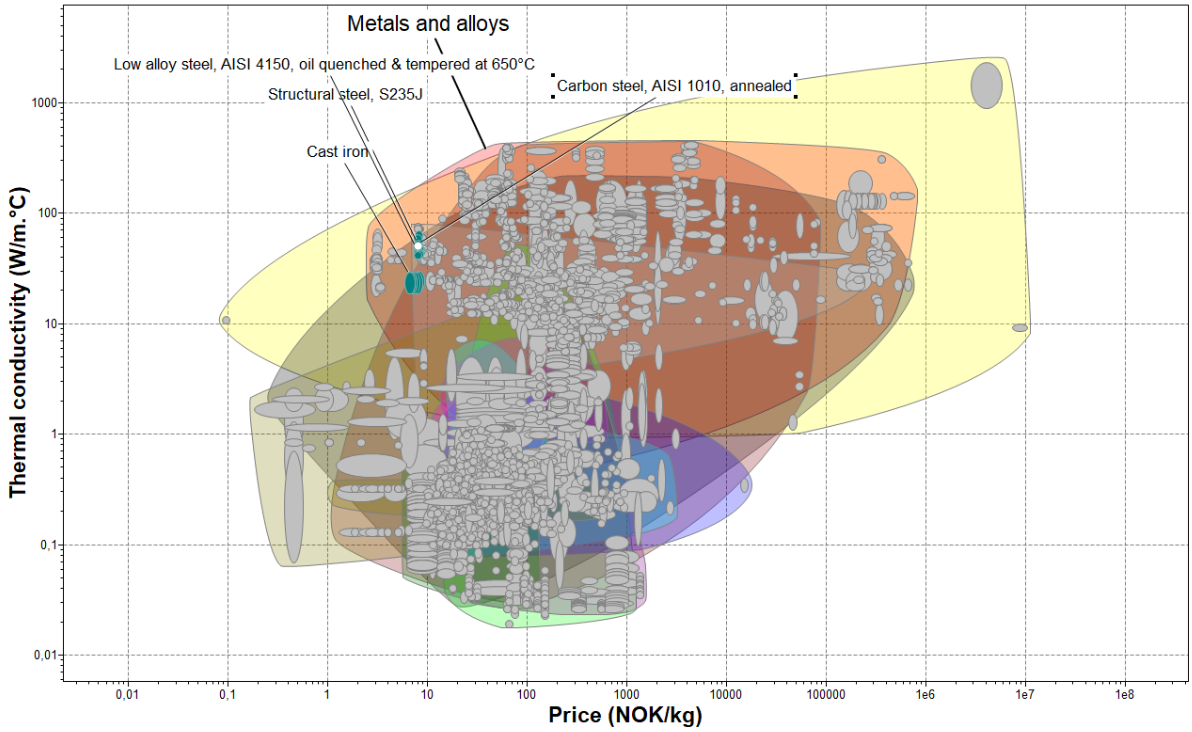


Figure 51 Optimized materials in the generated chart for thermal conductivity against price in Granta Edupack [54]

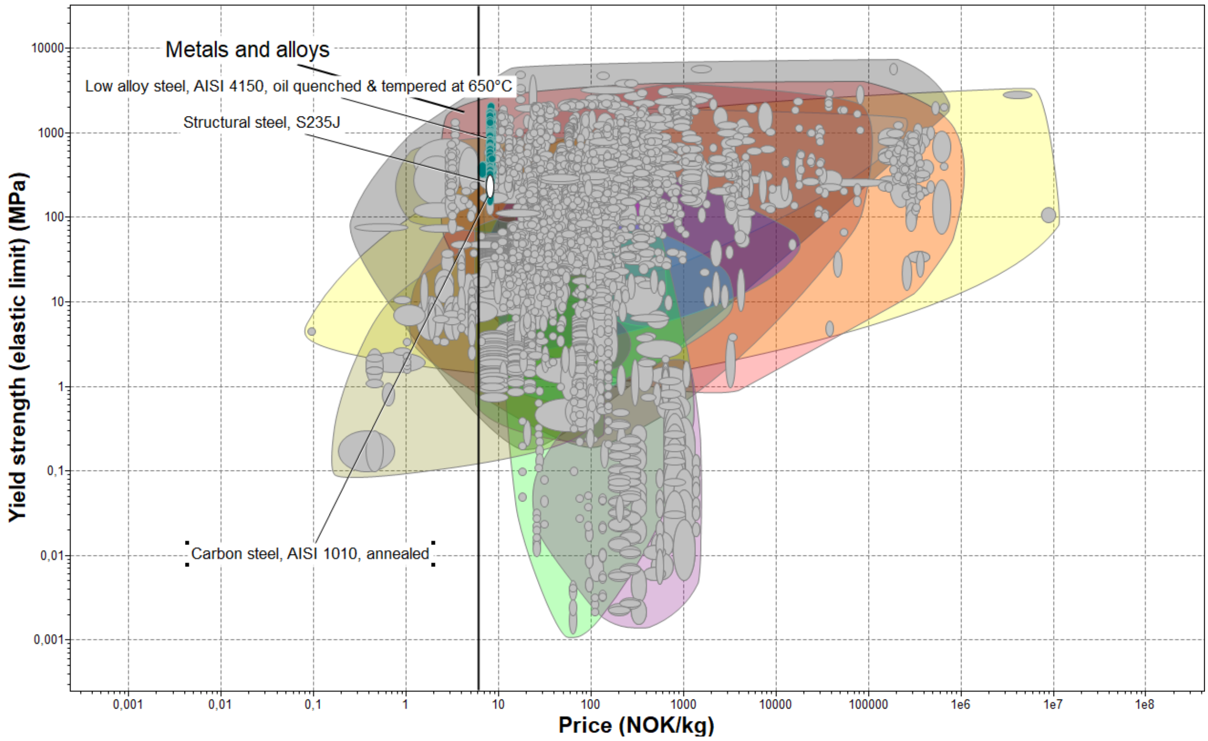


Figure 52 Optimized materials in the generated chart for yield strength against price in Granta Edupack [60]

Min. properties / Material's name	Price [Nok/ kg]	Density $10^3 *$ [kg/ m^3]	Yield strength σ_y[Mpa], [ksi]	Tensile strength σ [Mpa], [ksi]	Toughness G [kJ/m^2]	Fracture toughness [$Mpa.m^{0,5}$]	Thermal conductivit y [W/m. °C]	Comments
Low alloy steel AISI	7,89	7,8	755, 109,5	860, 124,7	10,3	45	40	Low thermal conductivity but

4150, oil quenched & tempered at 650°C								unnecessarily strong and not included in the tables of ASME B31.1
Structural steel, S235J	7,46	7,81	235, 34	360, 52.2	9,93	45,5	40	Offers more optimized properties for less price, but not included in the tables of ASME B31.1
Carbon steel, AISI 1010, annealed	7.47	7.8	172, 24,9	310, 44,9	9.21	43	50	Offers similar properties to structural steel and is included in the tables of ASME B31.1

Table 23 Material properties for pipes [54]

Carbon steel is the material that will be chosen for all pipes in this document.

- Wall thickness

From ASME-B31.1 we get the equation for wall thickness[55, Ch. 104.1]:

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$

Where

P = 999899,7 Pa = 999,89~1000 kPa which is the water hammer pressure that will be studied later in this appendix.

d = 200 mm

S = 7,7 ksi = 53089,63 kPa (Using 25 and 45 in yield and tensile strengths respectively. From table A-1 choosing Furnace Butt Welded Pipe API 5L at -15 °C)

E = 0,60

y = 0,4

A = 25 mm

$$t_m = \frac{1000 \cdot 200 + 2 \cdot 53089{,}63 \cdot 0{,}60 \cdot 25 + 2 \cdot 0{,}4 \cdot 1000 \cdot 25}{2(53089{,}63 \cdot 0{,}60 + 1000 \cdot 0{,}4 - 1000)} = 28{,}99 \sim 29 \text{ mm}$$

Which is the maximum diameter that is calculated considering safety against water hammer. The pipe's diameter can be decreased with elevation as the water hammer pressure decreases with the shorter pipe length. So, lowering the water hammer pressure P will lower the thickness of the pipe and subsequently the diameter.

1.1.6.2 Using two pumps

❖ **Lower pump**

- Suction pipe length

Using recommendations for pipes selection in Section 2.3.2.3, we find here also that the length of the suction pipe:

$$L_1 = 10d_{\text{pump}} = 10 \cdot 0{,}1 \text{ m} = 1 \text{ m}$$

- Pipe diameter

Recommendations advise using a suction pipe one size larger than the inlet nozzle which is d_{pump} = 100 mm, then we select the pipe diameter (ID) d_{pipe} = 125 mm both for the suction and discharge pipe. For this change in diameter, we need to use an eccentric reducer at the pump's inlet from 125 to 100 mm and an eccentric increaser from 100 to 125 mm as discussed in Section 2.3.2.3.

- Discharge pipe length

Like the pipe selection in the one pump case; in Section 2.3.2.3we find that different configurations for discharge pipe can be found, the final decision of this arrangement is influenced by other factors that are not included in this case study, such as topology and geology of the Niingen mountain. Assuming we choose the pipe length of $L_2 = 567{,}368$ m where at its higher end meets the higher pumping station.

- Wall thickness

From ASME-B31.1 we get the equation for wall thickness[55, Ch. 104.1]:

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$

Where

$P = 52$ Pa $= 0{,}052$ kPa which is the water hammer pressure that will be studied later in this appendix.

$d = 125$ mm

$S = 7{,}7$ ksi $= 53089{,}63$ kPa (Using 25 and 45 in yield and tensile strengths respectively. From table A-1 choosing Furnace Butt Welded Pipe API 5L at -15 °C)

$E = 0{,}60$

$y = 0{,}4$

$A = 25$ mm

$$t_m = \frac{0{,}052 \cdot 125 + 2 \cdot 53089{,}63 \cdot 0{,}60 \cdot 25 + 2 \cdot 0{,}4 \cdot 0{,}052 \cdot 25}{2(53089{,}63 \cdot 0{,}60 + 0{,}052 \cdot 0{,}4 - 0{,}052)} = 25 \text{ mm}$$

Which is the maximum diameter that is calculated considering safety against water hammer.

- Material

"Carbon steel, AISI 1010, annealed" was chosen.

❖ **Higher pump**

- Suction pipe length

The suction pipe for the higher pump is the discharge pipe for the lower pump. Therefore, we find that the length of the suction pipe is:

$$L_1 = 567{,}368 \text{ m}$$

- Pipe diameter

Recommendations advise using a suction pipe at least one size larger than the inlet nozzle, which is 80 mm, it is possible to select the pipe diameter (ID) of 90 mm, but the suction pipe for the higher pump is the discharge pipe for the lower pump which is selected to be (ID) 125 mm. Therefore, we select (ID) 125 mm both for the suction and discharge pipe in the higher pump. This way, we have the same pipe diameter along the pipeline which is selected to be (ID) 125 mm, except for the inlets/outlets for pumps.

- Discharge pipe length

The length of the discharge pipe length is the length of the penstock is:

$$L_2 = 3356 - 567{,}368 = 2788{,}632 \text{ m}$$

- Wall thickness

From ASME-B31.1 we get the equation for wall thickness[55, Ch. 104.1]:

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$

Where

$P = 2608434$ Pa $= 2608{,}43$ kPa which is the water hammer pressure that will be studied later in this appendix.

$d = 125$ mm

$S = 7{,}7$ ksi $= 53089{,}63$ kPa (Using 25 and 45 in yield and tensile strengths respectively. From table A-1 choose Furnace Butt Welded Pipe API 5L at -15 $°C$).

$E = 0{,}60$

$y = 0{,}4$

$A = 25$ mm

$$t_m = \frac{2608{,}43 \cdot 125 + 2 \cdot 53089{,}63 * 0{,}60 \cdot 25 + 2 \cdot 0{,}4 \cdot 2608{,}43 \cdot 25}{2(53089{,}63 \cdot 0{,}60 + 2608{,}43 \cdot 0{,}4 - 2608{,}43)} = 32{,}53 \text{ mm}$$

Which is the maximum diameter that is calculated considering safety against water hammer. The pipe's diameter can be decreased with elevation as the water hammer pressure decreases with the shorter pipe length. So, lowering the water hammer pressure P will lower the thickness of the pipe and subsequently the diameter.

- Material

"Carbon steel, AISI 1010, annealed" was chosen.

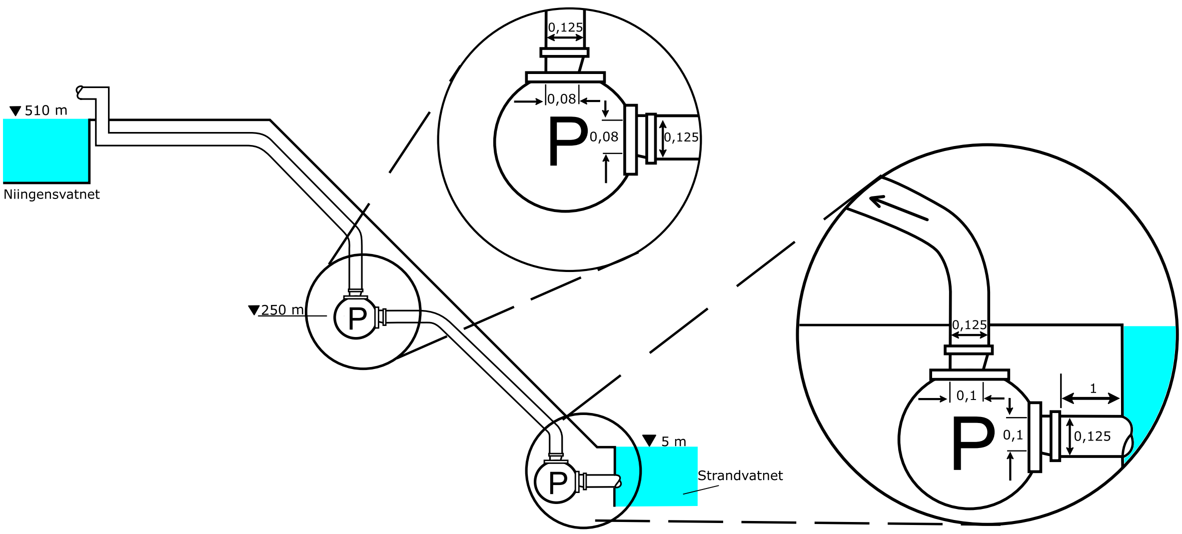


Figure 53 Detailed views of pipes dimensions at the lower and higher pump

1.1.7 Other calculations and recommendations of case study A

❖ Underground and overground pipeline

In Section 2.3.2.1 the trenched pipelines plan was recommended as it helps overcome the problem of icing in pipes. Note that pipes must either have an active flow or be empty, but not have stationary fluid as this will be a reason for internal icing.

❖ Separate and joined pipeline

As discussed in Section 2.3.2.1, joined pipelines are not economically feasible for the cases in this thesis.

1.1.7.1 Matching Pumps to System Demand

In Section 2.1.3 we found that the available total head must overcome the required total head (resistance) for the water to be pumped.

$$h_a > h_r$$

- Using one pump

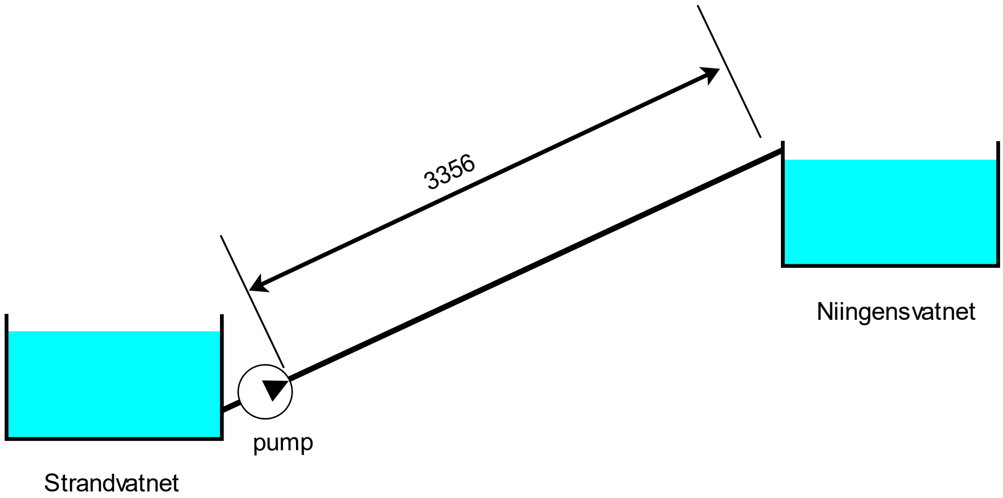


Figure 54 Understanding total pipe length between Strandvatnet and Niingensvatnet using one pump

h_a is the available head at the pump's discharge outlet in addition to the static head provided by the lower reservoir.

$$h_a = 550 + 3 = 553 \text{ m}$$

$$h_r = h_l + h_s$$

Assuming that minor head losses due to bending and fittings etc. are negligible, the head loss is friction only.

$$h_r = (\frac{f \cdot L_2 \cdot V^2}{d_{\text{pipe}} \cdot 2g}) + (505\ )$$

$$= \frac{0{,}0047 \cdot 3356 \cdot 0{,}69^2}{200 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} + 505 = 506{,}91 \text{ m}$$

$$553 \text{ m} > 506{,}91 \text{ m}$$

Which is accepted.

- Using two pumps

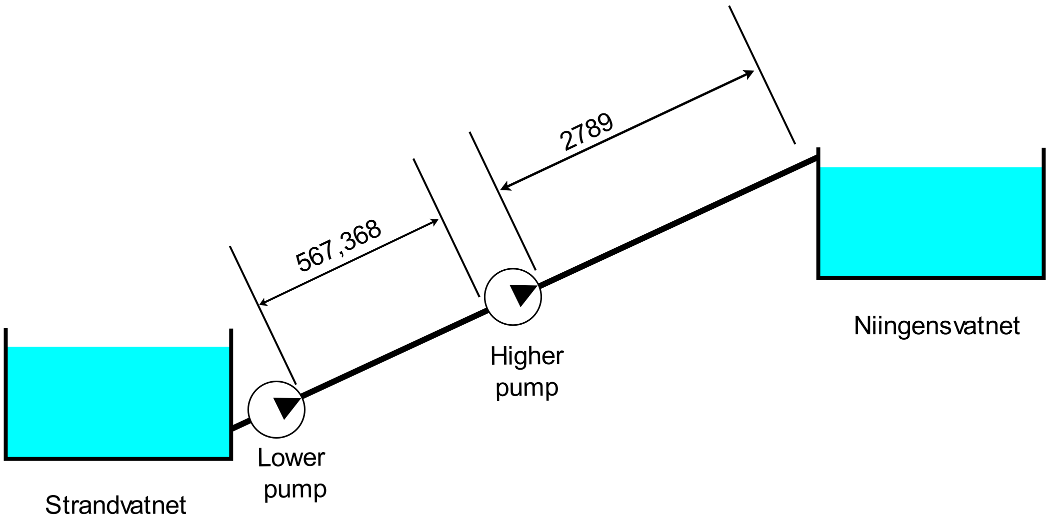


Figure 55 Understanding pipe length between Niingensvatnet and Strandvatnet using two pumps

From Section 2.1.3 we know the available total head provided by the two pumps connected in series is the sum of the heads of the two pumps in addition to the static head provided by the lower reservoir, minus the required suction head from the higher pump.

$$h_a = H_T = (H_1 + z) + (H_2 - \mathrm{NPSHr}_{\mathrm{Higher}})$$

$$= 300 + 250 + 3 - \mathrm{NPSHr}_{\mathrm{Higher}} = 553 - \mathrm{NPSHr}_{\mathrm{Higher}}$$

While H_1 and H_2 are knowns, $\mathrm{NPSHr}_{\mathrm{Higher}}$ is to be obtained from the supplier, therefore is left as a variable here.

$$h_r = h_l + h_s$$

Assuming that minor head losses due to bending and fittings etc. are negligible, the head loss is friction only.

$$h_r = h_{f1} + h_{f2} + h_s$$

$$= \left(\frac{f \cdot L_{\mathrm{pipe1}} \cdot V^2}{d_{\mathrm{pipe1}} \cdot 2g}\right) + \left(\frac{f \cdot L_{\mathrm{pipe2}} \cdot V^2}{d_{\mathrm{pipe2}} \cdot 2g}\right) + h_s$$

$$d_{\mathrm{pipe1}} = d_{\mathrm{pipe2}} = 125\ [mm]$$

$$= (L_{\mathrm{pipe1}} + L_{\mathrm{pipe2}})\left(\frac{f \cdot V^2}{d_{\mathrm{pipe}} \cdot 2g}\right) + h_s$$

$$= 3356 \cdot \frac{0{,}0047 \cdot 0{,}69^2}{200 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} + 505 = 506{,}91\ \mathrm{m}$$

$$553 - \mathrm{NPSHr}_{\mathrm{Higher}} > 506{,}91\ \mathrm{m}$$

1.1.7.2 Water hammer

Water hammers can have many scenarios. The one we study in this case assumes having the pump at the first end of the pipe, followed by a valve that closes after an amount of water has been pumped towards Niingensvatnet.

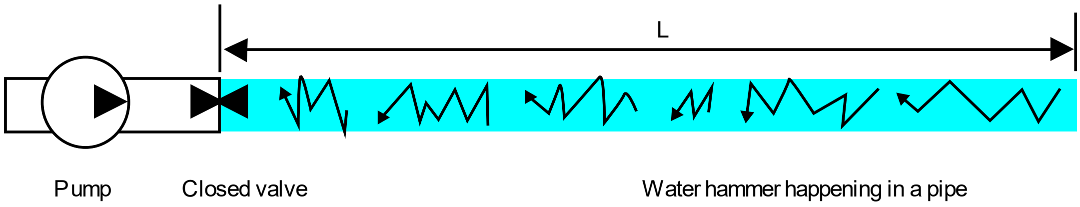


Figure 56 Water hammer in a pipe

Using two seconds as time for closing the valve and recalling equations from Section 2.3.2.4.

- **Using one pump**

We consider the valve closure to be gradual if:

$$T > \frac{2L}{C}$$

We consider the valve closure to be sudden because:

$$T < \frac{2L}{C}$$

$$2 < \frac{2 \cdot 3356}{1449,13}$$

$$2 < 4,63$$

The closing time has to be greater than 4,63 [sec] to be considered gradual.

- Sudden closure of the valve

$$P = \rho V C$$

$$= 1449,13 \cdot 0,69 \cdot 1000 = 999899,7 \ \frac{\mathrm{N}}{\mathrm{m}^2} = 999899,7 \ \mathrm{Pa} = 101,98 \ \mathrm{m} = 10,1 \ \mathrm{bar}$$

- Conclusion

We can see that the result of pressure surge is very high in this case and will lead to a rupture in pipes. Although it is unrealistic to have a distance of 4356 m without safety measures, segments, or other valves, this case shows the damaging effect of a water hammer in case it happens.

- **Using two pumps**
  - Lower pipeline

Using two seconds as time for closing the valve, we consider the valve closure to be gradual if:

$$T > \frac{2L}{C}$$

$$2 > \frac{2 \cdot 567,368}{1449,13}$$

$$2 > 0,78$$

- Gradual closure of the valve

$$P = \frac{LV}{gT}$$

$$= \frac{567{,}368 \cdot 1{,}8}{9{,}81 \cdot 2} = 52 \text{ Pa} = 0{,}005 \text{ m}$$

- Higher pipeline

Using two seconds as time for closing the valve, we consider the valve closure to be sudden if:

$$T < \frac{2L}{C}$$

$$2 < \frac{2 \cdot 2788{,}63}{1449{,}13}$$

$$2 < 3{,}84$$

The valve closure time must be higher than 3,84 to be considered gradual.

- Sudden closure of the valve

$$P = \rho VC$$

$$= 1449{,}13 \cdot 1{,}8 \cdot 1000 = 2608434 \text{ Pa} = 266{,}05 \text{ m} = 26{,}6 \text{ bar}$$

- Conclusion

We find from this section the importance of lowering the distance L on the value of water hammer pressure and the importance of putting an adequate number of valves in the pipes to lower the damage in case it happens.

1.1.8 Financial calculations

1.1.8.1 Energy storage in the higher reservoir

It has been explained in this appendix that the daily plan is proposed to be used in this case. Meaning 72 hours of pumping will occur every week if this plan was to be followed strictly. It was also found that the volume of water that will be pumped in each of these cycles of 72 hours equals:

$$V = Q \cdot t = 78 \cdot 72 = 5616 \text{ m}^3 \text{ per one cycle}$$

Putting pumping time to be a complete year (four cycles a month, each of 72 hours, for 12 months) we get 3456 hours of pumping:

$$V = Q \cdot t = 78 \cdot 3456 = 269568 \text{ m}^3 \text{ per year}$$

Putting V in the Equation 3.1 to get the amount of energy in this volume of pumped water:

$$E = 2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g h V [\text{kWh}]$$

$$= 2{,}77 \cdot 10^{-7} \cdot 0{,}95 \cdot 1000 \cdot 9{,}81 \cdot 510 \cdot 269568 = 354904 \text{ kWh} = 354{,}9 \text{ MWh}$$

1.1.8.2 Price per potential energy unit

Assuming that the high power price is 1000 NOK/MWh, from Equation 3.2 we get the financial value of pumped water:

$$\text{Yearly expected revenue} = E \cdot \text{high power price}$$

$$= 354{,}9 \cdot 1000 = 354904 \text{ NOK}$$

1.1.8.3 Cost estimations of the project

- Capital investment

The total capital investment is given by:

$$C_{\mathrm{Aca}} = C_{\mathrm{pump}} + C_{\mathrm{pipe}} + C_{\mathrm{dam}} + C_{\mathrm{tre}}$$

$$= 0{,}25 \cdot 10^6 + 6{,}87 \cdot 10^6 + 0{,}468 \cdot 10^6 + 18{,}98 \cdot 10^6 = 26{,}56 \cdot 10^6 \text{ NOK}$$

This value is based on the costs list below.

- Mechanical and electrical costs
  - Pumps costs

The price of one pump when using only one pump is estimated to be the same as the total price of two pumps, only the difference between both cases will be longer life for the case of two pumps and lower wear and tear.

$$C_{\mathrm{pump}} = C_{\mathrm{pump1}} + C_{\mathrm{pump2}} = 250000 = 0{,}25 \cdot 10^6 \text{ NOK}$$

  - Pipes costs

The length of discharge pipes in both cases of this case study (with only one or with two pumps) was set to be the same and equal to $L_2 = 3{,}356$ km.

NVE's guideline "Cost base for hydropower plants for generating capacity of less than 10000 kW" (Kostnadsgrunnlag for små vannkraftanlegg (< 10 MW)) has estimations for pipe costs including their installations[56, No. 2016/40]. Reading FIG.4.6.3 in the mentioned reference, we find that for the pressure head of 510 m, and diameter of 200 to 150 mm, the average pipe price is 1500 NOK/m. Since this price estimate was made based on market prices from 2015, NVE publishes a yearly report including updates to the cost developments of water hydropower projects [57] The updates from 2016 to 2023 show that mechanical costs have increased by 36,5%, causing the average pipe price to be 2047,5 Nok/m.

$$C_{\mathrm{pipe}} = 2047{,}5 \cdot 3356 = 6871410 = 6{,}87 \cdot 10^6 \text{ NOK}$$

  - Power lines

Since the location of the lower pumps is set to be near the power station at Strandvatnet, the power line for the pump will be easily available and therefore its cost is negligible. Apart from this, if two pumps were employed, the higher pump at 250 m elevation needs an extension of a powerline. Based on market research, since that NVE's guidelines have no cost estimation for power lines that are medium or small voltages, costs for power line of 5000-8000 kV is set to $4 \cdot 10^4$ NOK/km. For the higher pumping stations at the length of 250 m, assuming the power line's length to be approximately the same as suction pipe's length, which is 0,567 km. Therefore,

$$C_{\mathrm{line}} = 4 \cdot 10^4 \cdot 0{,}567 = 22680 \text{ NOK}$$

Since 22680 NOK is relatively small when compared to other costs, it can be negligible.

- Civil engineering costs
  - Dam construction and pumping chamber

For this project, dams must be built at reservoir outlets to control outflow and water levels. The pumping chamber has to be included in the dam construction, which is assumed to be a concrete gravity dam of five meters in height and 5 consecutive meters in width. Reading through NVE's estimation for dams, specifically FIG. 2.2.2[56, No. 2016/40], we notice that concrete dams cost 68000 NOK/consecutive meter, including price growth from 2015 to 2023 which NVE suggests that it is equal to 37,94 [57] we get that the up-to-date price is 93772 NOK/consecutive meter.

$$C_{\mathrm{dam}} = 5 \cdot 93772 = 468860 = 0{,}468 \cdot 10^6 \text{ NOK}$$

  - Pipe trenches

As discussed earlier in this appendix, trenched pipes are recommended for case study A along the whole discharge pipe. Reading through NVE's cost base for small-scale hydropower plants, especially chapter 2.5.2: Pipe trenches [56, No. 2016/40] we find that for a 1,5 m trench width at the bottom and 3,0 m depth, for a 3356 m length of combined earth/rock trench, the cost is set to 4160 Nok/m. No information included in the reports of NVE about the price development of trenches since 2015, so this value is assumed to be 36%, which is similar to the price development in concrete dams (37,9%) and mechanical costs (36,5%). The updated cost will be 5657,6 NOK/m.

$$C_{\mathrm{tre}} = 5657{,}6 \cdot 3356 = 18986905{,}6 = 18{,}98 \cdot 10^6 \text{ NOK}$$

- Operational costs
  - Maintenance and personnel costs

From Section 3.4.2 we follow IRENA's estimation for yearly personnel and maintenance costs, which is estimated to be around 3% of the total investment cost.

$$C_{\mathrm{ma}} + C_{\mathrm{per}} = 3\% C_{\mathrm{A}} = 0{,}03 \cdot 26{,}56 \cdot 10^6 = 0{,}7968 \cdot 10^6 \text{ NOK}$$

  - Pump power consumption

The pump's power consumption must be also added to the operational costs. Section 1.1.5.2 in this appendix shows how values for power were calculated. Using the daily plan, a pump works constantly for 72 hours a week, meaning that in the span of a year, it works $72 \cdot 4 \cdot 12 = 3456$ h.

To convert Megawatts to Megawatt hours one can multiply by the number of operation hours to get a yearly energy consumption.

The low power price is assumed to be 500 Nok/MWh.

- Using one pump

$$C_{\mathrm{power}} = P \cdot \text{hours per year} \cdot \text{low power price}$$

$$= 0{,}114 \cdot 3456 \cdot 500 = 197164{,}8 = 0{,}1971648 \cdot 10^6 \text{ NOK}$$

Annual operational costs will be:

$$C_{\mathrm{Aop}} = (C_{\mathrm{ma}} + C_{\mathrm{per}}) + C_{\mathrm{power}} = 0{,}7968 \cdot 10^6 + 0{,}1971648 \cdot 10^6 = 0{,}9938 \cdot 10^6 \text{ NOK}$$

- Using two pumps

$$C_{\mathrm{power}} = (P_1 + P_2) \cdot \text{hours per year} \cdot \text{low power price}$$

$$= (0{,}123) \cdot 3456 \cdot 500 = 212632{,}12 = 0{,}212 \cdot 10^6 \text{ NOK}$$

Annual operational costs will be:

$$C_{\mathrm{Aop}} = (C_{\mathrm{ma}} + C_{\mathrm{per}}) + C_{\mathrm{power}} = 0{,}7968 \cdot 10^6 + 0{,}212 \cdot 10^6 = 1{,}008 \cdot 10^6 \text{ NOK}$$

Since the difference in annual operational costs is small between the two cases, the larger value will be used in the cost calculation.

- Negligible or not considered costs:

As discussed in Section 3.4, the costs for valves, fittings, seals, and supports, as well as for taxes, land acquisition, transports, electro-technical equipment, and power lines, are not included in this study as they are either minimal or/and vary from project to project based on topology and geology of the region.

1.1.9 Conclusion of case study A

Capital investment cost [NOK]	$26{,}56 \cdot 10^6$
Yearly operational costs [NOK]	$1{,}008 \cdot 10^6$
Yearly expected revenue [NOK]	$0{,}35 \cdot 10^6$

Table 24 Comparison between costs and revenue of case A

Comparing capital investment costs to the expected revenue and operational costs, we find that the initial and operational costs of this project are much larger than the expected revenue.

$$\text{Economic feasibility} = \text{Yearly expected revenue} - \text{Yearly opertaional costs}$$

$$= 0{,}35 \cdot 10^6 - 1{,}008 \cdot 10^6 = -658000\ \text{NOK}$$

We see from the previous equation that a yearly loss of 658000 NOK will occur if this case study was applied using the values as they are. The reasons for these results are the large costs for power consumption since the head value is very high (510 m), as well as flow rate, and, consequently, water volume $V_{\max}$ that is to be pumped and turned to profit later. Let alone the high capital investment budget.

However, the low profitability can be solved by increasing the flow rate to higher values that it generates profit. For example, using the Excel document that is attached to this file, we can manipulate different values that affect economic feasibility and see how results change. The following chart shows the increase in economic feasibility with the increase in flow rate.

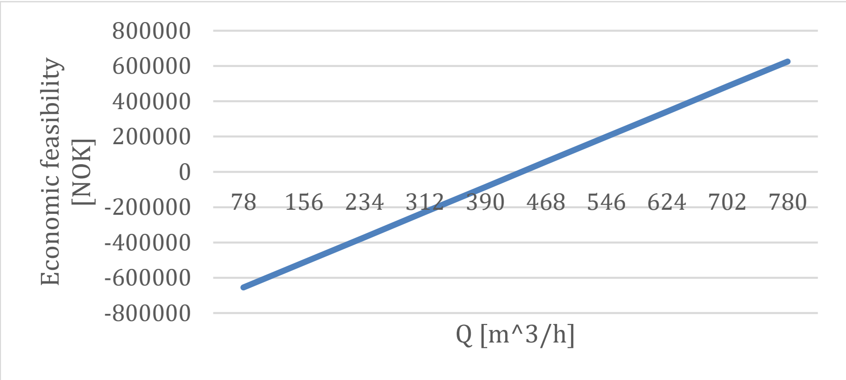


Figure 57

The chart shows that the project will turn out to be profitable only when the flow rate reaches the value of approx. 450 m^3/h, and by increasing the flow rate up to 780 m^3/h, the increase in yearly revenue reached 625329,786 NOK/year. Still, this yearly income is considered low compared to the capital investment cost of $26{,}56 \cdot 10^6$ NOK, meaning at this flowrate value the project will take 44,26 years to retain its capital investment value.

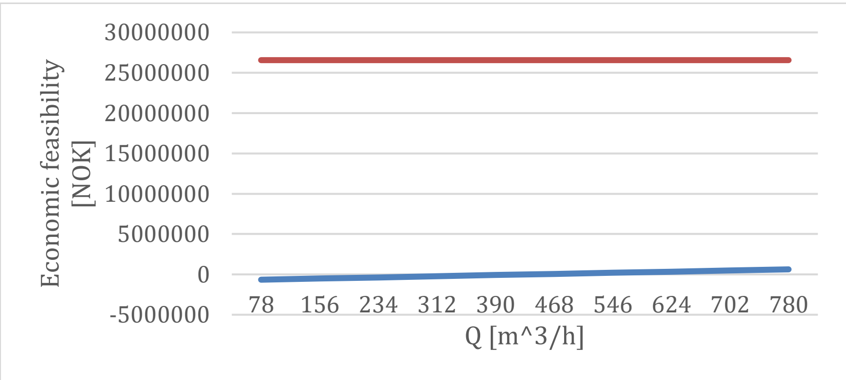


Figure 58 A chart showing the large gap between capital investment and yearly revenue in case study A

Nevertheless, it is necessary to remember that the key purposes of this project are not profit-making only, but many other benefits on the grid system such as load balance and stability of power generating. But since the capital investment and yearly operational costs largely exceed the yearly expected revenue, case A of this project, pumping from Strandvatnet to Niingensvatnet is considered to be uninteresting.

Moreover, to address the uncertainty in power prices, we define the price difference index, which is the result of dividing the high to low power prices. Generating the following table that compares the different effects of high and low power prices on economic feasibility, shows that, at flowrates of 480 and 780 m^3/h, and for different changes in prices the project is most profitable in two cases: one at an index value of greater than 5, and another at high power price greater than 1000 NOK. Otherwise, the table no signs of cost-effectiveness in this project which decreases its relevance as a pumped storage plant in the Niingen power plant.

At 480 m^3/h				At 780 m^3/h			
Low price [NOK]	High price [NOK]	Economic feasibility [NOK]	Index	Low price [NOK]	High price [NOK]	Economic feasibility [NOK]	Index
50	100	-709767,8801	2	50	100	-655050,763	2
50	150	-600566,6492	3	50	150	-477598,763	3
50	200	-491365,4184	4	50	200	-300146,762	4
50	300	-272962,9568	6	50	300	54757,2377	6
50	400	-54560,49519	8	50	400	409661,238	8
50	500	163841,9664	10	50	500	764565,238	10
75	100	-775195,4169	1,333333	75	100	-761370,51	1,333333
75	150	-665994,1861	2	75	150	-583918,51	2
75	200	-556792,9553	2,666667	75	200	-406466,51	2,666667
75	300	-338390,4937	4	75	300	-51562,5097	4
75	400	-119988,032	5,333333	75	400	303341,49	5,333333
75	500	98414,4296	6,666667	75	500	658245,491	6,666667
100	150	-731421,7229	1,5	100	150	-690238,257	1,5
100	200	-622220,4921	2	100	200	-512786,257	2
100	300	-403818,0305	3	100	300	-157882,257	3
100	400	-185415,5689	4	100	400	197021,743	4
100	500	32986,89275	5	100	500	551925,743	5
500	800	-358646,3118	1,6	500	800	-84478,2143	1,6
500	900	-140243,8502	1,8	500	900	270425,786	1,8
500	1000	78158,6114	2	500	1000	625329,786	2
600	1000	-183551,536	1,666667	600	1000	200050,797	1,666667
750	1000	-576116,757	1,333333	750	1000	-437867,688	1,333333
800	1000	-706971,8307	1,25	800	1000	-650507,182	1,25

Table 25 Economic feasibility in different power prices.

1.2 Case study B: Pumping from Buvatnet

This case study aims to give an example of how to use the equations of this document in a realistic situation.

1.2.1 Circumstances of this case study

Water temperature [°C]	0
Average weather temperature [°C]	-5
Kinematic viscosity [m^2/s]	$1.789 \cdot 10^{-6}$
The specific weight of water γ [$kg/m * s^2$]	9810
Vapor pressure of water P_v [kPa]	0,652
Atmospheric pressure [Pa]	101260,47
Density [kg/m^3]	1000
Gravitational acceleration [m/s^2]	9,81
Specific gravity, dimensionless	1
Bulk modulus [N/m^3]	$2{,}1 \cdot 10^9$
The velocity of pressure wave [m/s]	1449,13

Table 26 Circumstances of this case study (assumed to be constant in different elevations)

1.2.2 Assumptions of this case study

Depth of Buvatnet [m]	8
Volume of Buvatnet [m^3] assuming it is a container with a constant rectangular profile	$14{,}4 \cdot 10^5$
Water percentage allowed to be pumped off Buvatnet	10%
Pump's suction percentage per hour of the allowed water volume V_{max}	0,004%
Pump efficiency η_p	95%
Turbine efficiency η_t	95%
High power price [Nok/MWh]	1000
Low power price [Nok/MWh]	500
Price of power line (5000-8000 kV) [NOK/km]	$4 \cdot 10^4$
Velocity at the surface of the water in an open reservoir is negligible	
Head losses due to bends, fittings, and other minor losses are not included in this study as they depend on different changes in the layout that result from the area's topology. Therefore, assumed to be zero.	

Table 27 Table of assumptions in case study B

1.2.3 Location and layout

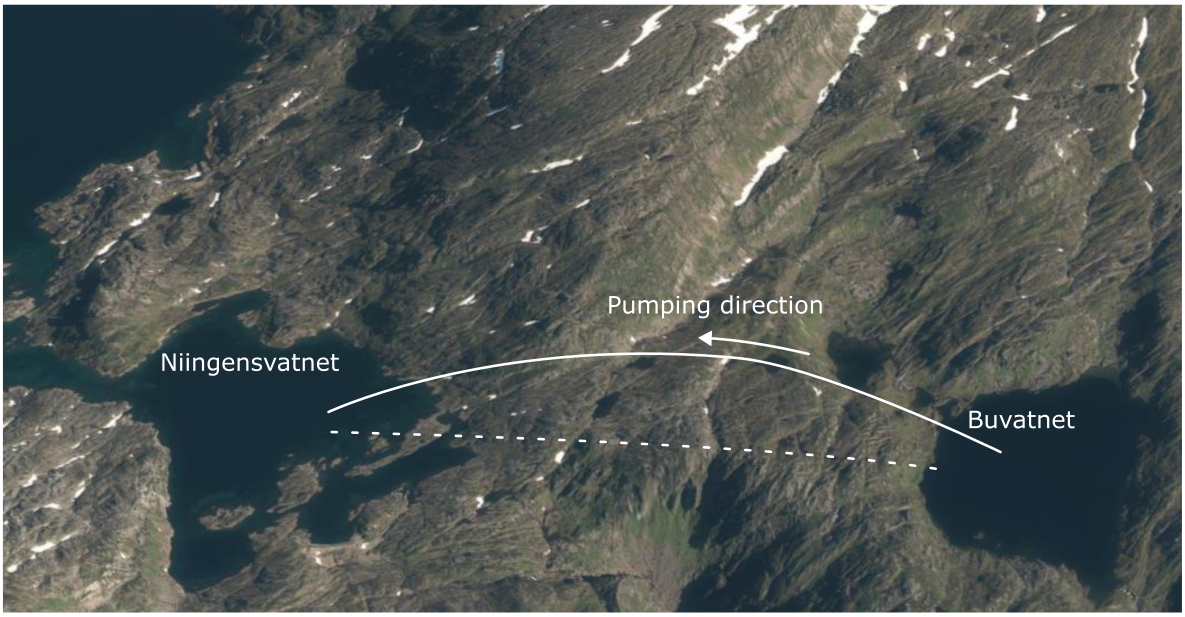


Figure 59 Proposed plan for the pipeline from Buvatnet to Niingensvatnet without a tunnel (constant line) or with a tunnel (dashed line) [39]

The three-dimensional map provided by Norgeibilder.no presents an opportunity to study the area's terrain and topology to make a rough estimate of recommended locations of pipes and pumping stations. In Buvatnet, it is visible that the increase of elevation from 465 m to 510 m is developed gradually and not steeply, this offers a simpler chance of trenched pipeline, but it comes with the price of an increase in Head to 575 m.

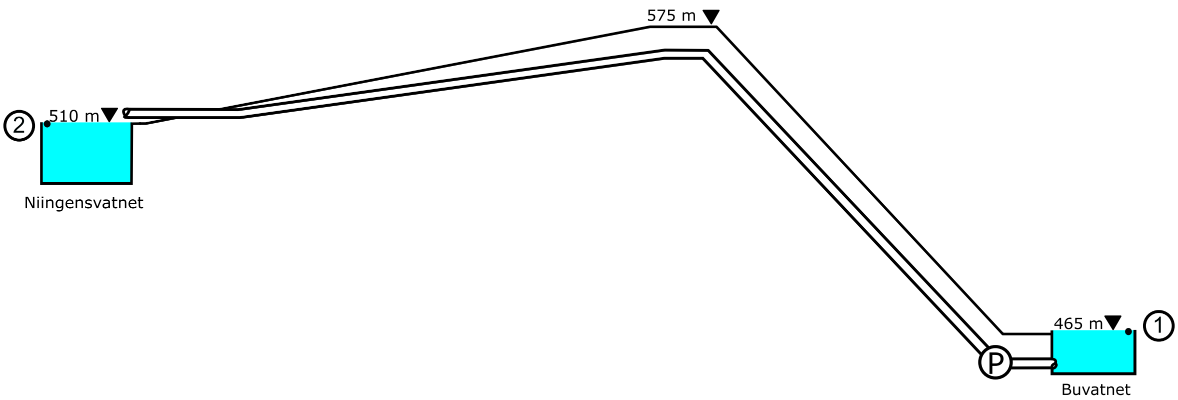


Figure 60 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Buvatnet to Niingensvatnet with no tunnel

Therefore, the layout of this pipeline with respective pumping stations can be illustrated in the following figure, a tunnel can be mined for the pipe at an elevation of 510 m as this increase in head to 575 m is unnecessary.

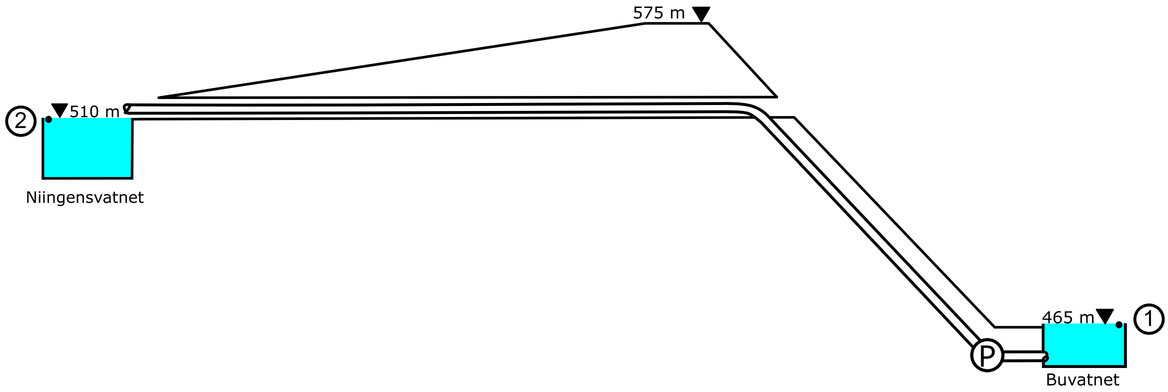


Figure 61 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Buvatnet to Niingensvatnet with a tunnel

The exact locations for the higher and lower pumps are left as variables depending on geological and topological studies. Pipes are recommended to be trenched where they are not tunneled and tunneled at the elevation of 510 m, and pumping chambers are suggested to be underground as we will see later in this case study.

1.2.4 Reservoirs geology

For the volume of water to be pumped, in Section 2.2.2 "Water levels allowed to be pumped from and added to lakes"; we defined the variable X_{max}, which is the maximum amount of water we can pump. And this variable can either describe the volume allowed to be pumped V_{max}, or the water level allowed to be pumped Y_{max}.

- Lake's volume

Assuming the depth of Buvatnet is 8 [m], then its volume will be the following:

$$V_{\text{Buvatnet}} = \text{Depth} \cdot \text{area}$$

$$= 8 \cdot 0{,}18$$

$$= 8 \cdot 1{,}8 \cdot 10^5 = 14{,}4 \cdot 10^5 \text{ m}^3$$

Note that the volume calculation assumes that Strandvatnet is container with a constant rectangular profile.

- Deciding the allowed water magnitudes to be pumped

Assume that:

$$V_{max} = 10\% \cdot V_{Buvatnet} \tag{1.3}$$

Then:

$$V_{\text{max}} = 0{,}10 \cdot 14{,}4 \cdot 10^5 = 14{,}4 \cdot 10^4 \text{ m}^3$$

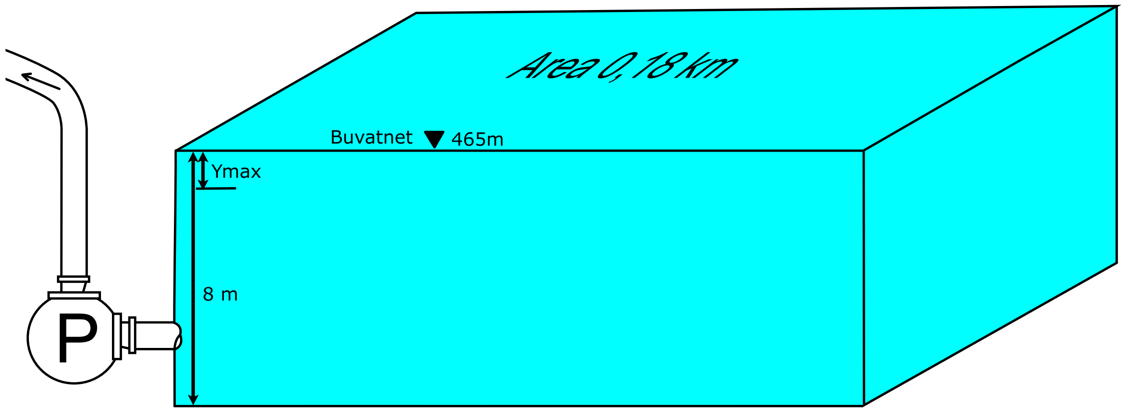


Figure 62 The reservoir at Buvatnet assuming it is a container with a constant rectangular profile

- Deciding the flow rate

As a preliminary step for choosing a pump, we need to know the flow rate and the head at the pumping station.

Finding the flow rate is necessary, as different pumps can deliver water to the required destination at different speeds. And knowing this value will help later in calculating pipe diameters. One can find the flow rate by dividing the water volume needed to be pumped by the time that will be consumed in pumping.

As Buvatnet is closer to Niingensvatnet, and the power consumed to pump water to it is less than from Strandvatnet, it can be used as a backup reservoir and use the hourly cycle. This needs a quick response in terms of pumping. We assume that we specify two minutes for the water to be pumped from Buvatnet to start reaching the height of 510 m where it flows in a tunneled horizontal pipe until it reaches Niingensvatnet.

Assuming that the pump will draw a volume of 0,004% of $V_{\max}$ per hour:

$$\text{Flow rate volume} = 0{,}004\% \cdot V_{\max}$$

$$= 0{,}004 \cdot 0{,}01 \cdot 14{,}4 \cdot 10^4 = 5{,}76 \ \text{m}^3$$

$$Q = \frac{\text{Flow rate volume}}{\text{time}} =$$

$$= \frac{5{,}76 \ \text{m}^3}{2 \ \text{min}} = \frac{5{,}76 \ \text{m}^3}{2/60 \ \text{h}} = 172{,}8 \frac{\text{m}^3}{\text{h}}$$

- Time taken to pump water volume from a lake

Recalling Equation 2.1:

$$\text{Time to drain lake} = \frac{\text{water volume in a lake}}{\text{Pumping capacity}}$$

$$= \frac{V_{\text{Buvatnet}}}{Q} = \frac{14{,}4 \cdot 10^5}{172{,}8} = 8333{,}33 \ \text{h}$$

- Following the hourly plan

For this case study, an hourly pumping cycle is proposed. In Section 2.1.1.3, the hourly plan was described and explained that according to it six hours of pumping is the optimal pumping time. In each cycle of six hours, the amount of pumped water is:

$$V = Q \cdot t = 172{,}8 \cdot 6 = 1036{,}8 \ \text{m}^3$$

- Time taken to fully pump $V_{\max}$

$$\text{Time to pump an allowed water volume of a lake} = \frac{\text{water volume allowed to be pumped } V_{\max}}{\text{Pumping capacity}}$$

$$= \frac{V_{\max}}{Q} = \frac{14{,}4 \cdot 10^4}{172{,}8} = 833{,}33 \text{ h} = \frac{833{,}33}{6} = 138 \text{ cycles (days) of the hourly plan}$$

Note that this result does not consider the availability of runoff or precipitation.

1.2.5 Pumps selection

Required flow rate [m^3]/[h]	172,8
Required total head[7] [m]	56,07
Required pressure at the pump outlet [bar]	5,6

Table 28 Parameters of flow in case study B

- Deciding on pump type

Recalling Equations 2.2 and 2.3 at $N = 1450$ rpm:

$$\omega_P = \frac{\omega\sqrt{Q}}{(gh)^{\frac{3}{4}}}$$

$$= \frac{151{,}84\sqrt{0{,}048}}{(9{,}81 \cdot 72)^{3/4}} = 0{,}24$$

Where:

$$\omega = \frac{2\pi N}{60}$$

$$= \frac{2\pi \cdot 1450}{60} = 151{,}84 \text{ rad/s}$$

And:

$$Q = 172{,}8 \frac{\text{m}^3}{\text{h}} = \frac{172{,}8}{3600} = 0{,}048 \frac{\text{m}^3}{\text{s}}$$

If:

$$\omega_P < 1 \qquad \text{radial flow pump}$$

- Using one pump

Studying pumps that "North Ridge Pumps" provide as an example, after studying the head-flow rate, power, efficiency, and NPSH curves, we find that their pump series "North Ridge SKM-E End Suction Horizontal Centrifugal Multistage Pump" fulfills the requirements of this project. Choosing the pump "SKM-K 125/2"[33] in this case study, we get the following data for this pump:

Max flow rate [m^3]/[h]	300
Max head [m]	65
Number of stages	2
Pump materials	AISI304, AISI316, AISI316L, Bronze, Cast Iron, Cast Steel, Ductile Iron, Duplex, NiAl Bronze, Super Duplex

[7] Will be calculated later in matching pumps to system design

Inlet/outlet sizes[8] d_{pump} [mm]	125
Max suction lift (max height of the suction pipe) [m]	-
Operating Temperature [°C]	-10 to +140
Estimated price [NOK]	$15 \cdot 10^4$

Table 29 Characteristics of the selected pump at 1450 rpm

1.2.5.1 Pumps characteristics

❖ **Power consumed**

In Section 2.3.1.2, it is explained how power consumption varies with the flow rates of the pump. However, it is given by Equation 2.7

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

As explained in Section 2.3.1, the pump's efficiency varies also with flow rate and depends on the specific final choice of the pump using parameters that are not studied in this case study such as the motor phases, voltage, and frequency. Assuming $\eta_p = 95\%$ for both types of pumps:

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

$$= \frac{172{,}8 \cdot 45 \cdot 9{,}81 \cdot 1000}{3600 \cdot 0{,}95}$$

$$= 22304{,}84 \left[\frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2}\right] \cdot \left[\frac{1}{\mathrm{s}}\right] = 22304{,}84 \left[\frac{\mathrm{J}}{\mathrm{s}}\right] = 22304{,}84\ [\mathrm{W}] = 22{,}30\ [\mathrm{kW}]$$

Where $\left[\frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{s}^2}\right] = [\mathrm{J}]$

❖ **NPSHa**

As we studied in Section 2.3.1.2, inlet pressure must be known to avoid cavitation.

Suggesting the layout in the following figure:

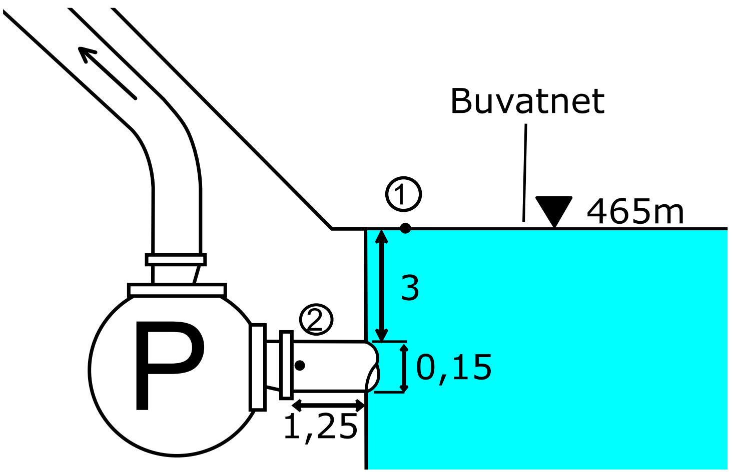


Figure 63 Proposed plan for the pumping station by considering recommendations in Chapter 2

We solve this problem by subtracting vapor pressure from pump inlet pressure and using the energy equation[11, Ch. 14.5].

- Applying the energy equation between points 1 and 2

[8] Assumed to be ID (inner diameter)

$$\left(\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2\right)+\sum h_l$$

Where

Water velocity at the water surface is negligible $V_1 = 0$, $z_1 = 0$ m, $z_2 = -2$ m, z_2 is an assumed value that can be changed later to achieve larger NPSHa.

- Atmospheric pressure in meters of head

$$\frac{P_1}{\gamma}=\frac{101260{,}47[\mathrm{Pa}]}{9810\left[\frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}^2}\right]}=\frac{10.32[\mathrm{m}]}{1[\mathrm{m}]}=10{,}32$$

Because $[\mathrm{Pa}] = [\frac{\mathrm{kg}}{\mathrm{m\cdot s^2}}][11, \mathrm{Tbl. F. 1}]$.

- Friction head in the pipe

From Equation 2.8 we get the friction head[9]:

$$h_f=\frac{f\cdot L_1\cdot {V_2}^2}{d_{pipe}\cdot 2g}$$

$$=\frac{0{,}0035\cdot 1{,}25\cdot (2{,}82)^2}{150\cdot 10^{-3}\cdot 2\cdot 9{,}81]}=0{,}012\ m$$

Where:

$$f=\frac{0{,}079}{R_e^{1/4}}=\frac{0{,}079}{(236444{,}94)^{\frac{1}{4}}}=0{,}0035$$

Because:

$$R_e=\frac{V_2\cdot d_{pipe}}{v}$$

$$=\frac{2{,}82\cdot 150\cdot 10^{-3}}{1.789\ \cdot\ 10^{-6}}=236444{,}94$$

Where:

$$V_2=\frac{Q}{A}$$

$$=\frac{\frac{172{,}8}{3600}}{0{,}017}=2{,}82\ \frac{\mathrm{m}}{\mathrm{s}}$$

Where:

$$A=\frac{\pi}{4}{d_{\mathrm{pipe}}}^2$$

$$=\frac{\pi}{4}(150\cdot 10^{-3})^2=0{,}017\ \mathrm{m}^2$$

- Head loss due to pipe entrance

From Equation 2.10, we get the head loss at the pipe entrance:

---

[9] L_1 is known from pipes calculations later in this case study

$$h_i = 0{,}5\frac{V_2{}^2}{2g}$$

$$= 0{,}5\frac{(2{,}82\ )^2}{2 \cdot 9{,}81} = 0{,}2\ \mathrm{m}$$

Putting the values into the energy equation:

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) + \sum h_l$$

$$10{,}322 + 0 + 0 = \frac{\mathrm{p}_2}{1} + \frac{(2{,}82)^2}{2(9{,}81\ )} - 2 + 0{,}2\ + 0{,}012$$

$$p_2 = 11{,}7\ \mathrm{m} = 1{,}17\ \mathrm{bar}$$

- Subtracting vapor pressure

Vapor pressure of water $P_v = 0{,}652\ \mathrm{kPa} = 652\ \mathrm{Pa} = 6.64\ \ \mathrm{m}$

$$\mathrm{NPSHa} = 11{,}7 - 6{,}64 = 5{,}06\ \mathrm{m} = 0{,}5\ \mathrm{bar}$$

$$\mathrm{NPSHa} > \mathrm{NPSHr}$$

$$5{,}06\ \mathrm{m} > \mathrm{NPSHr}$$

- Conclusion

To determine the NPSHr (Net Positive Suction Head Required) of the pump, one needs to consult the manufacturer to get the pump curve or datasheet provided by them. This value can change using different parameters that are outside the scope of this case study, such as frequency, voltage, number of phases, and speed of the motor. Therefore, NPSHr is left as a variable here.

Once the value of NPSHr is obtained, the comparison of Equation 2.6 must be made. If the value of NPSHr was greater than the calculated NPSHa, decreasing the value of z_2 will be the solution (manipulating the equation in order to increase NPSHa with other methods such as manipulating the flow rate is possible too).

1.2.6 Pipes selection

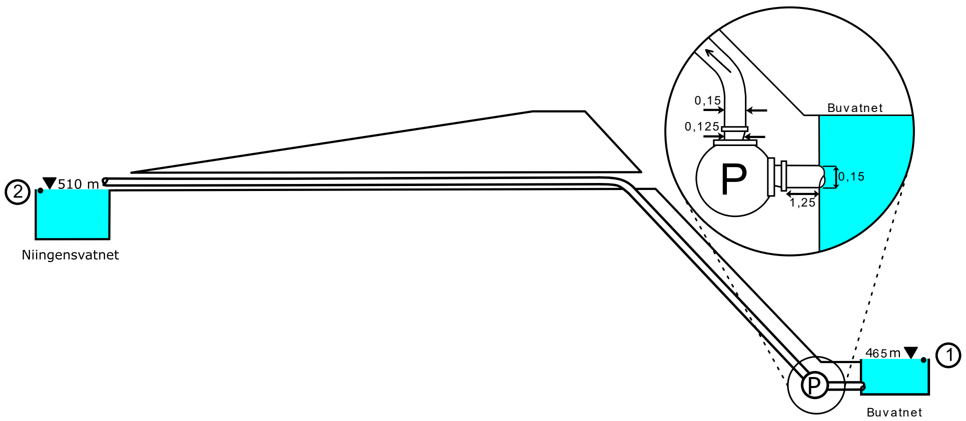


Figure 64 Dimensions for pumping station (in meters, unless otherwise stated)

- Suction pipe length

Using recommendations for pipes selection in Section 2.3.2.3, we find the length of the suction pipe

$$L_1 = 10d_{\mathrm{pump}} = 10 \cdot 0{,}125\ \mathrm{m} = 1{,}25\ \mathrm{m}$$

- Pipe diameter

Recommendations advise using a suction pipe one size larger than the inlet nozzle which is $d_{\text{pump}} =$ 125 mm, then we select the pipe diameter (ID) $d_{\text{pipe}} = 150$ mm both for the suction and discharge pipe. Of course, for this change in diameter, we need to use an eccentric reducer at the pump's inlet from 150 to 125 mm and an eccentric increaser from 125 to 150 mm as discussed in Section 2.3.2.3.

- Discharge pipe length

The length of the discharge pipe is a variable here due to that different layout plans will have different pipe lengths. For the sake of calculations of water hammer and pipe thickness, this length can be assumed to be 1000 m.

- Material

"Carbon steel, AISI 1010, annealed" was chosen for all pipes in this document, see pipes selection in case study A.

- Wall thickness

From ASME-B31.1 we get the equation for wall thickness[55, Ch. 104.1]:

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$

Where:

$P = 143{,}7 \text{ Pa} = 0{,}143 \text{ kPa}$ which is the water hammer pressure that will be studied later in this appendix.

$d = 150 \text{ mm}$

$S = 7{,}7 \text{ ksi} = 53089{,}63 \text{ kPa}$ (Using 25 and 45 in yield and tensile strengths respectively. From table A-1 choose Furnace Butt Welded Pipe API 5L at -15 °C).

$E = 0{,}60$

$y = 0{,}4$

$A = 25 \text{ mm}$

$$t_m = \frac{0{,}143 \cdot 150 + 2 \cdot 53089{,}63 \cdot 0{,}60 * 25 + 2 \cdot 0{,}4 \cdot 0{,}143 \cdot 25}{2(53089{,}63 \cdot 0{,}60 + 0{,}143 \cdot 0{,}4 - 0{,}143)} = 25 \text{ mm}$$

Which is the maximum diameter that is calculated considering safety against water hammer. The pipe's diameter can be decreased with elevation as the water hammer pressure decreases with the shorter pipe length. So, lowering the water hammer pressure P will lower the thickness of the pipe and subsequently the diameter.

1.2.7 Other calculations and recommendations of case study B

1.2.7.1 Underground and overground pipeline

In Section 2.3.2.1 the trenched pipelines plan was recommended as it helps overcome the problem of icing in pipes. Note that pipes must either be having an active flow or be empty, but not have stationary fluid as this will be a reason for internal icing.

1.2.7.2 Separate and joined pipeline

As discussed in Section 2.3.2.1, joined pipelines are not economically feasible for the cases in this thesis.

1.2.7.3 Matching Pumps to System Demand

In Section 2.1.3 we found that the available total head must overcome the required total head (resistance) for the water to be pumped.

$$h_a > h_r$$

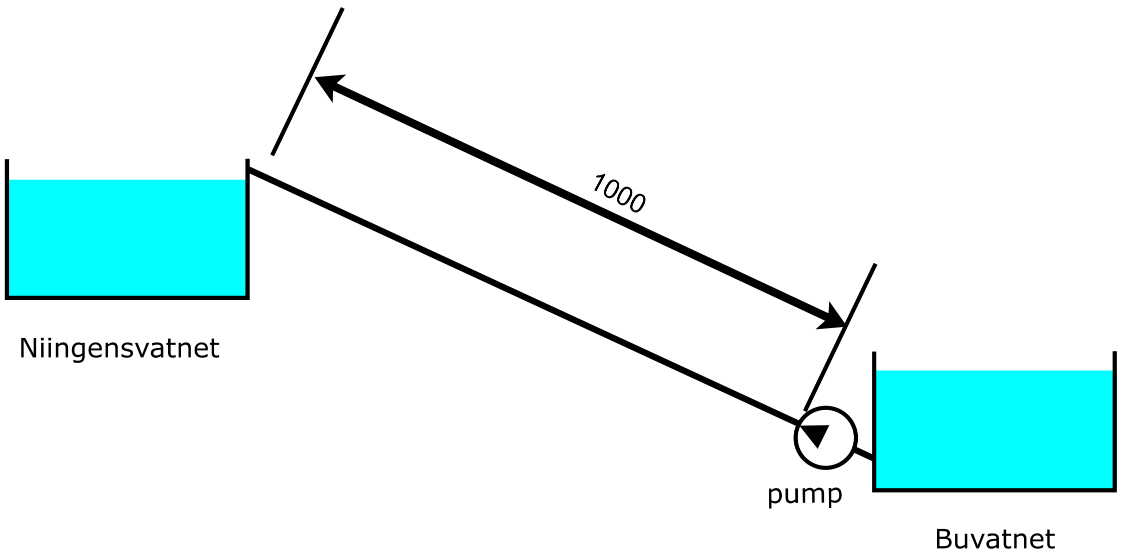


Figure 65 Understanding total pipe length between Buvatnet and Niingensvatnet

h_a is the available head at the pump's discharge outlet in addition to the static head provided by the lower reservoir.

$$h_a = 65 + 3 = 68 \text{ m}$$

$$h_r = h_l + h_s$$

Assuming that minor head losses due to bending and fittings etc. are negligible, the head loss is friction only.

$$h_r = (\frac{f \cdot L_2 \cdot V^2}{d_{\text{pipe}} \cdot 2g}) + (45)$$

$$= \frac{0{,}0041 \cdot 1000 \cdot 2{,}82^2}{150 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} + 45 = 56{,}07 \text{ m}$$

$$68 \text{ m} > 56{,}07 \text{ m}$$

Which is accepted.

1.2.7.4 Water hammer

Water hammers can have many scenarios. The one we study in this case assumes having the pump at the first end of the pipe, followed by a valve that closes after an amount of water has been pumped towards Niingensvatnet.

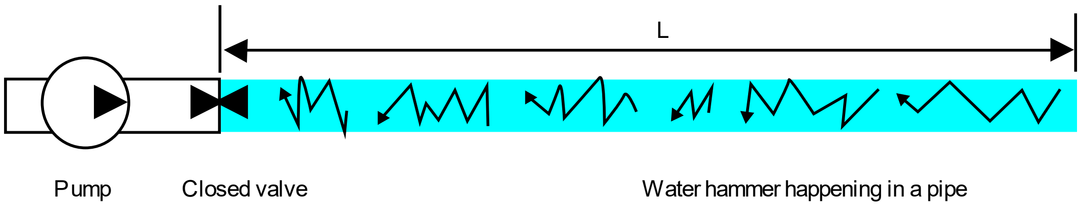


Figure 66 Water hammer in a pipe

Using two seconds as time for closing the valve and recalling equations from Section 2.3.2.4.

We consider the valve closure to be sudden if:

$$T < \frac{2L}{C}$$

We consider the valve closure to be gradual because:

$$T > \frac{2L}{C}$$

$$2 > \frac{2 \cdot 1000}{1449{,}13}$$

$$2 > 1{,}38$$

The closing time has to be greater than 1,38 [sec] to be considered sudden.

- Gradual closure of the valve

$$P = \frac{LV}{gT}$$

$$= \frac{1000 \cdot 2{,}82}{9{,}81 \cdot 2} = 143{,}7 \text{ Pa} = 0{,}0146 \text{ m}$$

1.2.8 Financial calculations

1.2.8.1 Energy storage in the higher reservoir

It has been explained in this appendix that the hourly plan is proposed to be used in this case. Meaning six hours of pumping will occur every day if this plan was to be followed strictly. It was also found that the volume of water that will be pumped in each of these cycles of six hours equals:

$$V = Q \cdot t = 172{,}8 \cdot 6 = 1036{,}8 \text{ m}^3 \text{ per one cycle}$$

Putting pumping time to be a complete year (seven cycles a week, each of six hours, four times a month, 12 times a year) we get 2016 hours of pumping.

$$V = Q \cdot t = 172{,}8 \cdot 2016 \; = 348364{,}8 \text{ m}^3 \text{ per year}$$

Putting V in the Equation 3.1 to get the amount of energy in this volume of pumped water:

$$E \; = 2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g h V [\text{kWh}]$$

$$= 2{,}77 \cdot 10^{-7} \cdot 0{,}95 \cdot 1000 \cdot 9{,}81 \cdot 510 \cdot 348364{,}8 = 458645{,}16 \text{ kWh} = 458{,}64 \text{ MWh}$$

1.2.8.2 Price per potential energy unit

Assuming that the high power-price is 1000 [NOK/MWh], from Equation 3.2 we get the financial value of pumped water:

$$\text{Yearly expected revenue} = E \cdot \text{high power price}$$

$$458{,}64 \cdot 1000 = 458645{,}16 = 0{,}45 \cdot 10^6 \text{ NOK}$$

1.2.8.3 Cost estimations of the project

- Capital investment

The total capital investment is given by:

$$C_{\text{Bca}} = C_{\text{pump}} + C_{\text{pipe}} + C_{\text{dam}} + C_{\text{tre}}$$

$$= 0{,}15 \cdot 10^6 + 2{,}04 \cdot 10^6 + 0{,}468 \cdot 10^6 + 5{,}65 \cdot 10^6 = 8{,}3 \cdot 10^6 \text{ NOK}$$

This value is based on the costs list below.

- Mechanical and electrical costs
  - Pumps costs

$$C_{\text{pump}} = 0{,}15 \cdot 10^6 \text{ NOK}$$

  - Pipes costs

The length of discharge pipes in this case study was assumed to be the same $L_2 = 1000$ m.

NVE's guideline "Cost base for hydropower plants for generating capacity of less than 10000 kW" (Kostnadsgrunnlag for små vannkraftanlegg (< 10 MW)) has estimations for pipe costs including their installations[56, No. 2012/3]. Reading FIG.4.6.3 in the mentioned reference, we find that for the pressure head of 510 m, and diameter of 125 to 150 mm, the average pipe price is 1500 NOK/m The updates from 2016 to 2023 show that mechanical costs have increased by 36,5%, causing the average pipe price to be 2047,5 Nok/m.

$$C_{\text{pipe}} = 2047 \cdot 1000 = 2{,}04 \cdot 10^6 \text{ NOK}$$

- Civil engineering costs
  - Dam and pumping chamber costs

For this project, dams must be built at reservoir outlets to control outflow and water levels. The pumping chamber has to be included in the dam construction, which is assumed to be a concrete gravity dam of five meters in height and 5 consecutive meters in width. Reading through NVE's estimation for dams, specifically FIG. 2.2.2[56, No. 2016/40], we notice that concrete dams cost 68000 NOK/consecutive meter, including price growth from 2015 to 2023 which NVE suggests that it is equal to 37,94[57] we get that the up-to-date price is 93772 NOK/consecutive meter.

$$C_{\text{dam}} = 5 \cdot 93772 = 468860 = 0{,}468 \cdot 10^6 \text{ NOK}$$

  - Pipe trench

As discussed earlier in this appendix, trenched pipes are recommended for case study A along the whole discharge pipe. Reading through NVE's cost base for small-scale hydropower plants, especially chapter 2.5.2: Pipe trenches [56, No. 2016/40] we find that for a 1,5 m trench width at the bottom and 3,0 m depth, for a 3356 m length of combined earth/rock trench, the cost is set to 4160 Nok/m. No information included in the reports of NVE about the price development of trenches since 2015, so this value is assumed to be 36%, which is similar to the price development in concrete dams (37,9%) and mechanical costs (36,5%). The updated cost will be 5657,6 NOK/m.

$$C_{\text{tre}} = 5657{,}6 \cdot 1000 = 5657600 = 5{,}65 \cdot 10^6 \text{ NOK}$$

  - Negligible costs:

As discussed in Section 3.4, the costs for valves, fittings, seals, and supports, as well as for taxes, land acquisition, transports, electro-technical equipment, and power lines, are not included in this study as they are either minimal or/and vary from project to project based on topology and geology of the region.

- Operational costs

- Maintenance and personnel costs

From Section 3.4.2 we follow IRENA's estimation for yearly personnel and maintenance costs, which is estimated to be around 3% of the total investment cost.

$$(C_{\text{ma}} + C_{\text{per}}) = 3\% C_{\text{Bca}} = 0{,}03 \cdot 8{,}3 \cdot 10^6 = 0{,}24 \cdot 10^6 \text{NOK}$$

- Pump power consumption

The pump's power consumption must be also added to the operational costs. Section 1.2.5.1 in this appendix shows how the value for power was calculated. Using the hourly plan, a pump works constantly for 6 hours a day, meaning that in the span of a year, it works 2016 h.

To convert Megawatts to Megawatt hours one can multiply by the number of operation hours to get a yearly energy consumption.

The low power price is assumed to be $500\ \text{Nok/MWh}$.

$$C_{\text{power}} = P \cdot \text{hours per year} \cdot \text{low power price}$$

$$= 0{,}022 \cdot 2016 \cdot 500 = 22478{,}4 = 0{,}022 \cdot 10^6\ \text{NOK}$$

Annual operational costs will be:

$$C_{\text{Bop}} = C_{\text{ma}} + C_{\text{per}} + C_{\text{power}} = 0{,}24 \cdot 10^6 + 0{,}022 \cdot 10^6 = 0{,}27 \cdot 10^6\ \text{NOK}$$

1.2.9 Conclusion of case study B

Capital investment cost[NOK]	$8{,}3 \cdot 10^6$
Yearly operational costs[NOK]	$0{,}27 \cdot 10^6$
Yearly expected revenue[NOK]	$0{,}45 \cdot 10^6$

Table 30 Comparison between costs and revenue of case B

Case B is perhaps the most interesting case, as we can see from comparing Table 29 to Table 24. Capital investment in case B is 3,25 times less than in case A, while the yearly expected revenue is 1,28 times higher in case B than in case A. In addition, yearly operational costs are 1,6 times less than the yearly expected revenue. In this case, the project will retain its capital investment value in 18,4 years.

$$\text{Yearly expected profit} = \text{yearly expected revenue} - \text{yearly operational costs}$$

$$= (0{,}45 - 0{,}27) \cdot 10^6 = 0{,}18 \cdot 10^6\ \text{NOK}$$

To increase the yearly expected profit, one can either increase the revenue or decrease the costs. To increase the revenue, the most relevant method is to increase the amount of energy produced by increasing the water volume that is pumped which is directly proportional to the flow rate.

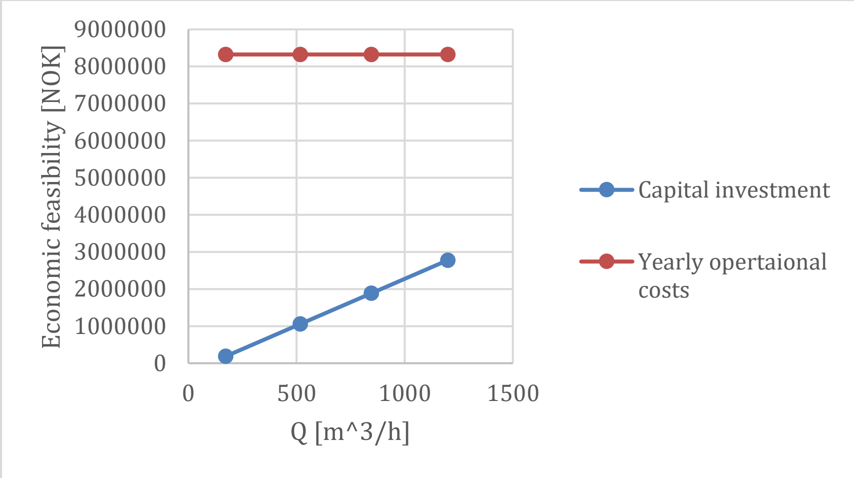


Figure 67 Increase in yearly expected profit with flowrate

Moreover, to address the uncertainty in power prices, we define the price difference index, which is the result of dividing the high to low power prices. Generating the following table that compares the different effects of high and low power prices on economic feasibility, it shows that, at flowrates of 172,8 and 500 m^3/h, and for different changes in prices the project is steadily lucrative and promising. At the flow rate 172,8, the profit was not made before the high price reached 800 NOK, and continued to be cost-effective for higher values even though the low power price did not make a difference. At a flow rate 500 m^3/h, the project became more stable and rewarding, which proves that the profit is proportional to the flow rate and not harshly affected by low power price. In short, the table shows signs of cost-effectiveness in this project which increases its relevance as a pumped storage plant in the Niingen power plant.

At 172,8 m^3/h				At 500 m^3/h			
Low price [NOK]	High price [NOK]	Economic feasibility [NOK]	Index	Low price [NOK]	High price [NOK]	Yearly profit [NOK]	Index
50	100	-206102,61	2	50	100	-123514,55	2
50	150	-183170,35	3	50	150	-57159,635	3
50	200	-160238,09	4	50	200	9195,27928	4
50	300	-114373,58	6	50	300	141905,108	6
50	400	-68509,06	8	50	400	274614,938	8
50	500	-22644,543	10	50	500	407324,767	10
75	100	-207226,78	1,333	75	100	-126767,34	1,333
75	150	-184294,52	2	75	150	-60412,425	2
75	200	-161362,26	2,667	75	200	5942,4898	2,667
75	300	-115497,74	4	75	300	138652,319	4
75	400	-69633,224	5,333	75	400	271362,148	5,333
75	500	-23768,707	6,667	75	500	404071,977	6,667
100	200	-162486,42	2	100	200	2689,70033	2
100	300	-116621,91	3	100	300	135399,529	3
100	400	-70757,388	4	100	400	268109,359	4
100	500	-24892,871	5	100	500	400819,188	5
500	800	94714,0547	1,6	500	800	746904,043	1,6
500	900	140578,572	1,8	500	900	879613,873	1,8
500	1000	186443,089	2	500	1000	1012323,7	2
600	1000	181946,432	1,667	600	1000	999312,544	1,667
750	1000	175201,448	1,333	750	1000	979795,807	1,333

800	1000	172953,12	1,25	800	1000	973290,228	1,25

Table 31 Different values for yearly profit against different power prices

1.3 Case study C: Pumping from Djupåvatnet

1.3.1 Circumstances of this case study

Water temperature [°C]	0
Average weather temperature [°C]	-5
Kinematic viscosity [$\mathrm{m^2/s}$]	$1.789 \cdot 10^{-6}$
The specific weight of water γ [$\mathrm{kg/m \cdot s^2}$]	9810
Vapor pressure of water P_v [kPa]	0,652
Atmospheric pressure [Pa]	101260,47
Density [kg/m^3]	1000
Gravitational acceleration [$\mathrm{m/s^2}$]	9,81
Specific gravity, dimensionless	1
Bulk modulus [$\mathrm{N/m^3}$]	$2{,}1 \cdot 10^9$
The velocity of pressure wave [m/s]	1449,13

Table 32 Circumstances of this case study (assumed to be constant in different elevations)

1.3.2 Assumptions of this case study

Depth of Djupåvatnet [m]	5
Volume of Djupåvatnet [$\mathrm{m^3}$] assuming it is a container with a constant rectangular profile	$5 \cdot 10^5$
Water percentage allowed to be pumped off Djupåvatnet	10%
Pump's suction percentage per hour of the allowed water volume V_{max}	0,004%
Pump efficiency η_p	95%
Turbine efficiency η_t	95%
High power price [Nok/MWh]	1000
Low power price [Nok/MWh]	500
Price of power line (5000-8000 [kV]) [NOK/km]	$4 \cdot 10^4$
Velocity at the surface of the water in an open reservoir is negligible	
Head losses due to bends, fittings, and other minor losses are not included in this study as they depend on different changes in the layout that result from the area's topology. Therefore, assumed to be zero.	

Table 33 Table of assumptions in case study C

1.3.3 Location and layout

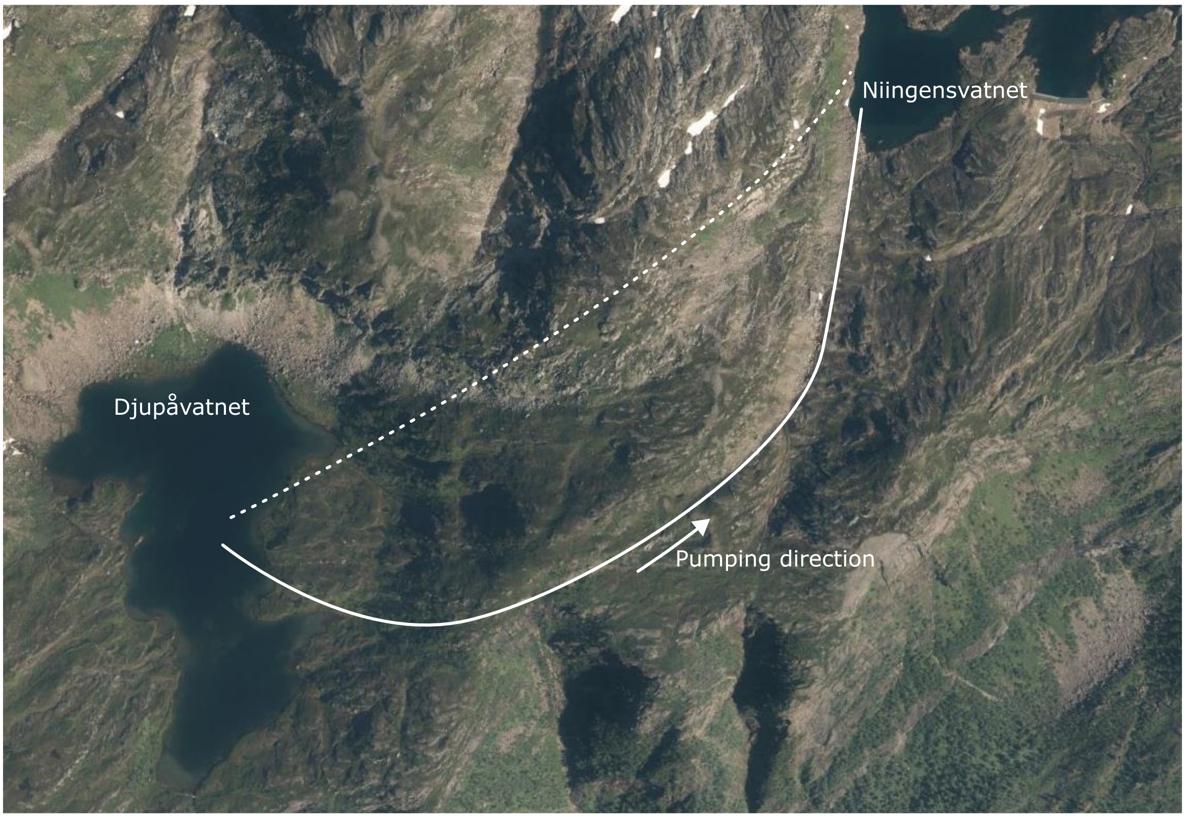


Figure 68 Proposed plan for the pipeline from Djupåvatnet to Niingensvatnet without a tunnel (constant line) or with a tunnel (dashed line [39]

The three-dimensional map provided by Norgeibilder.no presents an opportunity to study the area's terrain and topology to make a rough estimate of recommended locations of pipes and pumping stations. In Djupåvatnet, it is visually noticeable that it's surrounded by high hills from the northern and western sides, while from the north-eastern direction, an opportunity to set up pipelines without large differences in height is available.

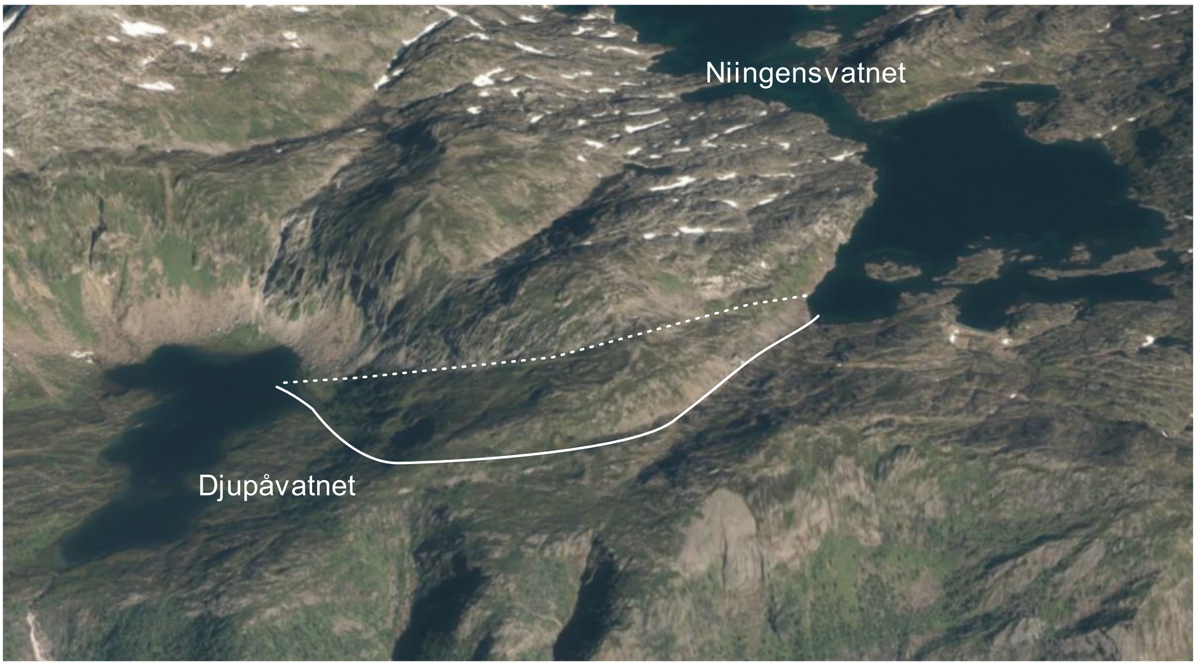


Figure 69 3D map of the Niingensvatnet-Djupåvatnet region with the suggested pipeline without a tunnel (constant line) or with a tunnel (dashed line)[39]

Aerial footage shows that the maximum height is 564 m for the trenched pipeline without a tunnel. Therefore, the layout of this pipeline with respective pumping stations can be illustrated in the following figure.

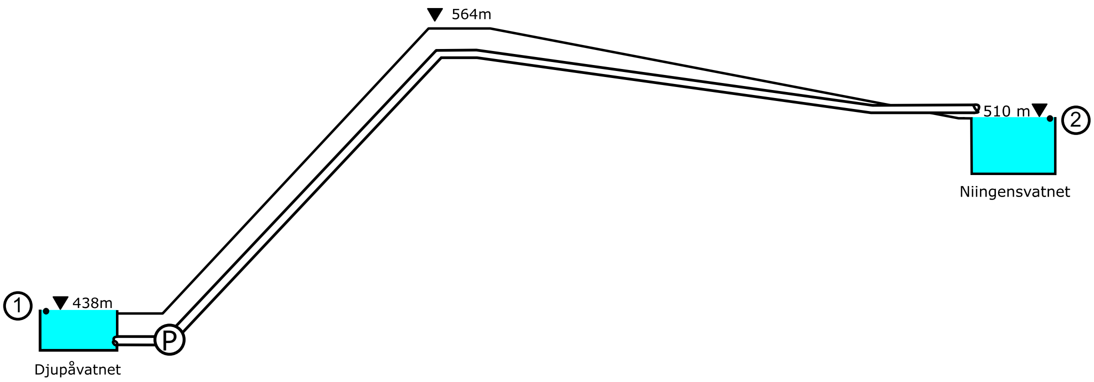


Figure 70 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Djupåvatnet to Niingensvatnet with no tunnel

As this increase in head over 510 m to 564 m is unnecessary, a tunnel can be excavated for the pipe at an elevation of 510 m as the following figure depicts.

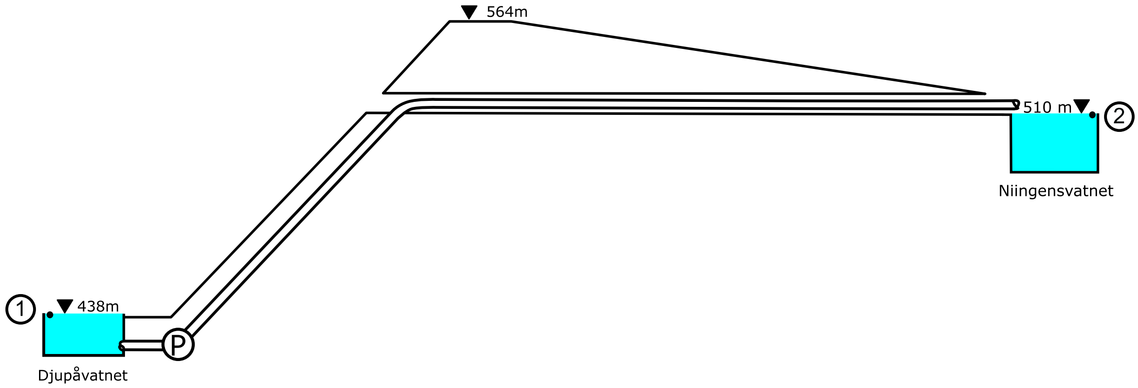


Figure 71 A simplified side-view illustration shows the lengths and elevations of the pumping plan from Djupåvatnet to Niingensvatnet with a tunnel

The exact locations for the higher and lower pumps are left as variables depending on geological and topological studies. Pipes are recommended to be trenched where they are not tunneled and tunneled at the elevation of 510 m, and pumping chambers are suggested to be underground as we will see later in this case study.

1.3.4 Reservoirs geology

For the volume of water to be pumped, in Section 2.2.2 "Water levels allowed to be pumped from and added to lakes"; we defined the variable $X_{\max}$, which is the maximum amount of water we can pump. And this variable can either describe the volume allowed to be pumped $V_{\max}$, or the water level allowed to be pumped $Y_{\max}$.

- Lake's volume

Assuming the depth of Djupåvatnet is 5 m, then its volume will be the following:

$$V_{\text{Djupåvatnet}} = \text{Depth} \cdot \text{area} \tag{1.4}$$

$$= 5 \cdot 0{,}10$$

$$= 5 \cdot 1 \cdot 10^5 = 5 \cdot 10^5 \text{ m}^3$$

Note that the volume calculation assumes that Strandvatnet is container with a constant rectangular profile.

- Deciding the allowed water magnitudes to be pumped

Assume that:

$$V_{max} = 10\% \cdot V_{Djupåvatnet} \tag{1.5}$$

Then:

$$V_{max} = 0{,}10 \cdot 5 \cdot 10^5 = 5 \cdot 10^4 \text{ m}^3$$

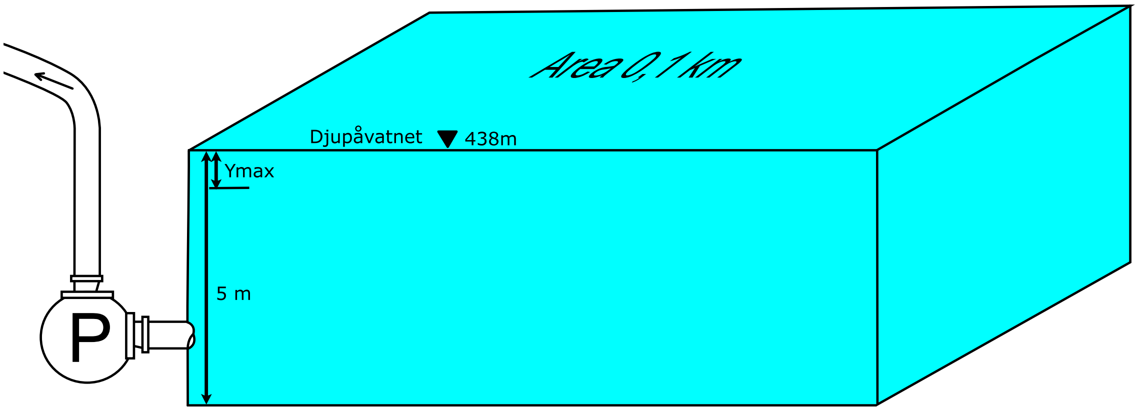


Figure 72 The reservoir at Djupåvatnet assuming it is a container with a constant rectangular profile

- Deciding the flow rate

As a preliminary step for choosing a pump, we need to know the flow rate and the head at the pumping station.

Finding the flow rate is necessary, as different pumps can deliver water to the required destination at different speeds. And knowing this value will help later in calculating pipe diameters. One can find the flow rate by dividing the water volume needed to be pumped by the time that will be consumed in pumping.

As Djupåvatnet is closer to Niingensvatnet, and the power consumed to pump water to it is less than from Strandvatnet, it can be used as a backup reservoir and use the hourly cycle. This needs a quick response in terms of pumping. We assume that we set two minutes for the water to be pumped from Djupåvatnet to start reaching the height of 510 m where it flows in a tunneled horizontal pipe until it reaches Niingensvatnet.

Assuming that the pump will draw a volume of 0,004% of $V_{\max}$ per hour

$$\text{Flow rate volume} = 0{,}004\% \cdot V_{\max}$$

$$= 0{,}004 \cdot 0{,}01 \cdot 5 \cdot 10^4 = 2 \text{ m}^3$$

$$Q = \frac{\text{Flow rate volume}}{\text{time}} =$$

$$= \frac{2 \text{ m}^3}{2 \text{ min}} = \frac{2 \text{ m}^3}{2/60 \text{ h}} = 60 \frac{\text{m}^3}{\text{h}}$$

- Time taken to pump water volume from a lake

Recalling Equation 2.1:

$$\text{Time to drain lake } = \frac{\text{water volume in a lake}}{\text{Pumping capacity}}$$

$$= \frac{V_{\text{Djupåvatnet}}}{Q} = \frac{5 \cdot 10^5}{60} = 8333{,}33 \text{ h}$$

- Following the hourly plan

For this case study, an hourly pumping cycle is proposed. In Section 2.1.1.3, the hourly plan was described and explained that according to it six hours of pumping is the optimal pumping time. In each cycle of six hours, the amount of pumped water is:

$$V = Q \cdot t = 60 \cdot 6 = 360 \text{ m}^3$$

- Time taken to fully pump $V_{\max}$

$$\text{Time to pump an allowed water volume of a lake } = \frac{\text{water volume allowed to be pumped } V_{\max}}{\text{Pumping capacity}}$$

$$= \frac{V_{\max}}{Q} = \frac{5 \cdot 10^4}{60} = 833{,}33\ \mathrm{h} = 138 \text{ cycles (days) of the hourly plan}$$

Note that this result does not consider the availability of runoff or precipitation.

1.3.5 Pumps selection

Required flow rate [m^3]/[h]	60
Required total head[10] [m]	83,83
Required pressure at the pump outlet [bar]	8,3

Table 34 Parameters of flow in case study C

- Deciding on pump type

Recalling Equations 2.2 and 2.3 at $N = 1450$ rpm:

$$\omega_P = \frac{\omega\sqrt{Q}}{(gh)^{\frac{3}{4}}}$$

$$= \frac{151{,}84\sqrt{0{,}016}}{(9{,}81 \cdot 72)^{3/4}} = 0{,}14$$

Where

$$\omega = \frac{2\pi N}{60}$$

$$= \frac{2\pi \cdot 1450}{60} = 151{,}84\ \mathrm{rad/s}$$

And

$$Q = 78\frac{\mathrm{m}^3}{\mathrm{h}} = \frac{60}{3600} = 0{,}016\frac{\mathrm{m}^3}{\mathrm{s}}$$

If

$$\omega_P < 1 \qquad \text{radial flow pump}$$

- Using one pump

Studying pumps that “North Ridge Pumps” provide as an example, after studying the head-flow rate, power, efficiency, and NPSH curves, we find that their pump series “North Ridge SKM-E End Suction Horizontal Centrifugal Multistage Pump” fulfills the requirements of this project. Choosing the pump “SKM-K 80/6”[33] in this case study, we get the following data for this pump:

Max flow rate $\frac{[\mathrm{m}^3]}{[\mathrm{h}]}$	80
Max head [m]	90
Number of stages	6
Pump materials	AISI304, AISI316, AISI316L, Bronze, Cast Iron, Cast Steel,

[10] Will be calculated later in matching pumps to system design

	Ductile Iron, Duplex, NiAl Bronze, Super Duplex
Inlet/outlet sizes[11] d_{pump}[mm]	80
Max suction lift (max height of the suction pipe) [m]	-
Operating Temperature [°C]	-10 to +140
Estimated price [NOK]	$15\cdot 10^4$

Table 35 Characteristics of the selected pump at 1450 rpm

1.3.5.1 Pumps characteristics

❖ **Power consumed**

In Section 2.3.1.2, it is explained how power consumption varies with the flow rates of the pump. However, it is given by Equation 2.7

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

As explained in Section 2.3.1, the pump's efficiency varies also with flow rate and depends on the specific final choice of the pump using parameters that are not studied in this case study such as the motor phases, voltage, and frequency. Assuming $\eta_p = 95\%$ for both types of pumps

$$P = \frac{Q \cdot H \cdot g \cdot \rho}{3600 \cdot \eta_p}$$

$$= \frac{60 \cdot 72 \cdot 9{,}81 \cdot 1000}{3600 \cdot 0{,}95}$$

$$= 12391{,}57 \left[\frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2}\right] \cdot \left[\frac{1}{\mathrm{s}}\right] = 12391{,}57 \left[\frac{\mathrm{J}}{\mathrm{s}}\right] = 12391{,}57\ [\mathrm{W}] = 12{,}39\ [\mathrm{kW}] = 0{,}0123[\mathrm{MW}]$$

Where $\left[\frac{\mathrm{kg}\cdot \mathrm{m}^2}{\mathrm{s}^2}\right] = [\mathrm{J}]$

❖ **NPSHa**

As we studied in Section 2.3.1.2, inlet pressure must be known to avoid cavitation.

Suggesting the layout in the following figure:

[11] Assumed to be ID (inner diameter)

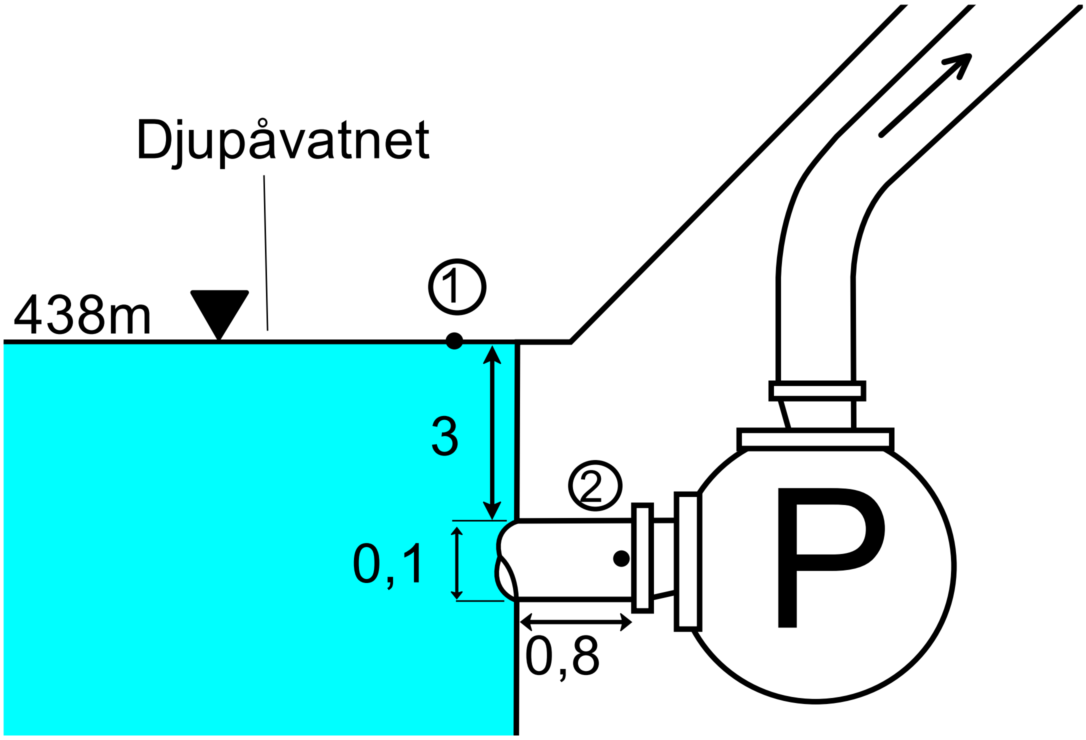


Figure 73 Proposed plan for the pumping station by considering recommendations in Chapter 2

We solve this problem by subtracting vapor pressure from pump inlet pressure and using the energy equation[11, Ch. 14.5].

- Applying the energy equation between points 1 and 2

$$\left(\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2\right)+\sum h_l$$

Where

Water velocity at the water surface is negligible $V_1 = 0$, $z_1 = 0m$, $z_2 = -2\ m$, z_2 is an assumed value that can be changed later to achieve larger NPSHa.

- Atmospheric pressure in meters of head

$$\frac{P_1}{\gamma}=\frac{101260{,}47[\mathrm{Pa}]}{9810\left[\frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}^2}\right]}=\frac{10.32[\mathrm{m}]}{1[\mathrm{m}]}=10{,}32$$

Because $[\mathrm{Pa}] = [\frac{\mathrm{kg}}{\mathrm{m}\cdot \mathrm{s}^2}][11, \mathrm{Tbl. F. 1}]$

- Friction head in the pipe

From Equation 2.8 we get the friction head[12]:

$$h_f = \frac{f \cdot L_1 \cdot {V_2}^2}{d_{pipe}\cdot 2g}$$

$$= \frac{0{,}0041\cdot 1\cdot (2{,}38)^2}{100\cdot 10^{-3}\cdot 2\cdot 9{,}81} = 0{,}011\ m$$

[12] L_1 is known from pipes calculations later in this case study

Where

$$f = \frac{0{,}079}{R_e^{1/4}} = \frac{0{,}079}{(133088{,}45)^{\frac{1}{4}}} = 4{,}13 * 10^{-3} = 0{,}0041$$

Because

$$R_e = \frac{V_2 \cdot d_{pipe}}{v}$$

$$= \frac{2{,}38 \cdot 100 \cdot 10^{-3}}{1.789 \ \cdot \ 10^{-6}} = 133088{,}45$$

Where

$$V_2 = \frac{Q}{A}$$

$$= \frac{\frac{60}{3600}}{0{,}007} = 2{,}38 \ \frac{\mathrm{m}}{\mathrm{s}}$$

Where

$$A = \frac{\pi}{4} d_{\mathrm{pipe}}{}^2$$

$$= \frac{\pi}{4} \cdot (100 \cdot 10^{-3})^2 = 0{,}007 \ \mathrm{m}^2$$

- Head loss due to pipe entrance

From Equation 2.10, we get the head loss at the pipe entrance

$$h_i = 0{,}5 \frac{{V_2}^2}{2g}$$

$$= 0{,}5 \frac{(2{,}38 \ )^2}{2 \cdot 9{,}81} = 0{,}14 \ \mathrm{m}$$

Putting the values into the energy equation

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) + \sum h_l$$

$$10{,}322 + 0 + 0 = \frac{\mathrm{p}_2}{1} + \frac{(2{,}38)^2}{2(9{,}81\ )} - 2 + 0{,}14 + 0{,}011$$

$$p_2 = 11{,}88 \ \ \mathrm{m} = 1{,}1 \ \mathrm{bar}$$

- Subtracting vapor pressure

Vapor pressure of water $P_v = 0{,}652$ kPa $= 652$ Pa $= 6.64$ m

$$\mathrm{NPSHa} = 11{,}88 - 6{,}64 = 5{,}24 \ \mathrm{m} = 0{,}52 \ \mathrm{bar}$$

$$\mathrm{NPSHa} > \mathrm{NPSHr}$$

$$5{,}24 \ \mathrm{m} > \mathrm{NPSHr}$$

- Conclusion

To determine the NPSHr (Net Positive Suction Head Required) of the pump, one needs to consult the manufacturer to get the pump curve or datasheet provided by them. This value can change using different parameters that are outside the scope of this case study, such as frequency, voltage, number of phases, and speed of the motor. Therefore, NPSHr is left as a variable here.

Once the value of NPSHr is obtained, the comparison of Equation 2.6 must be made. If the value of NPSHr was greater than the calculated NPSHa, decreasing the value of z_2 will be the solution (manipulating the equation to increase NPSHa with other methods such as manipulating the flow rate is possible too).

1.3.6 Pipes selection

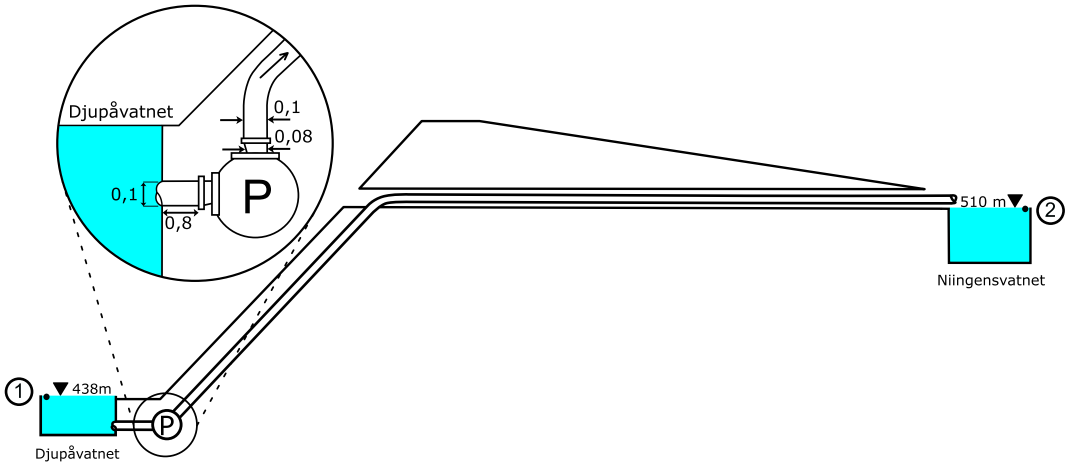


Figure 74 Dimensions for pumping station (in meters, unless otherwise stated)

- Suction pipe length

Using recommendations for pipes selection in Section 2.3.2.3, we find the length of the suction pipe

$$L_1 = 10 d_{\text{pump}} = 10 \cdot 0{,}08 = 0{,}8 \text{ m}$$

- Pipe diameter

Recommendations advise using a suction pipe one size larger than the inlet nozzle which is $d_{\text{pump}} = 80$ mm , then we select the pipe diameter (ID) $d_{\text{pipe}} = 100$ mm both for the suction and discharge pipe. Of course, for this change in diameter, we need to use an eccentric reducer at the pump's inlet from 100 to 80 mm and an eccentric increaser from 80 to 100 mm as discussed in Section 2.3.2.3.

- Discharge pipe length

The length of the discharge pipe is kept a variable here due to that different layout plans will have different pipe lengths. For the sake of calculations of water hammer and pipe thickness, this length can be assumed to be 1000 m.

- Material

"Carbon steel, AISI 1010, annealed" was chosen for all pipes in this document, see pipes selection in case study A.

- Wall thickness

From ASME-B31.1 we get the equation for wall thickness[55, Ch. 104.1]:

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$

Where

$P = 121{,}3 \text{ Pa} = 0{,}121 \text{ kPa}$ which is the water hammer pressure that will be studied later in this appendix.

$d = 100$ mm

$S = 7{,}7$ ksi $= 53089{,}63$ kP] (Using 25 and 45 in yield and tensile strengths respectively. From table A-1 choose Furnace Butt Welded Pipe API 5L at -15 $°C$).

$E = 0{,}60$

$y = 0{,}4$

$A = 25$ mm

$$t_m = \frac{0{,}121 \cdot 100 + 2 \cdot 53089{,}63 \cdot 0{,}60 \cdot 25 + 2 \cdot 0{,}4 \cdot 0{,}121 \cdot 25}{2(53089{,}63 \cdot 0{,}60 + 0{,}121 \cdot 0{,}4 - 0{,}121)} = 25{,}0002 \sim 25 \text{ mm}$$

Which is the maximum diameter that is calculated considering safety against water hammer. The pipe's diameter can be decreased with elevation as the water hammer pressure decreases with the shorter pipe length. So, lowering the water hammer pressure P will lower the thickness of the pipe and subsequently the diameter.

1.3.7 Other calculations and recommendations of case study C

❖ Underground and overground pipeline

In Section 2.3.2.1 the trenched pipelines plan was recommended as it helps overcome the problem of icing in pipes. Note that pipes have to either have an active flow or empty, but not have stationary fluid as this will be a reason for internal icing.

❖ Separate and joined pipeline

As discussed in Section 2.3.2.1, joined pipelines are not economically feasible for the cases in this thesis.

1.3.7.1 Matching Pumps to System Demand

In Section 2.1.3 we found that the available total head must overcome the required total head (resistance) for the water to be pumped.

$$h_a > h_r$$

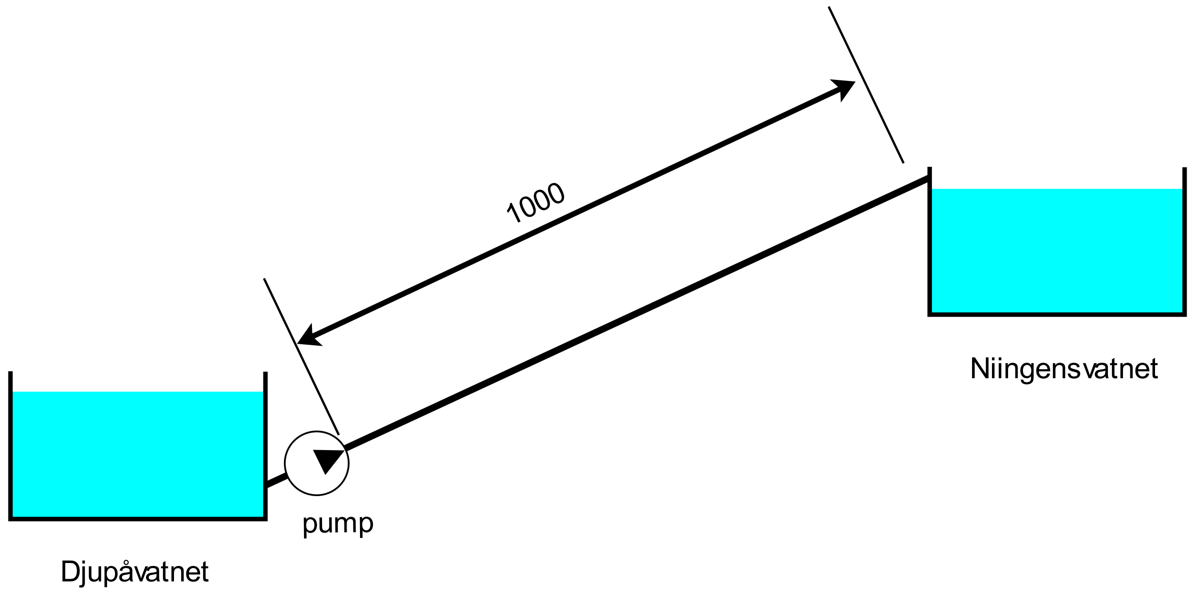


Figure 75 Understanding total pipe length between Djupåvatnet and Niingensvatnet

h_a is the available head at the pump's discharge outlet in addition to the static head provided by the lower reservoir.

$$h_a = 90 + 3 = 93 \text{ m}$$

$$h_r = h_l + h_s$$

Assuming that minor head losses due to bending and fittings etc. are negligible, the head loss is friction only.

$$h_r = \left(\frac{f \cdot L_2 \cdot V^2}{d_{\text{pipe}} \cdot 2g}\right) + (72)$$

$$= \frac{0{,}0041 \cdot 1000 \cdot 2{,}38^2}{100 \cdot 10^{-3} \cdot 2 \cdot 9{,}81} + 72 = 83{,}83 \text{ m}$$

$$93 \text{ m} > 83{,}83 \text{ m}$$

Which is accepted.

1.3.7.2 Water hammer

Water hammers can have many scenarios. The one we study in this case assumes having the pump at the first end of the pipe, followed by a valve that closes after an amount of water has been pumped towards Niingensvatnet.

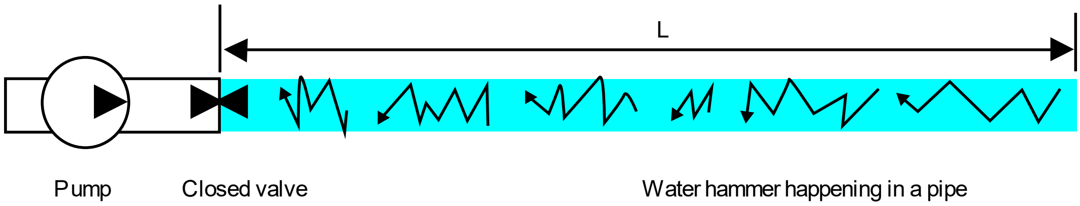


Figure 76 Water hammer in a pipe

Using two seconds as time for closing the valve and recalling equations from Section 2.3.2.4.

We consider the valve closure to be sudden if:

$$T < \frac{2L}{C}$$

We consider the valve closure to be gradual because:

$$T > \frac{2L}{C}$$

$$2 > \frac{2 \cdot 1000}{1449{,}13}$$

$$2 > 1{,}38$$

The closing time has to be greater than 1,38 $[sec]$ to be considered sudden.

- Gradual closure of the valve

$$P = \frac{LV}{gT}$$

$$= \frac{1000 \cdot 2{,}38}{9{,}81 \cdot 2} = 121{,}3 \text{ Pa} = 0{,}0123 \text{ m}$$

1.3.8 Financial calculations

1.3.8.1 Energy storage in the higher reservoir

It has been explained in this appendix of this appendix that the hourly plan is proposed to be used in this case. Meaning six hours of pumping will occur every day if this plan was to be followed strictly. It was also found that the volume of water that will be pumped in each of these cycles of six hours equals:

$$V = Q \cdot t = 60 \cdot 6 = 360 \text{ m}^3 \text{ per one cycle}$$

Putting pumping time to be a complete year (seven cycles a week, each of six hours, four times a month, 12 times a year) we get 2016 hours of pumping:

$$V = Q \cdot t = 60 \cdot 2016 \ = 120960 \text{ m}^3 \text{ per year}$$

Putting V in the Equation 3.1 to get the amount of energy in this volume of pumped water:

$$E \ = 2{,}77 \cdot 10^{-7} \cdot \eta_t \rho g h V [\text{kWh}]$$

$$= 2{,}77 \cdot 10^{-7} \cdot 0{,}95 \cdot 1000 \cdot 9{,}81 \cdot 510 \cdot 120960 = 159251{,}79 \text{ kWh} = 159{,}25 \text{ MWh}$$

1.3.8.2 Price per potential energy unit

Assuming that the high power-price is 1000 NOK/MWh, from Equation 3.2 we get the financial value of pumped water:

$$\text{Yearly expected revenue} = E \cdot \text{high power price}$$

$$= 159{,}25 \cdot 1000 = 0{,}15 \cdot 10^6 \text{ NOK}$$

1.3.8.3 Cost estimations of the project

- Capital investment

The total capital investment is given by:

$$C_{\text{Cca}} = C_{\text{pump}} + C_{\text{pipe}} + C_{\text{dam}} + C_{\text{tre}}$$

$$= 0{,}15 \cdot 10^6 + 2{,}04 \cdot 10^6 + 0{,}468 \cdot 10^6 + 5{,}65 \cdot 10^6 = 8{,}3 \cdot 10^6 \text{ NOK}$$

This value is based on the costs list below.

- Mechanical and electrical costs
  - Pumps costs

$$C_{\text{pump}} = 15 \cdot 10^4 \text{ NOK}$$

  - Pipes costs

The length of discharge pipes in this case study was assumed to be the same $L_2 = 1000\ m$

NVE's guideline "Cost base for hydropower plants for generating capacity of less than 10000 kW" (Kostnadsgrunnlag for små vannkraftanlegg (< 10 MW)) has estimations for pipe costs including their installations[56, No. 2012/3]. Reading FIG.4.6.3 in the mentioned reference, we find that for the pressure head of 510 m, and diameter of 80 to 200 mm, the average pipe price is 1500 NOK/m The updates from 2016 to 2023 show that mechanical costs have increased by 36,5%, causing the average pipe price to be 2047,5 Nok/m.

$$C_{\text{pipe}} = 2047 \cdot 1000 = 2{,}04 \cdot 10^6 \text{ NOK}$$

- Civil engineering costs
  - Dam and pumping chamber costs

For this project, dams must be built at reservoir outlets to control outflow and water levels. The pumping chamber has to be included in the dam construction, which is assumed to be a concrete gravity dam of five meters in height and 5 consecutive meters in width. Reading through NVE's estimation for dams, specifically FIG. 2.2.2[56, No. 2016/40], we notice that concrete dams cost 68000 NOK/consecutive meter, including price growth from 2015 to 2023 which NVE suggests that it is equal to 37,94[57] we get that the up-to-date price is 93772 NOK/consecutive meter.

$$C_{\text{dam}} = 5 \cdot 93772 = 468860 = 0{,}468 \cdot 10^6 \text{ NOK}$$

- Pipe trench

As discussed earlier in this appendix, trenched pipes are recommended for case study C along the whole discharge pipe. Reading through NVE's cost base for small-scale hydropower plants, especially chapter 2.5.2: Pipe trenches [56, No. 2016/40] we find that for a 1,5 m trench width at the bottom and 3,0 m depth, for a 1000 m length of combined earth/rock trench, the cost is set to 4160 Nok/m. No information included in the reports of NVE about the price development of trenches since 2015, so this value is assumed to be 36%, which is similar to the price development in concrete dams (37,9%) and mechanical costs (36,5%). The updated cost will be 5657,6 NOK/m.

$$C_{\text{tre}} = 5657{,}6 \cdot 1000 = 5657600 = 5{,}65 \cdot 10^6 \text{ NOK}$$

- Negligible costs:

As discussed in Section 3.4, the costs for valves, fittings, seals, and supports, as well as for taxes, land acquisition, transports, electro-technical equipment, and power lines, are not included in this study as they are either minimal or/and vary from project to project based on topology and geology of the region.

- Operational costs
  - Maintenance and personnel costs

From Section 3.4.2 we follow IRENA's estimation for yearly personnel and maintenance costs, which is estimated to be around 3% of the total investment cost.

$$(C_{\text{ma}} + C_{\text{per}}) = 3\% C_{\text{Cca}} = 0{,}03 \cdot 8{,}3 \cdot 10^6 = 0{,}24 \cdot 10^6 \text{NOK}$$

  - Pump power consumption

The pump's power consumption must be also added to the operational costs. Section 1.2.5.1 in this appendix shows how the value for power was calculated. Using the hourly plan, a pump works constantly for 6 hours a day, meaning that in the span of a year, it works 2016 h.

To convert Megawatts to Megawatt hours one can multiply by the number of operation hours to get a yearly energy consumption.

The low power price is assumed to be 500 Nok/MWh.

$$C_{\text{power}} = P \cdot \text{hours per year} \cdot \text{low power price}$$

$$= 0{,}0123 \cdot 2016 \cdot 500 = 12398{,}4 = 0{,}0123 \cdot 10^6 \text{ NOK}$$

Annual operational costs will be:

$$C_{\text{Cop}} = (C_{\text{ma}} + C_{\text{per}}) + C_{\text{power}} = 0{,}24 \cdot 10^6 + 0{,}0123 \cdot 10^6 = 0{,}25 \cdot 10^6 \text{ NOK}$$

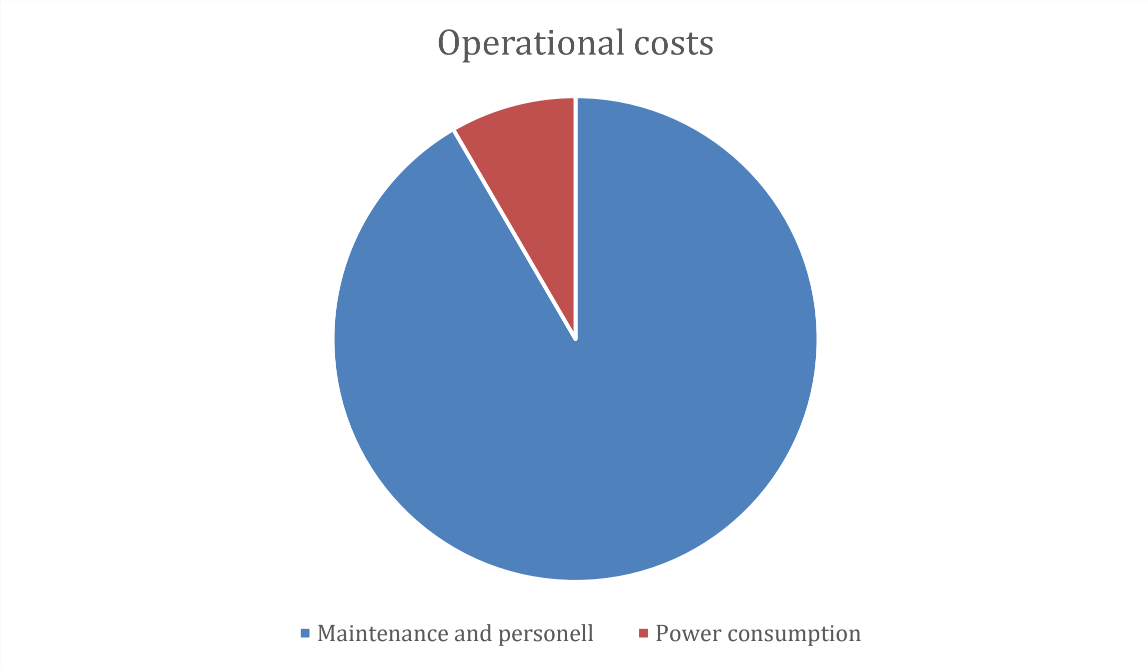


Figure 77 Pie chart of the proportions of operational costs

1.3.9 Conclusion of case study C

Capital investment cost[NOK]	$8{,}3 \cdot 10^6$
Yearly operational costs[NOK]	$0{,}25 \cdot 10^6$
Yearly expected revenue[NOK]	$0{,}15 \cdot 10^6$

Table 36 Comparison between costs and revenue of case C

Because $V_{\max}$ in case C is less than case B by two thirds, the revenue expected is less with almost the same capital and operational costs. Meaning that utilizing case study C will lead to yearly losses of 100000 NOK.

$$\text{Economic feasibility} = \text{Yearly expected revenue} - \text{Yearly opertaional costs}$$

$$= 0{,}15 \cdot 10^6 - 0{,}25 \cdot 10^6 = -100000 \text{ NOK}$$

This fact makes Djupåvatnet a less interesting reservoir for a pumped storage project as it can get drained much faster. On the other hand, considering the nearby lake, Blåvatnet is much more promising and cost-efficient, as it has a larger capacity at a higher elevation, reducing the operational costs generally while increasing the expected profit at the same time.

Profit can be made from Djupåvatnet only if yearly revenue exceeded the operational costs, and that only happens if V was in reality larger than its calculated value here. Moreover, developing the yearly expected revenue formula with respect to V.

$$\text{Yearly expected revenue} = E \cdot \text{high power price}$$

$$\text{Yearly expected revenue} = 2{,}77 \cdot 10^{-7} \cdot 10^{-3} \cdot \eta_t\, \rho g h V \cdot 1000$$

$$\text{Yearly expected revenue} = 2{,}77 \cdot 10^{-7} \cdot 10^{-3} \cdot 0{,}95 \cdot 1000 \cdot 9{,}81 \cdot 510 \cdot V \cdot 1000$$

$$\text{Yearly expected revenue} = 1{,}394V\,[\text{NOK}]$$

If the yearly expected revenue has to be larger or equal to yearly operational costs for profit to be made:

$$V \geq \frac{\text{yearly operational costs}}{1{,}394} = \frac{0{,}25 \cdot 10^6}{1{,}394} = 179340 \text{ m}^3 \text{ per year}$$

Meaning the pumping rate has to be at least:

$$Q = \frac{V}{t} = \frac{179340}{2016} = 88{,}95 \ \frac{\text{m}^3}{\text{h}} \text{ instead of } 60 \text{ m}^3/\text{h}.$$

To increase profitability, one can increase Q by tripling its value, for example, will increase yearly expected revenue three times, making the project able to retain its capital investment cost many times faster to start making a profit afterward, especially since the operational costs mostly are not proportional to power consumption as Figure 77 shows.

Using $Q = 288 \text{ m}^3/\text{h}$, in a course of a year V will be

$$V = Q \cdot t = 288 \cdot 2016 = 580608 \text{ m}^3 \text{ per year}$$

$$\text{Yearly expected revenue} = 1{,}394V[\text{NOK}]$$

$$= 1{,}394V[\text{NOK}] = 1{,}394 \cdot 580608 = 809367{,}552 = 0{,}8 \cdot 10^6 \text{ NOK}$$

At this point:

$$\text{Economic feasibility} = \text{Yearly expected revenue} - \text{Yearly opertaional costs}$$

$$= 0{,}8 \cdot 10^6 - 0{,}25 \cdot 10^6 = 0{,}55 \cdot 10^6 \text{ NOK}$$

Meaning it will take 10,375 years to retain the value of the capital investment and then starts making a profit. Note that further topological and geological studies have to be made to gain certain values of depth and volume of Djupåvatnet to be able to decide the practical flow rate values.

2 Additional knowledge

2.1 Pumped storage requirements

Generally, pumped storage hydropower systems have specific requirements to function effectively. Some of the essential requirements include:

1. Water supply: A constant supply of water is needed to ensure that the system can operate efficiently. This water is typically drawn from a natural water source, such as a river, and stored in a reservoir. It is then used to generate electricity when needed.
2. Two reservoirs: A pumped storage hydropower system requires two reservoirs, one at a higher elevation and one at a lower elevation. The difference in elevation between the two reservoirs creates the potential energy that is used to generate electricity.
3. Pumping system: A pumping system is needed to move water from the lower reservoir to the higher reservoir. This typically involves the use of pumps, which require energy to operate, as well as pipes used to transfer flow.
4. Turbines and generators: Turbines and generators are used to generate electricity from the potential energy created by the difference in elevation between the two reservoirs.
5. Transmission lines: Transmission lines are required to transport the electricity generated by the system to the power grid.
6. Environmental considerations: The construction and operation of a pumped storage hydropower system can have environmental impacts, particularly on local ecosystems and water resources. Careful consideration must be given to these impacts, and appropriate mitigation measures should be implemented as needed.[10]
7. Meteorological prediction types of equipment for better forecasting of weather changes in the watershed are precisely estimating operating cycles based on the data.
8. Regulating the lakes is required by installing measurement devices on the dams, outflow, and inflow streams to monitor the water levels of reservoirs at all times.

In terms of the Niingen power plant, as it is in the arctic circle, more requirements must be achieved to assure its security and functionality. Some of the requirements are:

2. Ability to perform water pumping in the given conditions. In the case of the Niingen power plant, under the harsh arctic winter weather which includes low temperatures and high snowfall.
3. Extreme weather protection: The equipment and infrastructure associated with pumped storage hydropower systems must be designed to withstand extreme weather conditions, such as high winds, heavy snowfall, and freezing temperatures.
4. Insulation: Insulation is essential for protecting equipment from extreme cold, as well as for reducing energy loss during the pumping and generation processes.
5. Anti-icing measures: In areas with extreme cold and ice buildup, anti-icing measures may be necessary to prevent the buildup of ice on equipment, such as turbines and transmission lines, which can cause damage and reduce efficiency.
6. Remote monitoring and control: Given the remote location of many pumped storage hydropower systems in the Arctic Circle, remote monitoring and control systems are essential for ensuring that the system is functioning properly and for identifying and addressing any issues in real-time.
7. Environmental considerations: In the Arctic Circle, there are additional environmental considerations, such as the impact of the system on local wildlife and the need to protect delicate ecosystems. Appropriate mitigation measures should be implemented as needed to minimize these impacts.

2.2 Pumped storage advantages and drawbacks

Advantages

- Larger and longer storage than batteries [3]
- Cost-effective and cheaper for overnight and long-term storage [3] The energy efficiency of pumped storage projects varies from 70% to 80% but also can reach up to 87%"[15] Energy

losses result from the water evaporating from the surfaces and from the losses of mechanical efficiency when flow converts to energy[58]

- Can provide profitable opportunity by storing water as potential energy during energy low prices times and converting it to electrical energy and selling it during high prices times.
- Compensates for intermittent power sources such as wind and solar in hybrid systems. For instance, in solar-hydro and wind-hydro power plants.
- Flexible start/stop and fast response speed. [15], [59]
- Ability to track load changes and adapt to drastic load changes [15], [59]
- Can modulate the frequency and maintain voltage stability [15], [59]
- Mature technology, meaning that numerous pumped storage developments have been done in the previous decades and there is great accumulative storage of data and experience in this domain.
- Renewability and sustainability. Pumped storage is one of the most feasible and sustainable methods for storing energy and is a significant assist to hydroelectric power plants.

"The water can cycle between upper and lower reservoirs for a hundred years or more. In all, the amount of water needed to support a 100% renewable electricity system is about 3 liters per person per day, equivalent to 20 seconds of a morning shower. This is one-tenth of the water evaporated per person per day in the cooling systems of U.S. fossil fuel power stations." [3]

Drawbacks

- Risk of water evaporation and loss is still existing in the places where the reservoir has no source for refilling it, especially when using closed-loop pumped storage systems.
- The need for upper heights of the water reservoir compared to the water outlet to make the power production more efficient because of the low energy density of the system.