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A Study of hydro and pumped storage hydropower in Northern Norway

Emefa Akua Ampim
Sujan Maharjan
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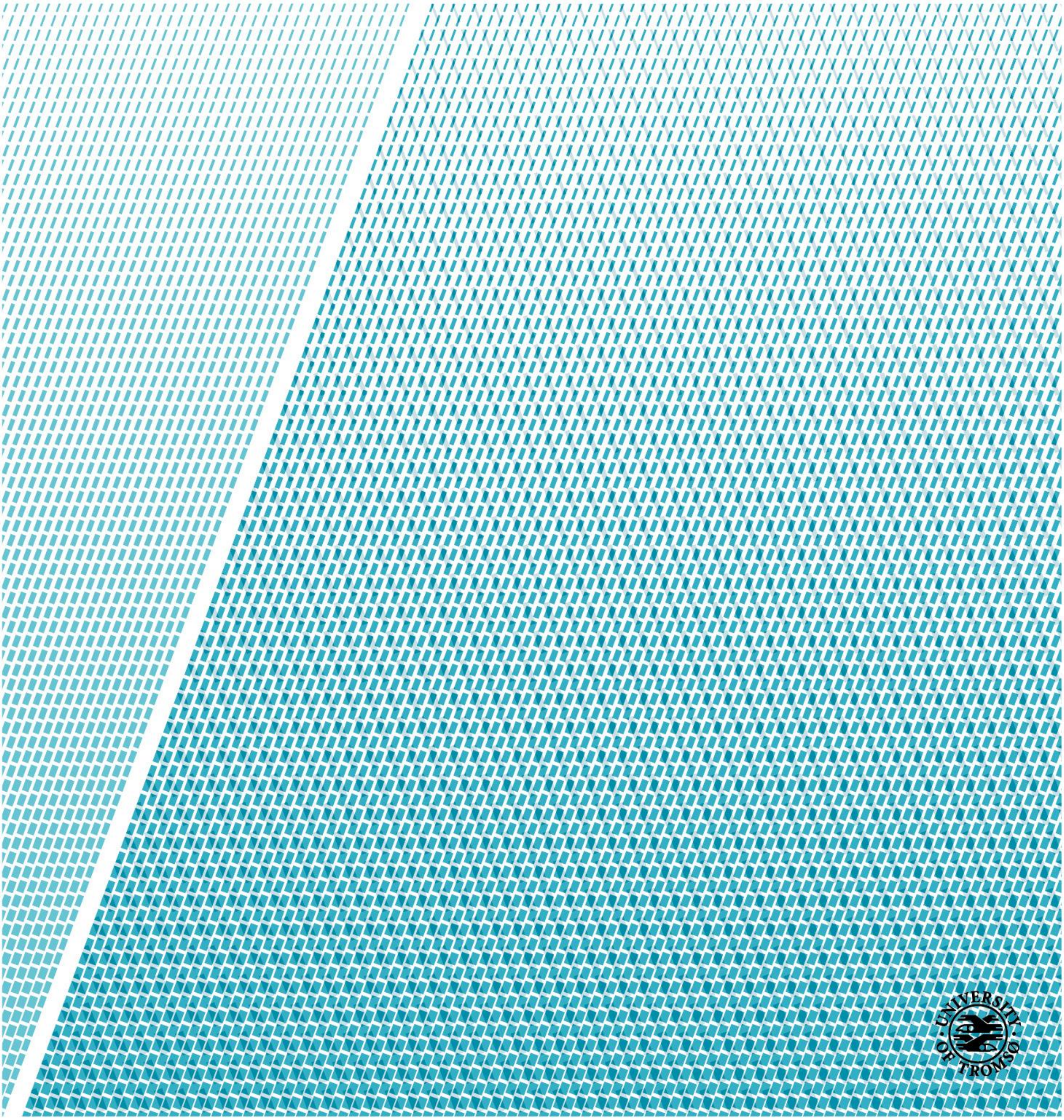

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PREFACE

This thesis was undertaken as part of a master's programme under Engineering Design at the Faculty of Engineering Science and Technology of University of Tromsø in Norway. Our keen interest in incorporating renewable sources of energy where ever possible in most of our design projects at school made this thesis topic on "A Study of hydro and pumped storage hydropower in Northern Norway" catch our attentions.

The thesis format is in three sections which are as follows:

Section A	A detailed review into renewable energy systems on goals, policies, achievements and future developments in the European Union. The state of Norway energy sector is also included.
Section B	Gives a detailed study into hydropower and pumped storage hydropower, its design parameters and cost hypothesis
Section C	A trial study on PSH potential sites in Norway and operations in balancing energy by using the PSH model
Appendix	

These sections sum up our study on the topic. Hope you enjoy reading. Thanks

Emefa Akua Ampim (eam009)
eam009@post.uit.no
Sujan Maharjan (sma119)
sma119@post.uit.no

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Also, we are grateful to our Supervisor, Associate Professor Guy Beeri Mauseth for the critical work in pointing out important things about our preliminary write-ups which helped in the concise presentation of our work.

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Sujan Maharjan

Emefa Akua Ampim

ABSTRACT

The role of renewable sources of energy in combating climate change cannot be overemphasised. Profound measures taken especially by the European Union (EU) in reducing global rising temperatures has seen massive development of renewable sources of energy such as solar and wind. This strategic plan taken by the EU has led to the an increase in national efforts to promote further development of renewable energy systems as well as increased exchange of power between member states due to the challenge of storing energy generated from these sources.

If much energy is going to be produced from these sources, this challenge calls for an increasing need for energy storage to balance power by compensating for the difference between production and consumption. The growing synergy among EU member states has made it possible for Norway to be selected as the “Green Battery” of Europe by developing Pumped Storage Hydropower (PSH) plants as a means of storage technology, the most feasible among all the storage technologies available today. This is achieved by using “surplus” power to pump water to an upper reservoir which can be release back into a lower reservoir to generate power when there is demand.

With the topography of Norway favouring the development of PSH schemes, much research has been carried out especially in Southern Norway and it is estimated that 20 000 MW of power is possible to be generated. This report carries a review specifically on possible sites for the development of PSH in Northern Norway. Results gathered from the screening process in the region shows that a total of 84 pairs of reservoirs can be used, summing up to 19 different potential PSH projects in Northern Norway. The power generation from these PSH projects is estimated to be 25 000 MW. The total cost from an estimated cost analysis reaches to about 526 Million Kroner.

The study further carries out a detailed analysis on the proposed Isvatn-Langvatnet PSH project by running the PSH Model on the chosen reservoir pairs with wind data from the North Sea (in our case). The water level fluctuation used for the reservoirs in the study is 13cm/h for the HRWL and LRWL. Considering factors such as turbine capacity and free reservoir volumes, it is observed that there is 1 hour having no balancing demand with 160 hours also having no actual balancing operation. Number of hours have a balancing demand but no actual operation is 159 hours, this is due to the limitation of shared capacity and limitation of the lower reservoir. The outcome of the simulation process, considers factors which optimises the mode of the PSH power plant in terms of the economical and its effective operation, which was also used in the hypothesis cost estimation for the PSH projects.

LIST OF ABBREVIATIONS

7 Days Avg	:	7 Days Moving Average Scenario
CEDREN	:	Centre for Environmental Design of Renewable Energy
Dev Avg	:	Deviation Average Scenario
EEA	:	European Environmental Agency
EES	:	Electrical Storage System
EPA	:	Environmental Protection Agency
ESA	:	Energy Storage Association
EU	:	European Union
GW	:	Gigawatt
GWEC	:	Global Wind Energy Council
GWh	:	Gigawatt per hour
HRWL	:	Highest Regulated Water Level
IEA	:	International Energy Agency
IEC	:	International Electrotechnical Commission
LRWL	:	Lowest Regulated Water Level
masl	:	Metres above sea level
MW/kW	:	Mega/Kilowatt
NASA	:	National Aeronautics and Space Administration
NMPE	:	Norwegian Ministry of Petroleum and Energy
NOK	:	Norwegian Kroner
NSCOGI	:	North Seas Countries' Offshore Grid Initiative
NVE	:	Norwegian Water Resources and Energy Directorate (Norges vassdrags og energidirektorat)
PSH	:	Pumped Storage Hydropower
REN21	:	Renewable Energy Policy Network for the 21st Century
SINTEF	:	Foundation for Scientific and Industrial Research (Stiftelsen for industriell og teknisk forskning)
TWh	:	Terawatt per hour
WEC	:	World Energy Council

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1 INTRODUCTION

The increasing rise of temperatures on earth has led to more awareness on global warming with diverse measures being put in place to protect the planet. Climate and Energy Organisations have enacted stringent measures aimed at cutting down on the increasing trend of global temperatures. The warming is mainly due to the emission of greenhouse gases which trap heat in the atmosphere, these gases include carbon dioxide (81%), methane (11%), Nitrous oxide (6%) and fluorinated gasses (3%) (EPA, 2017). The rise in global temperatures has challenging consequences on subsistence of lives with adverse effects such as severe droughts, storms and floods, the risk of extinction of several animal species and the melting of glaciers that will lead to rising sea levels with low lying lands facing the danger of being submerged.

These devastating effects as stated above are avoidable by the measures being put in place since most of the sources comes from the careless activities of humans. Organisational bodies such as the EU, IEA, WEC and other several organisations have put several measures and policies in place with all determination to meet the targets that they have set in place. In meeting these targets, agencies and campaign committees have been set up to fully channel the course of saving the earth including more research programs that are being undertaken on how best renewable sources of energy available can be fully exploited for maximum utilization.

The action taken is reflected in global energy statistics with the reduction in the use of fossil fuels (Fossil fuels are non-renewable energy, meaning, they utilize limited resources that will ultimately deplete, hence, driving up overall energy costs) (Kukreja, u.d.) to renewable sources especially among member states of the EU.

The plan to switch more to renewable sources of energy and other non-pollutant sources has its own challenges to deal with. One main challenge is that renewable sources of energy are unreliable and depends on the state of the weather. There may be less output of energy when in demand and vice versa.

The EU in an attempt to deal with this challenge has established that there should be more cooperation between member states in the area of energy where member states can trade energy with less restrictions. This has led to the increasing study into possible applications of energy storage in power systems across borders to compensate for the difference between the production and consumption in other to balance the power generated. These energy storage systems can help solve this challenge since energy captured can be converted efficiently and controlled to correspond demands.

Investigations pointed out that Norway, had resources that can solve the problem in terms of being the “Green Battery” to store the surplus renewable energy generated by member states. Norway has 96% of its power generated from hydropower and it is of no doubt the country because of its geographical conditions came out to be the best country to facilitate this storage program by the adaptation of Pumped Storage Hydropower.

The PSH system works by the use of two reservoirs, where the surplus energy generated will be used to pump water to a higher reservoir, when the energy is in demand the potential energy gained by the storage in the upper reservoir is converted to electrical energy by running the water through turbines again to the lower reservoir. This project investigates the possibility of the PSH projects in the Northern Norway.

1.1 Objectives of the Study

The objective of the study is to compare the current patterns of water level fluctuation to the simulated patterns such as time periods, change frequency and rate, and to analyse which factors (e.g. Turbine capacity, free reservoir volumes) determine how much power can be balanced compared to how much is required with pumped storage hydropower in the North of Norway.

2 STATE-OF-THE –ART: WORLD CLIMATE

Climate change is the change in climate (i.e. regional temperature, precipitation, extreme weather, etc.) caused by increase in the greenhouse effect. The greenhouse effect comes about when greenhouse gasses such as carbon dioxide, methane, nitrous oxide, etc. in the atmosphere absorb and re-emit heat being radiated from the earth. This phenomenon eventually increases the average global temperature by trapping heat when they absorb infra-red radiation.

Historical measurements show that the current global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide are unprecedented compared with the past 800,000 years (Anon., 2017). A greater part of the greenhouse gas emission comes from energy related carbon dioxide emissions. These emissions can be lowered in two as stated by IEA.

- Lowering CO2 emissions on the supply side. Example: by switching electricity generation from fossil fuels to renewables.
- Lowering emissions on the consumption side through reduced consumption, substitution and improved efficiency. Example: using a bicycle for a short journey instead of a car. (EPA, 2017)

The IEA's Energy Technology Perspective 2008(ETP) publication projects that the energy sector emissions of GHG will increase by 130% over 2005 levels, by 2050 in the absence of new policies (IEA, 2010). NASA and NOAA data on the earth's surface temperatures reports that 2016 was the warmest since modern record keeping began.

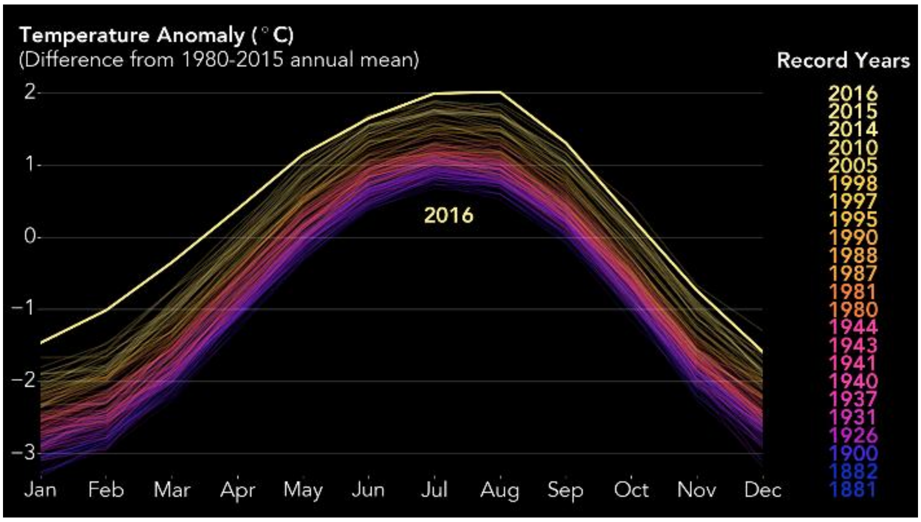


Figure 1: Increasing temperatures over the years (NASA, 2017)

From NASA records, the global-average temperature was recorded to be 0.99°C, thus the average surface temperature of the earth's surface has risen by about 1.1°C, this rise mainly attributable to increased carbon dioxide and other emissions.

2.1.1 Consequences of Global Warming

The rise in the average global temperature means;

- Glaciers in the artic will continue to melt and sea levels will rise by 1-4 feet by 2100 (NASA, 2017) putting low lying lands at the risk of being submerged under water
- Drastic change in the weather patterns that can lead to changes in rainfall patterns (flooding), storms becoming more strong and intense and rising temperatures leading to heat waves and draught.
- Negative impacts on economy due to health-related issues and on lives.
- Negative impacts on ecosystems and agriculture altering the normal pattern of planting and harvesting which can spark regional conflicts, malnutrition, famine and immigration issues.
- High risk of the extinction of some plant and animal species

2.1.2 Pollution Trends from power generation

Fossil fuels used for power production continue to dominate the energy mix globally. There has been an immerse expansion in the generation of electricity from renewable sources, howbeit majority of the world's power generation continues to come from the combustion of fossils, with coal-fired generation still providing the backbone of the global power system which is around 40% of global electricity supply. (IEA, 2016) . It is estimated that over 80% of the energy turnout comes from fossil fuels, which during their processing give off carbon dioxide supposedly being the main greenhouse gas.

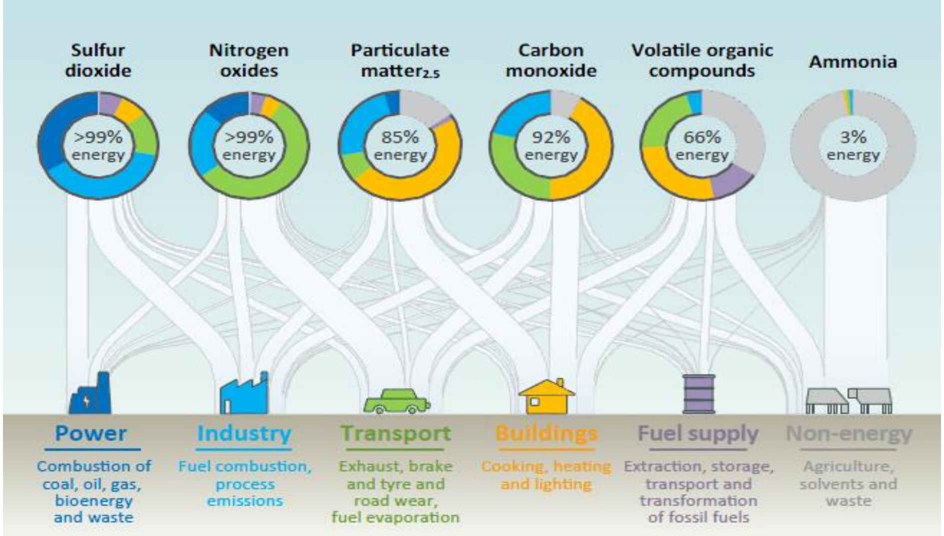


Figure 2: Primary Air pollutants and their sources in 2015 (IEA, 2016)

From Figure 2 it can be seen that the combustion of coal has a fair percentage in the pollutants emission, it is in this regard that renewable energy sources are being developed to serve as a major source of power generation. The underlying factor is that the negative effects of climate change cannot be addressed without taking action on energy.

2.2 European Union on Climate Change

The EU is the world's second largest economy consumes one fifth of the world's energy and the world's largest importer of energy. Between 2000 and 2015, the share of renewables in the EU's total power capacity increased from 24% to 44%, and, as of 2015, renewables were Europe's largest source of electricity (REN21, 2016). At the end of 2014 out of the 13805 Mtoe of energy produce globally, EU had a percentage share of 5.6%. (EU, 2016)

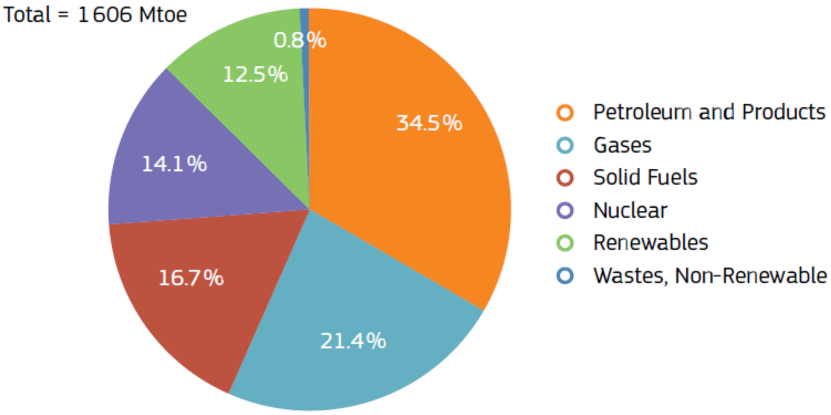


Figure 3: Percentage of non-renewable energy

The energy mix of the EU shows clearly that the percentage of non-renewables energy production is far greater than renewables. To cut down on the GHG, EU has the obligation to increase its share of renewables and to achieve this, measures have been put in place to reduce the current levels by the implementation of goals and policies especially in the energy sector. The policies on climate change are tailored towards:

- Protecting the source of energy supply

- Safeguarding that these policies on energy does not make Europe's energy market less competitive
- Protecting the environment especially by addressing issues with climate change.
- improving energy grids in the region

With climate change being the most challenging of the goals, the international community has agreed on targets to be achieved to keep the climate change below dangerous levels. The climate and energy framework sets three (3) key targets;

- To cut greenhouse gas emissions (from 1990 levels) by at least 20% by 2020 and 40% by 2030
- To increase the share for renewable energy up by at least 20% by 2020 and 27% minimum share by 2030
- To improve energy efficiency by 20% by 2020 and 27% minimum improvement by 2030.

These objectives have seen much advancement throughout Europe and has led to a striking increase in renewable energy production capacity. In 2011 over 100 gigawatts of solar panels were installed worldwide and Europe's percentage share was 70% (EU, 2014).

2.3 Renewable Energy Development in the EU

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. (Wikipedia, 2017) The increasing awareness on global warming and its negative impacts on the planets has led to the shifting from the dependency on fossil fuels to these sources of energy to facilitate the drive towards sustainable development. From the United Nations;

> *"Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs and calls for concerted efforts towards building an inclusive, sustainable and resilient future for people and planet; this to be achieved by three core elements: economic growth, social inclusion and environmental protection, which are interconnected and all are crucial for the well-being of individuals and societies"* (UN, u.d.)

The talk on environmental protection cannot be discussed without the mention of renewable energies in sustainable development. The role of renewable energy is immense by contributing factors such as;

- The provision of jobs, it is estimated that solar PV has the highest employment in the renewable energy sector, with roughly 2.5 million jobs, liquid biofuels coming second with 1.8 million jobs followed by wind power with approximately one million jobs across the globe. (Hettipola, u.d.)
- Emission of greenhouse gasses (GHG) are cut down drastically with the use of renewable sources of energy
- Renewable sources of energy are diverse and promotes energy security.

In 2013 renewable sources of energy accounted for almost 22% of global electricity, which is foreseen to increase by 26% in 2020 (IEA, 2016). Ten (10) countries that have developed their wind power capacity according to GWEC are China, United States of America, Germany, Spain, India, United Kingdom, Canada, France, Italy and Brazil.

Wind power now provides 2.5% of global electricity demand and the second largest renewable electricity source – and up to 30% in Denmark, 20% in Portugal and 18% in Spain (IEA, 2013). Depending on where the energy can be best harnessed, wind farms can be either onshore or offshore. The offshore sector had a strong year with an estimated 3.4 GW connected to grids, mostly in Europe, for a world total exceeding 12 GW. (REN21, 2016)

On solar energy, WEC reports that the global installed capacity for solar-powered electricity has seen an exponential growth, reaching around 227 GW at the end of 2015, comprising 1% of all electricity used globally (WEC, 2016). The total global Capacity by the end of 2015 amounted to about 227GW (REN, 2016). The leading country in PV installations is china followed by the USA, Japan, Germany and Italy.

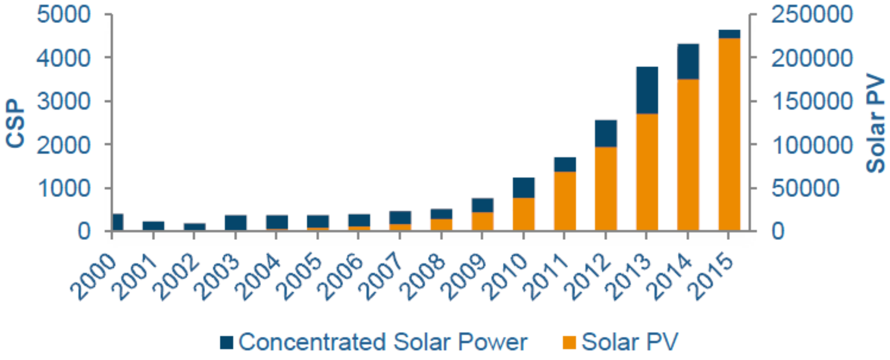


Figure 4: Global installed solar power capacity, 2000-2015 (WEC, 2016)

Hydropower is the leading renewable source of electricity generation globally, supplying 71% of all renewable electricity at the end of 2015, with 33.7 GW of new installed capacity, including 2.5 GW pumped storage, bringing the total hydropower capacity to 1,212 GW worldwide (IHA, 2016). Undeveloped potential is approximately 10000 TWh/y worldwide (WEC, 2016). Estimates show that hydropower of which pumped storage is included forms about 99% of the world’s electricity storage capacity (IEA, 2016). A report from the WEC on World Energy Resources Hydropower indicates that,

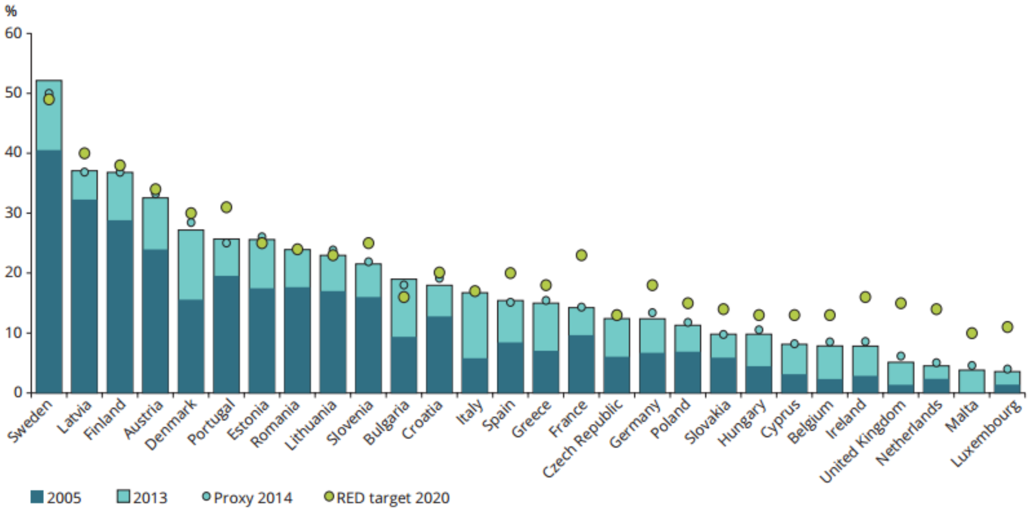
> *“Hydropower is the leading renewable source for electricity generation globally, supplying about 71% of all renewable electricity. Reaching 1,064 GW of installed capacity in 2016, it generated 16.4% of the world’s electricity from all sources. It also estimates the availability of approximately 10,000 TWh/year of unutilised hydropower potential worldwide.”*

Due to its technological, economic, and environmental benefits, hydropower is considered to be a significant contributor to the future world’s energy supply (Gonzalez, et al., 2011).

2.3.1 European Union’s Progress on the development of Renewable Energy

The EEA’s report on renewable energy in Europe for 2016 indicates that the EU’s policies in meeting its targets of reducing emissions is working according to plan. In 2015, greenhouse gas emissions in the EU were 22% below the 1990 level (EU, 2017). Energy statistics from the British Petroleum published in June 2016 shows that Europe and Eurasia regions regions had the highest share of power from renewables with a percentage share of 39.2%.

In solar energy, Germany is the world's largest producer of solar power with an overall installed capacity of 38.2 GW and second after China with 20.6% in total PV installed capacity in 2015 (wikipedia, 2017). Wind power for example in the EU had its capacity in operation at end of 2015 enough to cover an estimated 11.4% of electricity consumption in a normal wind year (REN21, 2016).



Note: The dark blue bars show the RES shares in 2005. The tops of the light blue bars show the levels that the RES shares reached in 2013.

Figure 5: 2013 RES shares for EU Member States [EEA, 2016]

Figure 5 above shows the actual RES shares in the EU Member States for 2005 and 2013 and the approximated RES shares for 2014. Member states including Sweden (52.1 %), Latvia (37.1 %) and Finland (36.8 %) achieved the highest shares of renewable energy in 2013 with some hitting their 2020 targets already. However, countries such as Malta, Luxembourg and the Netherlands being the last three countries on the chart have not seen much development. Wind Europe's annual statistics report released in February 2017 indicates that the renewable energy accounted for 86% of all EU power installations constituting 21.1 GW of a total of 24.5 GW of new power capacity. This is an indication of the increasing efforts of the EU in adding more capacity to the already existing renewable sources of energy available which is mostly in the area of wind and solar energy. This in effect has put the EU second to Japan on the GHG emissions intensity statistics. The massive development of these energy sources has consequently led to the need to balance power generated from these renewable powers due to fluctuations in their output, as such there is the need to indemnify the disparity between the production and consumption by possible electrical energy storage systems available.

2.4 EU and the NSCOGI

North Seas Countries Offshore Grid Initiative (NSCOGI), is a collaboration between EU member-states and Norway to create an integrated offshore energy grid which links wind farms and other renewable energy sources across the northern seas of Europe (Wikipedia, 2017).

The need to store energy generated from these renewable sources led to the formation of this initiative so as to meet the EUs objective to provide consumers with sustainable, secure and affordable energy, placing much importance on the need to enhance regional cooperation and to create good conditions for the development of offshore wind energy (E U, 2016).

Norway, considered to become the “battery” of Europe is to help make this possible by the use of PSH storage mechanism due to the favourable topography of mountains, gorges, fjords and natural lakes ideal for the development of hydropower and the PSH system.

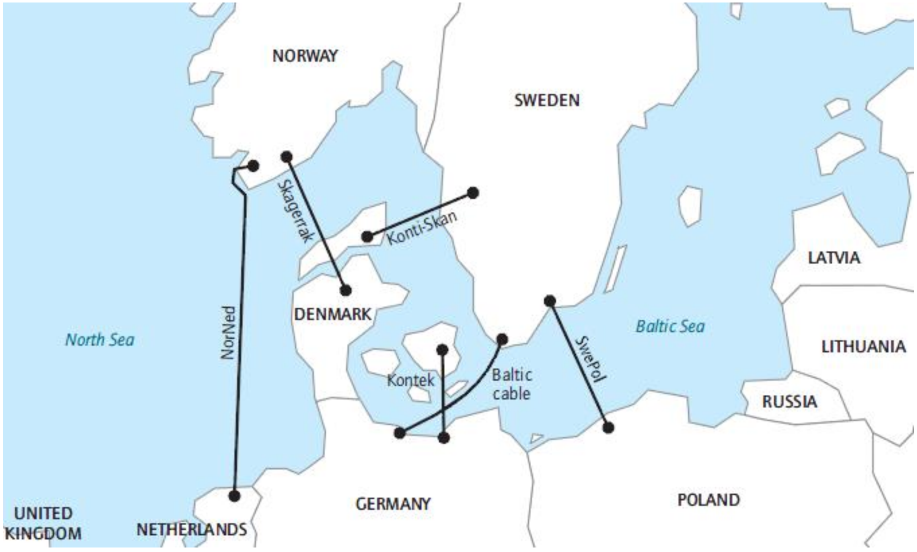


Figure 6: Northern Europe interconnections (source: Hydropower roadmap 2012

Studies from IEA estimates that Europe requires close to 100 GW of new added capacity between 2016 and 2035 to sustain the grid reliability while supporting the 250W increase in renewable capacity (IEA, 2014).

The CEDREN HydroBalance project has found the balance capacity potential of southern parts of Norway to be at least 20 000 MW of energy using existing reservoirs, in addition to the construction of new hydropower and pumped storage plants (Solvang , et al., 2014).

3 ENERGY IN NORWAY

Energy and water resources in Norway are manged by the Ministry of Petroleum and Energy, with Statnett SF and Enova SF as enterprises under the ministry.

3.1 Wind Energy

In 2016, 2.1 TWh of energy was generated from wind power from the total installed capacity which stands at 873 MW spreading over 374 wind turbines. In the overall power production, it accounted for 1.4% of the total. Figure 7 below shows the data for installed capacity of wind power in Norway.

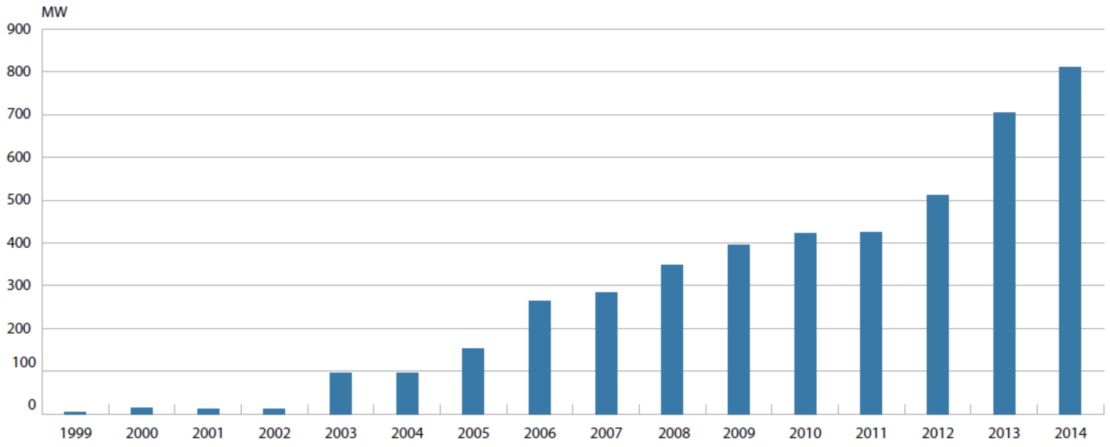


Figure 7: installed wind power capacity in Norway (1999 to 2014). (NMPE, 2015)

The Fosen project, is a group of six onshore wind power farms now being built on the Fosen peninsula in the Trøndelag region of Norway. The wind farms will contain a total of 278 giant wind turbines, which together will generate 1 GW of energy. This will make the project will be one of Europe's largest onshore wind farm and more than double Norway's wind energy generation capacity currently. Offshore wind energy in the North Sea has seen major developments.

3.1.1 Wind Energy in Northern Norway

In Northern Norway, there are about seven wind farms, with only five of them on large scale and being operated fully. Most of the windfarms are located in the Finnmark County. The planned and decided wind power projects to be developed in the future are listed in Appendix A.1 and A.2.

3.1.1.1 Nygårdsfjellet wind farm

The Nygårdsfjellet wind farm is located in Narvik and operated by Nordkraft. It consists of 14 wind turbines with a total capacity of 32.2MW with each installed capacity of 2.3MW. The average annual production is 105GWh.

3.1.1.2 Fakken wind farm

The Fakken wind farm operates with a total of 18 turbines and generates a total power of 54,000kW. The farm produces about 138 GWh/year and it is operated by Troms kraft AS.

3.1.1.3 Havøygavlen wind farm

Located in the Måsøy municipality, the farm has an installed capacity of 40.5MW. A total of 16 turbines are installed with each turbine capacity ranging between 2.5-3MW and has an annual output of about 100GWh. It is operated by Finnmark Kraft.

3.1.1.4 Raggovidda wind farm

Raggovidda wind farm has a total capacity of 45MW, consisting of 15 wind turbines with a capacity of 3MW each.

3.1.1.5 Kjøllejord wind farm

Kjøllejord wind farm is also located in Finnmark specifically on Mount Gartefjell. It has a total installed capacity of 39.1MW. A total of 17 wind turbines are installed, with each installed capacity of 2.3MW and operated by Statkraft AS.

3.2 Gas-fired power plants and other thermal sources energy

Gas-fired and thermal sources of energy forms a small percentage in Norway's energy mix. There are three major gas-fired power plants located in Kårstø, Mongstad and Melkøya. Melkøya has an installed capacity of 215 MW and 167 MW for electricity and heating respectively, of which 1.5 TWh of annual electricity production is expected. Mongstad also has an installed capacity of 280 MW (NMPE, 2015). However, due to less power prices from the Kårstø power plant it is was shut down in 2014.

3.3 Hydropower

Norway is Europe's largest producer of hydropower, sixth in the world and has about 4000 rivers systems each of which comprise a river and all its streams, lakes, snowfields and glaciers.

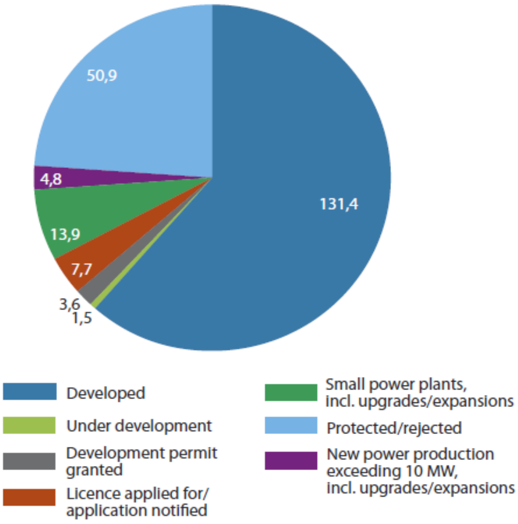


Figure 8: Norway's hydropower (TWh/year) potential overview as of January 2014. Source: (NMPE, 2015)

The figure above shows the percentages of the state of hydropower resources in the country.

3.3.1 Pumped Storage Hydropower in Norway

Currently there are a few existing pumped storage hydropower plants in Norway mostly in the southern part of the country. Studies show that there are many possible sites for PSH using only existing reservoirs with capacity from about 250 to 2500 MW and a capacity of up to 5000 GWh per cycle for bulk storage (Eivind Solvang, 2014). Lake Blåsjø, one of the reservoirs stores up to 8 TWh of energy. PSH balancing capacity has 29 GW installed currently and 20 GW capability in the future by 2030 (Harby , et al., 2013). Currently, there are no pump storage hydropower systems in Northern Norway, all the existing PSH systems are located in the Southern part of the country.

3.4 Norway’s Energy Statistics for year 2015

Norway’s energy statistics is affected by demographic, economic, technological and climatic factors. Electricity accounts for a significantly higher share in energy consumption in Norway as compared to other countries and this is attributed to the large energy-intensive manufacturing sector in the country and its usage in the heating of buildings and water. Figures by Statistics Norway shows that a total of 2398 TWh of energy was produced in 2015. Natural gas constituted about 1188.9 TWh amounting to 49.6% forming the highest percentage followed by crude oil (37.3%) and hydroelectric and wind energy (5.9%). The lowest percentage being coal with a percentage share of 0.4%.

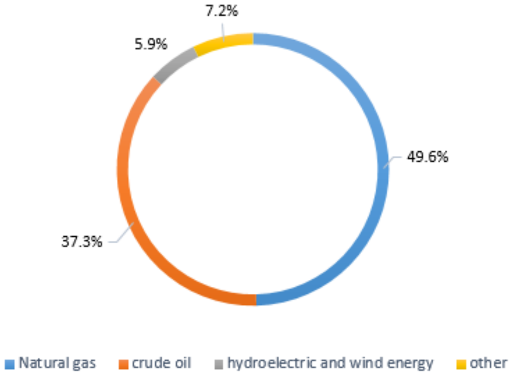


Figure 9: Total energy production in 2015 (Statistics Norway, 2016)

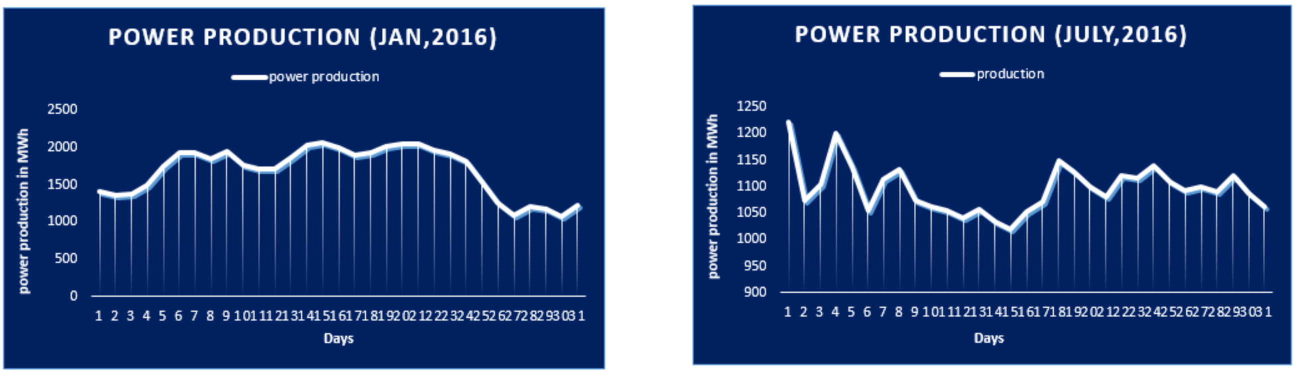
Out of the total of 2398 TWh of energy produced, 2142 TWh was exported to countries such as United Kingdom, Netherlands, Germany and France accounting for 75% of the energy export from Norway whereas an amount of 90 TWh was imported. The net domestic energy consumption excluding raw materials in total was 213 TWh with the manufacturing, mining and quarrying sector using 66 TWh. The transport sector utilised 58 TWh of the amount leaving 89 TWh of energy to be used by other sources such as electricity, district heating, etc. The use raw materials such as petroleum, LPG and natural gas in manufacturing for energy purposes rose by 23 TWh, a percentage rise of 5% over the previous year which is 2014. This is reflected the rise in energy consumption in households and services.

In the transport sector, around three-quarters of the total consumption of petroleum products in the form of oil products were used for transport purposes and this saw an increase of about 0.7% from 2014-2015. In totality, production of primary energy products increased by 5% from 2014-2015.

3.4.1 Power load curves

The power load curves for Norway normally follow a trend dependent on temperature and activities in businesses and households. Peak electricity consumption occurs during the winter when high proportion of electricity is used for heating spaces in households and commercial buildings. This decreases gradually towards summer when there is less or no heating.

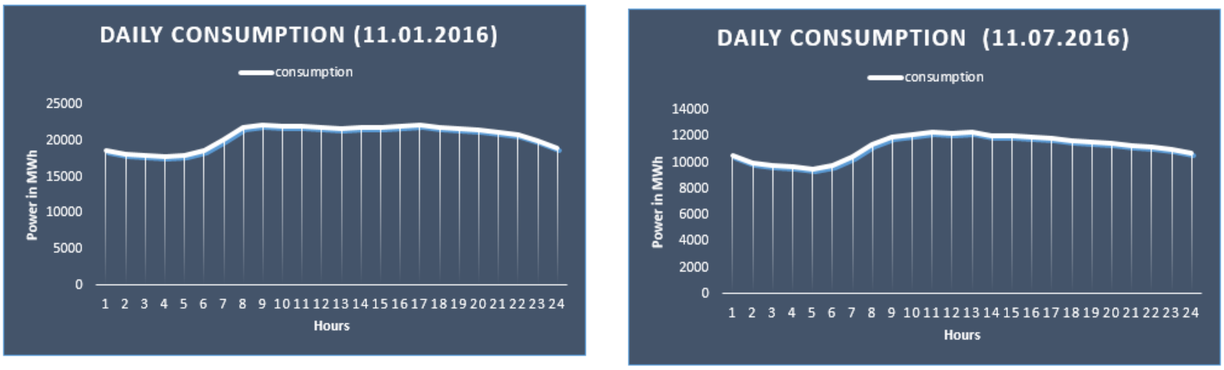
The power curve below gives a detailed analysis of daily power production in the year 2016 with the months of January and July as case studies.



(a) (b)

Figure 10 Power production trend (a) January and (b) July; 2016 (Statnett, 2017)

On daily basis, peak electricity consumption occurs in the mornings which starts to increase from around 6am. Comparing the two daily consumption curves, it can be deduced that whilst summer values ranges between 9000MWh to 13000MWh, winter values falls into a higher range from 17000MWh to 23000MWh.



(a) (b)

Figure 11: Daily consumption trend (a) January and (b) July; 2016 *(Statnett, 2017)*

SECTION B: DESIGN PARAMETERS OF RENEWABLE ENERGIES

4 HYDROPOWER

The harnessing of power from water dates back to china between 202 BC and 9 AD during the Han Dynasty and also in ancient Egypt. The power was generated mainly for mechanical power for milling grain and pumping water. Key developments in hydropower technology occurred in the first half of the 19th century. In 1827, French engineer Benoit Fourneyron developed a turbine capable of producing about 6 horsepower, the earliest version of the Fourneyron reaction turbine (IHA, 2016). Later, James Francis developed the first modern water turbine which is the commonest. Other turbines that been invented are the Pelton impulse wheel turbine by Lester Allen Pelton in the 1870's and the Kaplan propeller type turbine by Viktor Kaplan in 1913. In

4.1 Principle, design and operation of hydropower

Conventional hydropower plants consist of:

- High elevation in topography between a storage system and generating system serving as a form of potential energy.
- A storage / diversion facility for water in the form of a dam or barrage.
- A headrace system for water conveyance to a turbine. The conveyance system can either be a conduit or an open channel.
- Installed turbines connected to generators.
- A tailrace flow-discharging conduit of open channel that conveys the water out of the turbine to a water body.

In operation, the potential energy is converted kinetic energy by running it through penstocks by intakes to turbines. As water rushes through the turbines, it causes the spinning of the blades due to the force with which it hits against it. This action converts the kinetic energy into mechanical energy. The turbine mostly coupled to a generator by a shaft causes the generator also to spin. The spinning of the generator then uses electromagnetic field system to convert the mechanical energy into electrical energy. Transformers converts the electrical energy into high voltages and transmitted through power lines to end users.

4.1.1 Design Alternatives for Hydropower Projects based on topography

Based on the topography of the area where hydropower is developed; there are four main types of hydropower development which are;

Run-of-river scheme: in this hydropower scheme, flowing water from a river is channelled through canals or penstocks to turbines for generation, mostly with no storage reservoir. One advantage of this project scheme is that it provides a continuous supply of base load electricity with some flexibility of operation since water flow can be regulated for fluctuations in daily demands.

Figure 12: Run-of-river hydropower scheme. (SWR, 2008)

Storage hydropower: this hydropower scheme makes use of a dam that is used to store water in a reservoir. Water from the reservoir then runs through turbines which generates electricity. Aside providing base load electricity, it can also be shut down and be operated on short notices according to peak load demands. Due to its storage capabilities, they can be operated irrespective of hydrological inflow for some period of time.

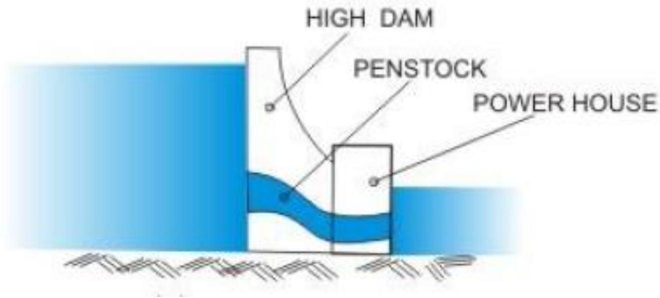


Figure 13: Storage hydropower scheme. (SWR, 2008)

Pumped-storage hydropower: in pumped-storage hydropower scheme, two reservoirs mainly of an upper and lower one. The operation is similar to storage hydropower; however water is either pumped to store energy or released to generate power for balancing purposes in peak and off-peak times.

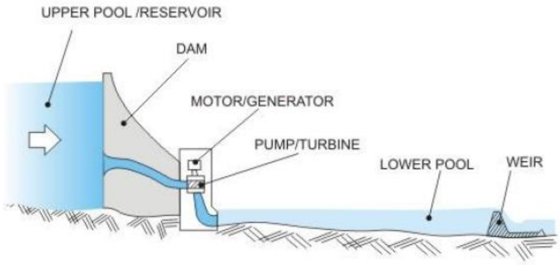


Figure 14: Pumped storage hydropower scheme (SWR, 2008)

Offshore (Tidal) hydropower: mechanism utilizes the rise in water levels during high tides to generate power. It’s operated where a sea with a bay is present, at high tides the water from the sea rising is channelled through turbines to flow into the bay generating power and vice versa if the scheme has turbines installed in the opposite direction during low tides.

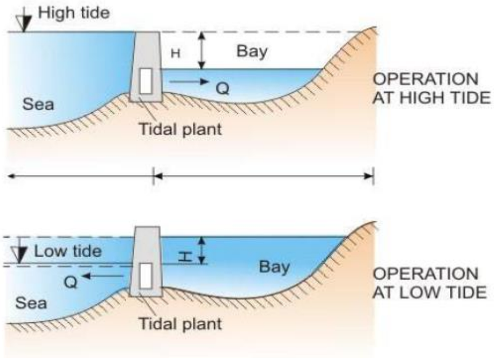


Figure 15: Tidal power scheme. (SWR, 2008)

4.1.1.1 Design Parameters

The operation as explained above makes use of potential energy, conduits and pressure. These operational elements are governed by equations. When it comes to the passage of water through penstocks or conduits, the continuity equation is applied implying that flow rate at any point in the penstock is constant at any point. The continuity equation is given as

$$Q = c_1 A_1 = c_2 A_2$$

Where;

Q = discharge (m^3/s)
A= area (m^2)
c= velocity (m/s^2)

The potential energy converted to kinetic energy to move the turbines is governed by the conservation of energy principle, energy can neither be created nor destroyed. This equation is given as

$$mgh = \frac{1}{2} mv^2$$

Where;

h= pressure head (m)
g= acceleration due to gravity (m/s^2)
v= velocity (m/s)

Now under steady state conditions in a closed conduit, the Bernoulli equation is used to asset that the energy is conserved. Losses such as friction is also accounted for in this equation given as:

$$z_1 + h_1 + \frac{c_1}{2g} = z_2 + h_2 + \frac{c_2}{2g} + \sum loss$$

Where;

z= elevation (m)

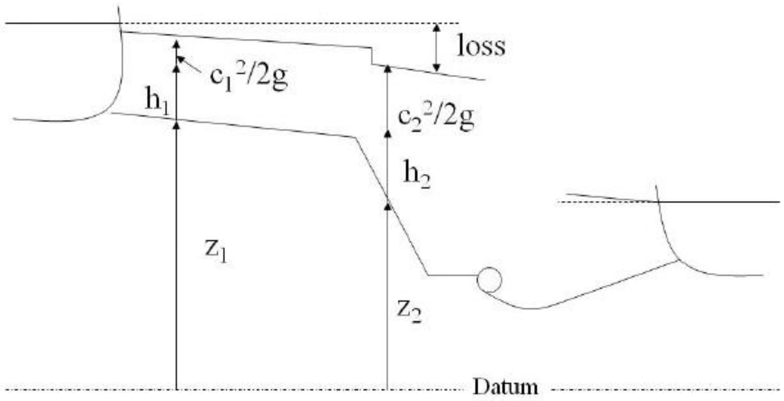


Figure 16: Application of Bernoulli's equation to hydropower

The head H is the sum of the hydraulic pressure h and the elevation z is calculated by:

$$H = h + z$$

At the reservoir, the $H = z$, that is the hydraulic pressure is zero.

The energy available to be extracted at the turbine defined by the net head, H_n and this can be determined as follows:

$$H_n = z_1 - z_2 + h_1 - h_2 + \frac{c_1^{\,2}}{2g} - \frac{c_2^{\,2}}{2g}$$

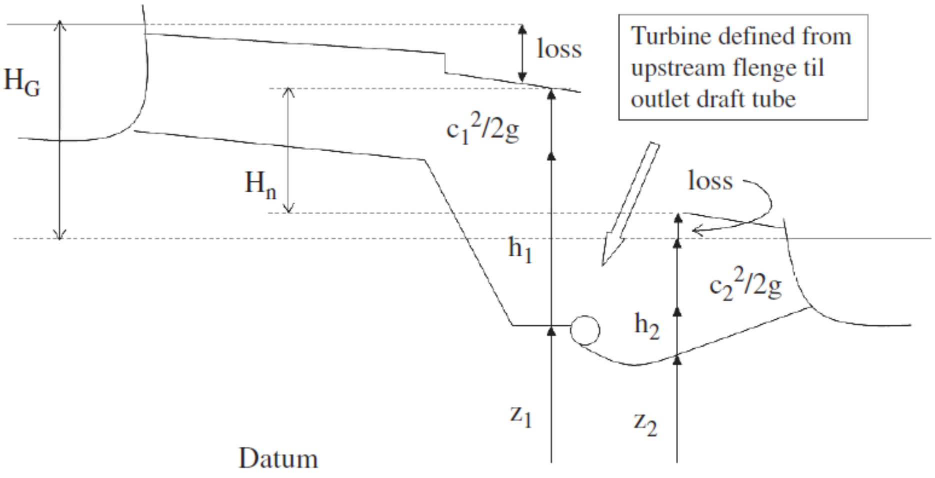


Figure 17 Definition of net head, H_n. (Nielsen, 2013)

From Figure 17, it can be deduced that H_n is the head difference over the turbine, which is equal to the gross head, H_G when all the hydraulic losses such as friction are subtracted given by:

$$H_n = H_G - \sum losses$$

4.1.2 Turbine

The turbine transforms the energy of water into mechanical energy of rotation and the main function is to drive hydroelectric generators. The variation in pressure heads make use of different turbines such as the reaction or impulse turbine. They are classified into two namely; impulse and reaction. In an impulse turbine, the driving energy is supplied by the water in kinetic form, where high pressure jets of water is directed into buckets at an angle that ensures that almost all the energy in the water is converted into rotary motion of the turbine wheel. One key to its operation is that it must rotate in the air, an example is the Pelton turbines. The reaction turbine on the other hand is one in which the driving energy is provided by the water partly in kinetic and partly in pressure form and must be completely submerged to operate efficiently. An example is the Francis turbine, with a key feature of changing the water direction as it passes through the turbine.

The transformation of hydraulic power to rotating mechanical power is based on the reaction forces that are obtained both from the pressure difference and by the change of velocity through the runner, an example is the Pelton Turbine. In terms of head and flow, the Pelton turbine is a low-flow, high-head turbine as compared to the Kaplan turbine which is a high-flow, low-head turbine.

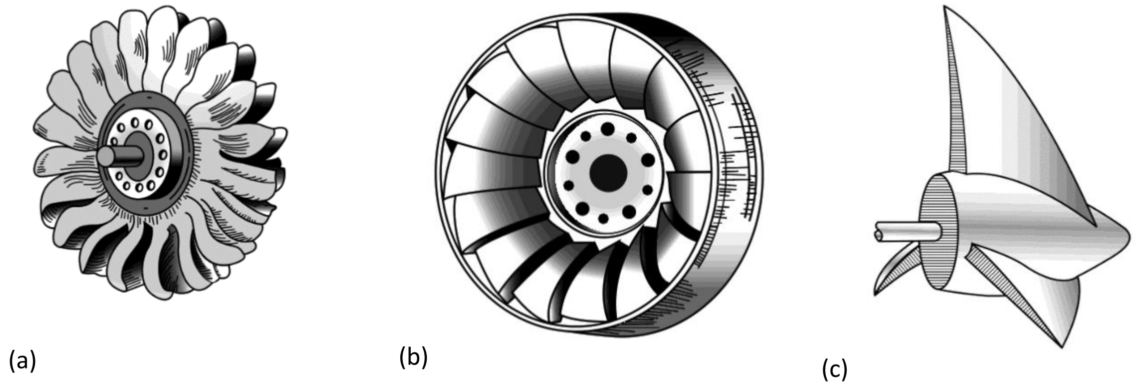


Figure 18: (a) Pelton (b) Francis and (c) Propeller turbines (EPG, u.d.)

The selection of a particular turbine type for a hydropower project is mostly determined by the head and flow conditions at the site.

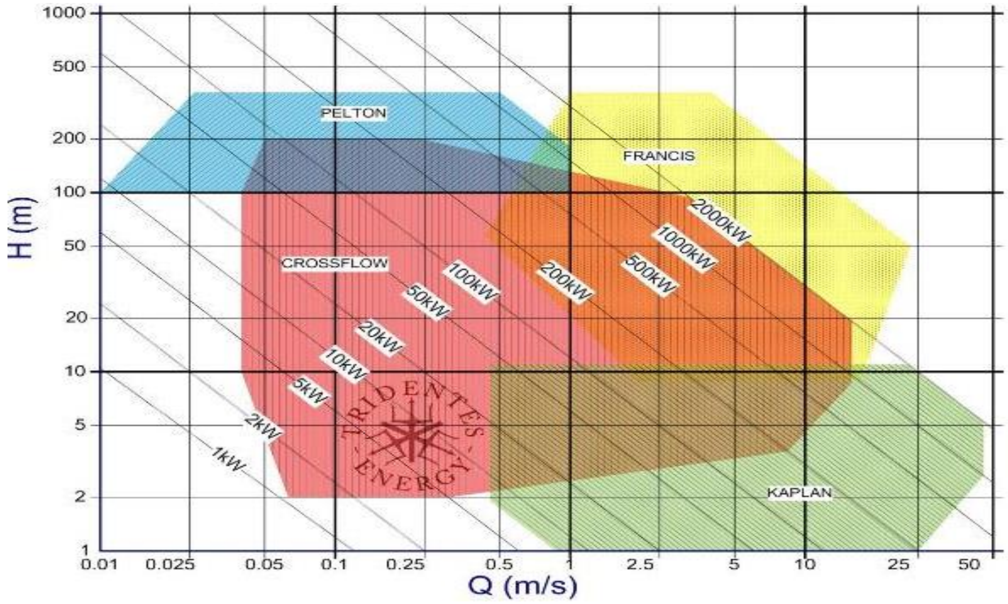


Figure 19: chart for selection of turbine types (source: http://tridentes.com/energy/en/turbines.html)

Table 1: A table of Turbine types, their class and head range

Turbine types	Class	Head range
Propeller turbines with fixed blade turbines	Reaction	10 – 60m
Propeller turbines with adjustable blade, e.g. Kaplan	Reaction	10 – 60m
Diagonal flow turbines	Reaction	50 – 150m
Francis turbine	Reaction	30 – 400m (even up to 500 to 600m)
Pelton turbine	Impulse	Above 300m

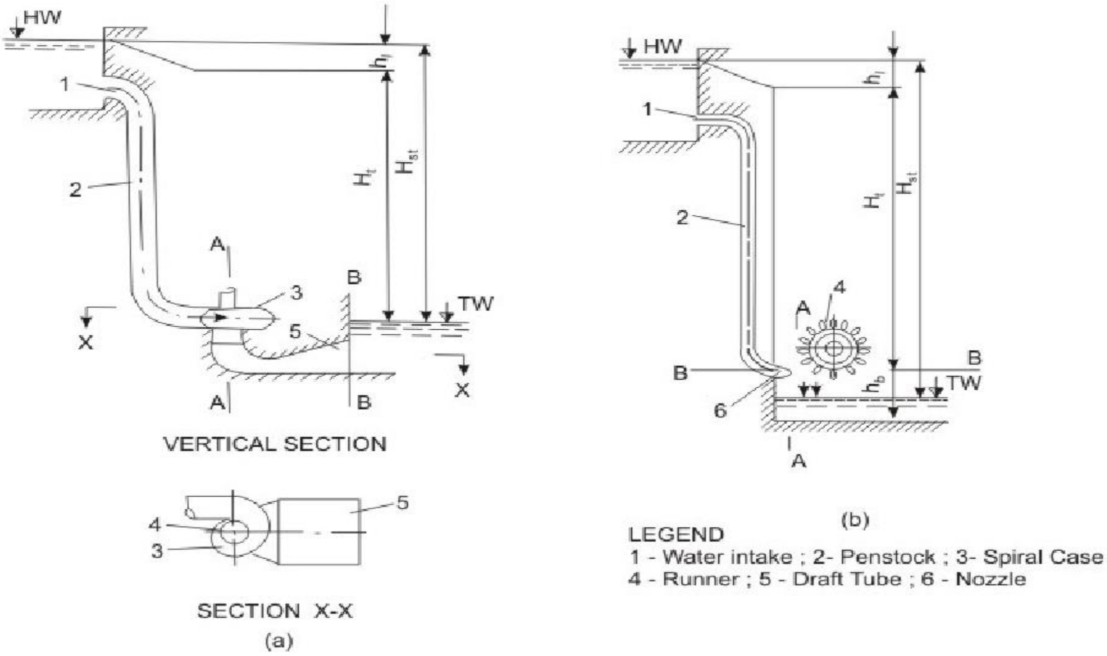


Figure 20: Layout for (a) Reaction turbine; (b) Impulse turbine Source: (SWR, 2008)

Depending on the flow axis, reaction turbines can be further be grouped into: axial, radial or diagonal flow reaction turbines.

4.1.3 Tunnel design

The factors that affect the suitability of excavation principles for a tunnel project includes contract related factors (e.g. Construction time), project- specific factors (e.g. tunnel length, shape) and geological factors (e.g. rock type, rock mass quality) (Palmstrom & Stille, 2010). There are several advantages in the use of a tunnel, like limited impact on the surface, degree of liberty concerning design and future extension, cost effectiveness, Environment concern (visual, noise and protection of natural habitat) or safety (Capo, 2012).

The tunnel layout should be considered first to determine the best excavation process and secondly the size and shape which can be determined from the amount of water that is to be conveyed under the given head difference (SWR, 2008). Two main techniques are available depending on the geological features of the area. For the purpose of our project, the Drill and blast excavation and Mechanical excavation with tunnel boring machines (TBM) is considered because excavation done in mountainous areas.

4.1.3.1 Drill and blast excavation

This method of excavation is favourable where there is hard rock like granite. The process of drill and blast involves the drilling of a number of holes into the rock mass and then filled with explosives. The detonating of the explosives breaks up the rock and the rubbles removed. The cycle is repeated until the desired result is achieved. In rock support for this technique, rockbolts and shotcrete can be applied immediately after blasting, which is often followed by a cast in-situ concrete lining using formwork.

4.1.3.2 Tunnel boring machine (TBM)

The tunnel boring machines are used to excavate tunnels with circular cross section through a variety of subterranean matter; hard rock, sand or almost anything in between. The mechanism for excavation is such that as the boring machine moves forward, the round cutter heads cut into the tunnel face and splits off large chunks of rock carving a smooth round hole through the rock. Conveyor belts carry the rock shavings through the TBM and out the back of the machine to a dumpster.

5 PUMPED STORAGE HYDROPOWER

The first PSH plants were built in the Alpine regions of Switzerland, Italy and in Austria and also in Germany, of which most of them were constructed in the period between 1960 and 1990. During this period, the integration of large capacities of conventional power plants into the energy system was profound (Harby , et al., 2013).

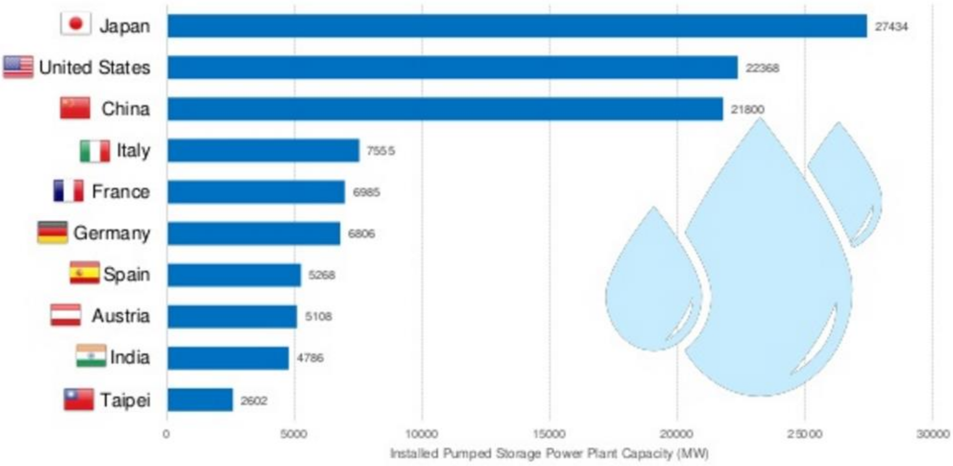


Figure 21: Total installed capacity of PSH in 2014 (IEA, 2016)

5.1 Principle, design and operation of pumped storage hydropower

A typical pumped storage hydropower consists of an upper and lower reservoir with pumps and turbines.

5.2 Design Concepts for Pumped Storage Hydropower

5.2.1 Sub surface pumped hydroelectric storage

This design alternative for pumped storage hydropower make use of abandoned mines, caverns and man-made storage reservoirs as potential reservoirs. Although not widely spread, they have become attractive due to their perceived site availability and their potential for reduced environmental impacts.

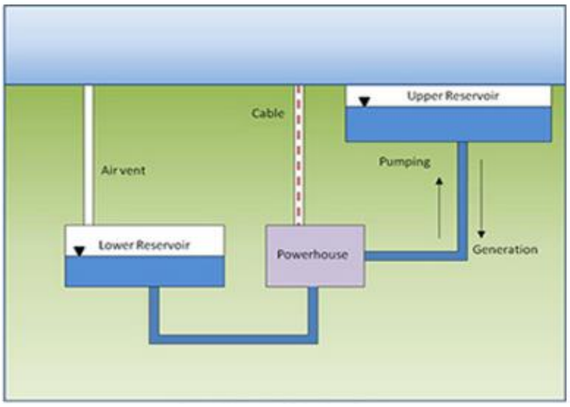


Figure 22: Sub-surface pumped hydroelectric storage (ESA, 2017)

5.2.2 Surface reservoir pumped storage hydroelectric storage

This concept makes use of either natural or artificial surface water bodies such as rivers, lakes or seas. They can be classified either as Closed-loop or Open-loop pumped storage system. Closed-loop systems are not continuously connected to a naturally-flowing water feature whilst Open-loop systems are continuously connected to naturally-flowing water feature.

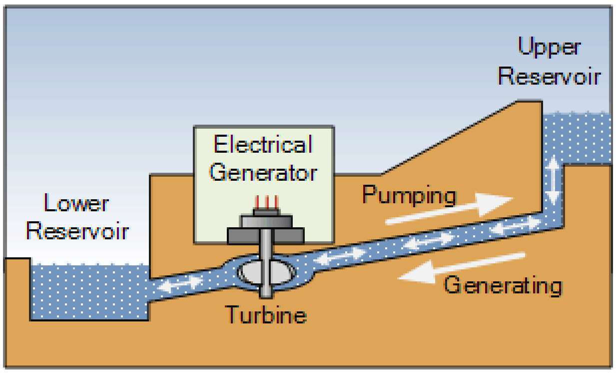


Figure 23: Surface pumped storage hydroelectric power (AET, 2017)

5.3 Main design parameters for Pump turbine

The selected turbine speed of rotation is based on rated output during operation and corresponding to rated head, the turbine specific speed is obtained and speed of rotation is calculated using:

$$n_{st} = \frac{n\sqrt{P_t \times 1.358}}{Ht^{5/4}}$$

Where;

n_{st} = *Specific speed of pump turbine when operating in pumping mode*
n = *Rated speed in rev/min*
P_t = *Turbine output in kW*
Ht = *Rated read acting in meters*

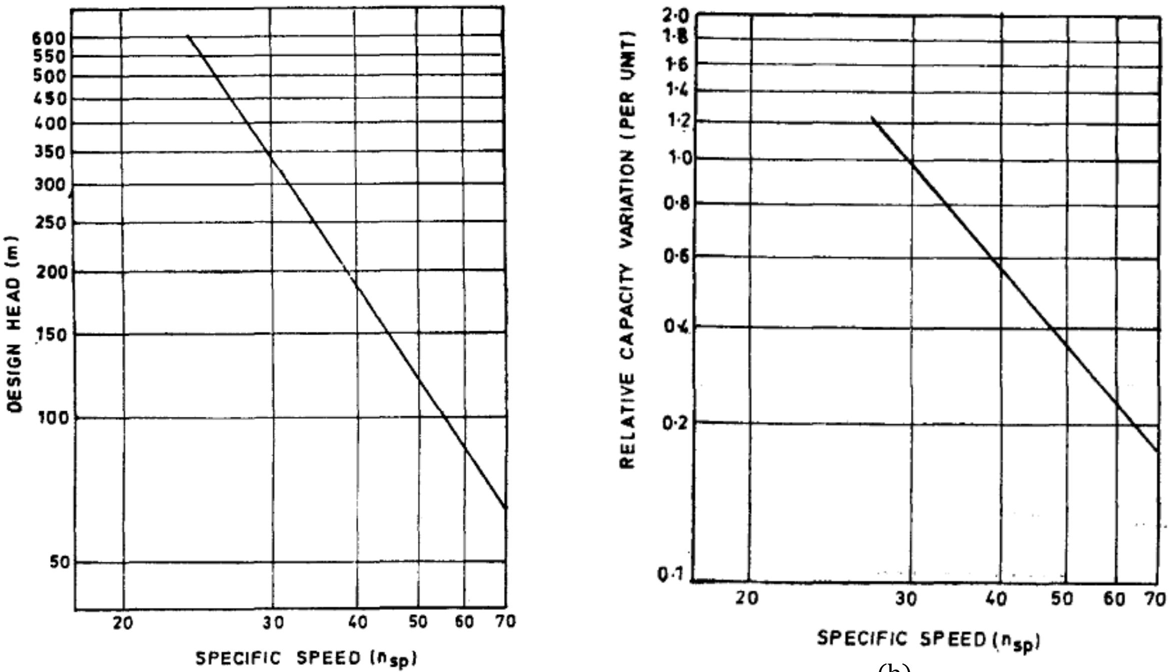
The pump input at rated head in kW and the specific speed are obtained from the formula:

$$P_p = 9.8\, Q_p\, H_P / E_p$$

Where;
E_p = Pumping efficiency
The pump specific speed is determined graphically from figure 32(a) below and the rated pump discharge is obtained from the formula;

$$n_{sp} = \frac{n\sqrt{Q_p}}{{H_p}^{3/4}}$$

n_{sp} = Specific speed of pump turbine when operating in pumping mode
n = Rated speed in rev/min
Q_t = Discharge in m^3/s
Hp = Rated dynamic head in meters



(a) (b)

Figure 24: (a) Specific speed as pump vs Design head, (b) Relative capacity variation vs Specific speed as pump (HPSC, 1990)

In the evaluation of the capacity of the motor generator, it is significant that the maximum capacity in pumping mode is determined. Figure 24(b) gives a relation between the relative capacity variation and specific speed in pumping mode, from which the maximum pump capacity can be calculated by:

$$P_{p\,max} = P_p\left(1 + \frac{\lambda\,\Delta\,H_p}{H_p}\right)$$

Where
P_p = Pump input
$\Delta\,H_p$ = Maximum dynamic head design – dynamic head
λ = Relative capacity variation
Hp = Dynamic pumping head. At least 5 percent margin and is taken for pump input

The pump turbine setting also has to be calculated to prevent excessive cavitation, submergence requirements are more critical during pumping than turbining. The suction height is determined by

$$H_s = H_b - \sigma H_p - H_v$$

And this is with respect to the minimum tail water level.

Where;

H_s = *Suction head in meters*

H_b = *Barometric pressure* = $10.3 - \frac{elevation\ of\ power\ staion\ in\ meters\ of\ water\ coulmn}{900}$

H_v = *Vapour pressure = 0.4m of water column at 30°C*

σ = *Cavitation co-efficient*

The design Parameter for motor generator is given by number of pair of poles is determined using

$$P = \frac{60f}{n}$$

Where;

P= *number of pairs of poles*

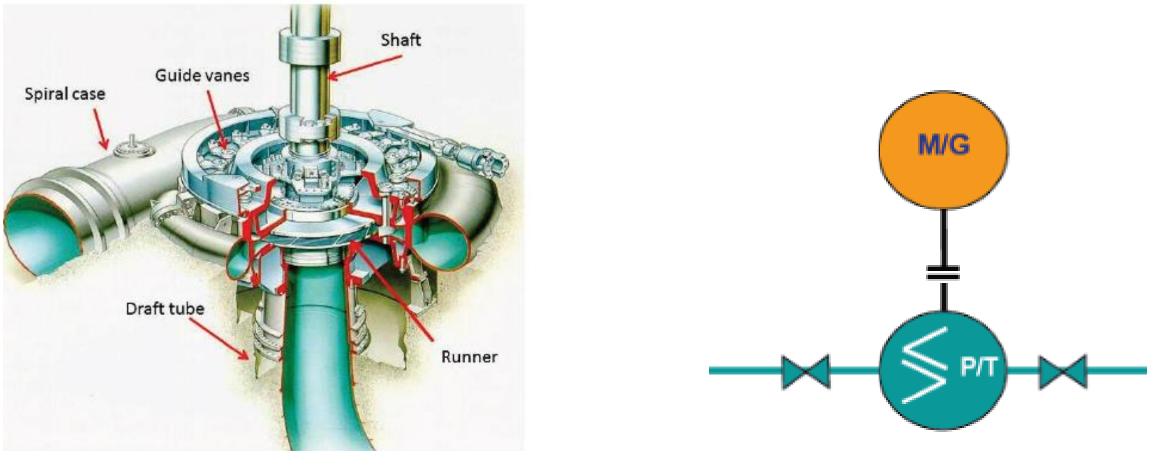
f= *frequency in cycles per second*

n= *rated speed of machine in rev/min*

5.3.1 Pump and Generator classifications

The pumped storage hydro plant can have different configurations for the pump and generator. The configurations are classified as:

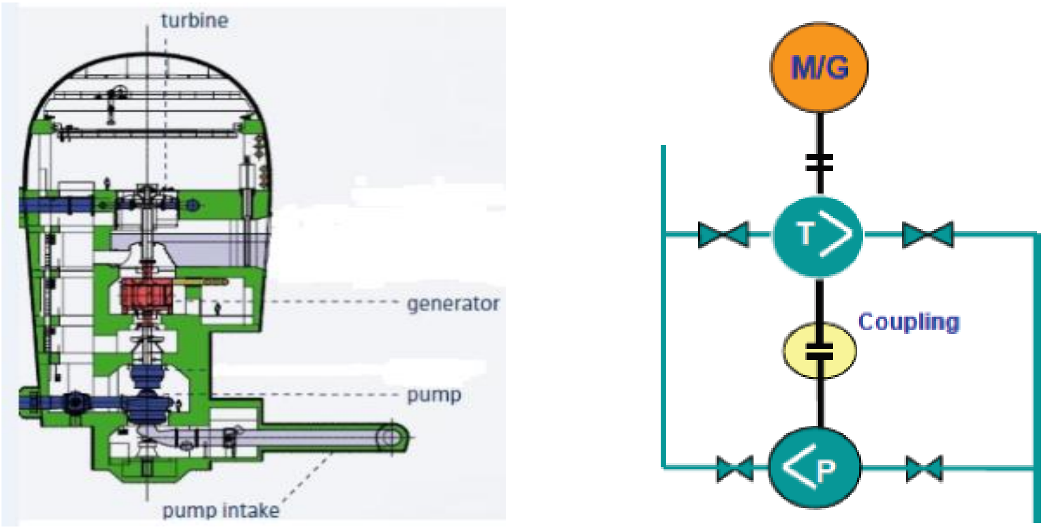
Binary set: this set consists of a pump-turbine and one electrical machine (motor/generator) and rotates in one direction when supplying energy to the grid (generating) and in the opposite direction when consuming energy from the grid (pumping). With heads from about 10m to 70m, the single stage pump turbines can be used whilst the multi stage pump turbines can be used for heads from 700m up to 1200m. It is the most used scheme because of it is cost effective in terms of installation, maintenance and operation.



(a) *(b)*

Figure 25: (a) binary set configuration: (b) Line diagram of a binary set configuration *(Solvang , et al., 2014)*

Ternary set: this set of configuration consists of a turbine, an electrical motor /generator and a pump coupled altogether on the same shaft, where both the pump and turbine rotate in the same direction in both operating modes.



(a) *(b)*

Figure 26:(a) ternary set configuration *(Cavazzini, et al., 2014)*; (b) line diagram of ternary set configuration *(Solvang , et al., 2014)*

Quaternary set: turbines and pumps in this configuration are not mechanically coupled in that, two separate powerhouses are used, one for pump units and the other for turbine units. That is the hydraulic circuit consists of two water reservoirs connected by two different penstocks, one for generating and the other for pumping.

5.4 Air cushion chamber

The surge chamber is used to dissipate pressure energy associated with the effects of rapid valve closure in pipes connected to the reservoirs. This pressure energy is generated by the kinetic energy of the moving water and the elastic energy stored in the liquid and pipes.

5.4.1 Design parameters

In the design of the air cushion chamber, because the pressure energy is transferred only as work without the transfer of heat or matter between the system and its surroundings, the Laplacian law is used given by:

$$P\ * V^{\gamma} = cst$$

Where

P is the pressure inside the air cushion chamber (atm/Pa/bar)

V the volume of air (m^3)

$$\gamma = C_p/C_V$$

The area of the surge chamber can be determined from the equation:

$$A_{eq} = \frac{1}{\frac{1}{A_{ac}} + \gamma * \frac{h_p}{V_o}}$$

A_{ac} *: Area of the air cushion chamber* (m^2)

V_o *: Volume of air at equilibrium given by* $V_o = A_{ac} * H_{o\,ac}$

$H_{o\,ac}$*: Height of free air at equilibrium*

h_p*: Pressure at equilibrium inside the air cushion chamber found by the Bernoulli equation.*

5.5 Design Parameters for Power House

The overall dimensions of the turbine, draft tube, scroll case and generator including the number of units in a power station and the size of erection bay affects the design of power stations. The length of the power station depends on the unit spacing, length of erection bay and length for crane to handle the last unit.

5.6 Length of Power Station

The length can be determined by:

$$L = N_o \times (unit\ spacing) + L_s + K$$

Where;
N_o *= number of units*
L_s *= length of erection bay*
K *= space required for the crane to handle the last unit depending on the number and size of the crane which is usually 3.0 – 5.0m.*

5.7 Width of Power Station

The width of the powerhouse mostly accommodates the machines and the overall dimensions of the spiral casing and the hydro generator may be drawn with respect to the vertical axis of the machine. The following provisions are to be made for the upstream side of the powerhouse;
A clearance of about 1.5 to 2.0m for concrete upstream of scroll case
A gallery of 1.5 to 2.0 m width for approaching the draft tube manhole
If the main inlet valve is housed in the powerhouse, the width of the valve pit should be designed to accommodate all the available valves such as the conventional butterfly, spherical or pressure relief valves.
Provision of width for auxiliary equipment in the floors.

5.8 Height of Power Station

The height of power station from the bottom of the draft tube to the centre line of the spiral casing, which brings water flow to the turbine is denoted as H_1 and H_2. The height from the centre line of the spiral casing up to the top of the generator is of length H_4 and calculated as:

$$H_4 = L_T + h_j + K$$

Where;
L_T *= length of stator frame*
h_j *= height of load bearing bracket*
K *= constant ranging from 5.5 to 5.0m depending on the size of the machine*

5.9 Advantages and disadvantages of Hydropower and PSH hydropower

Table 2: Advantages and Disadvantages of Hydropower and PSH Hydropower

Advantages	Disadvantages
Renewable energy: hydropower is a renewable source of energy which can be harnessed without depletion	**Environmental impacts:** construction of hydropower dams can cause imbalances in aquatic ecosystems and changes in topography
Clean source of energy: hydropower does not pollute the environment like fossil fuel sources of energy	**Erosion:** the holding back of sediments by the dam deprives downstream water bodies and this causes erosion in the banks and channels downstream
Reliable and flexible: hydropower is a reliable source of energy and its generation can be regulated to meet energy demands	**Dam failure risks:** in cases where failure of dam occurs, the effects are catastrophic to the environment and lives
Environmental purposes: dams can be used for purposes such as irrigation, water supply and flood control	**Cost**: hydropower dams are very expensive to build and must run for long periods to be cost effective

6 WIND POWER

Wind power is generated by the force wind exerts on the blades of a turbine, causing the turbine's shaft to rotate at a speed of 10 to 20 revolutions per minute (rpm) (Busby, 2012). The rotor shaft is connected to a generator that converts mechanical energy into electrical energy.

The history of wind power dates back to around 1000 BC when the sailboats where developed by the Egyptians before this time. The time period between 1390 to about 1854, windmills were used mainly purposes such as water pumping, grinding grain, sawing wood and as energy for powering ships.

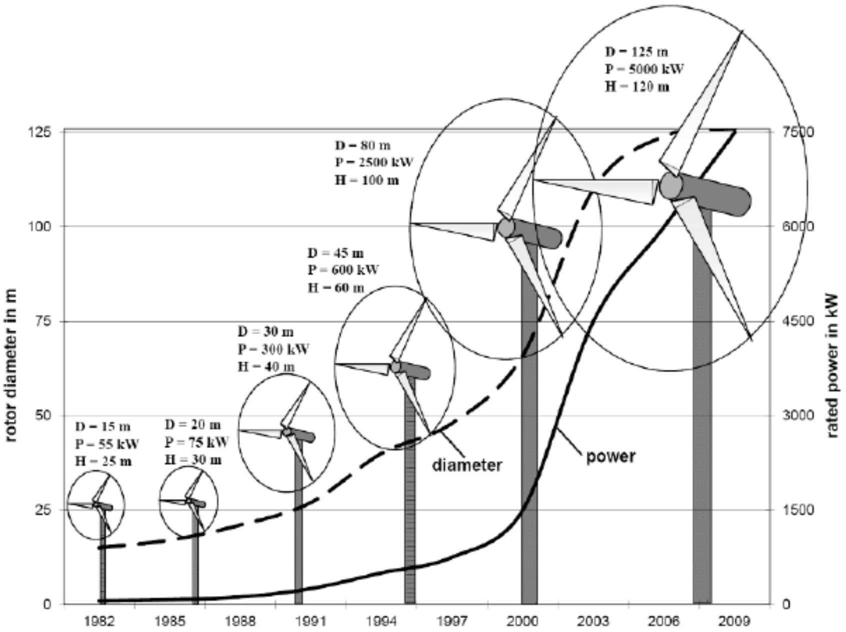


Figure 27: Developments in wind turbine size and output. (Gasch & Twele, 2012)

6.1 Wind Turbine design

Wind turbines designs comes in horizontal axis and vertical axis, with the most common being the horizontal-axis design coupled with three propeller-type blades. The major components of grid-connected wind turbines can be narrowed down into these major sections which includes:

- Rotor (blades and hub)
- Drivetrain (gearbox and generator, which are connected to the rotor by a shaft)
- Yaw system between nacelle and tower: yaw bearing and yaw drive
- Supporting structure (tower and foundation
- Electrical system for control and grid connection

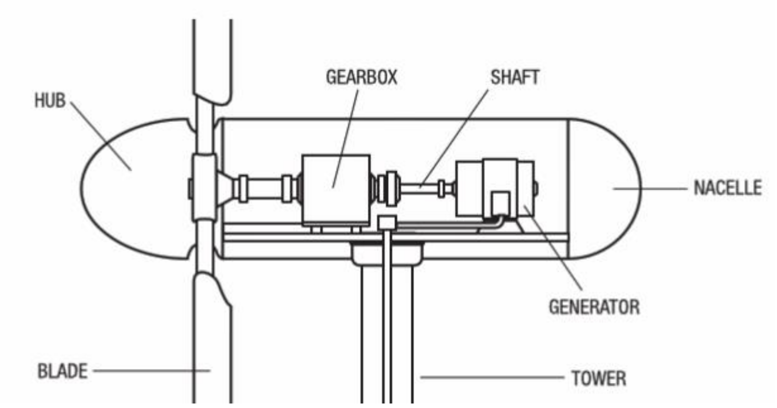


Figure 28: design layout of major wind turbine components (Busby, 2012)

6.1.1 Rotor

The heart of a wind turbine is the rotor which converts the wind energy into mechanical energy of rotation (Gasch & Twele, 2012). It consists of the entire blade assembly which consists of the blades and the hub where the blade roots are attached to a driveshaft (Busby, 2012). The blades designed with good aerodynamic properties, converts the kinetic energy extracted from the moving wind into mechanical power by turning the driveshaft dependent on the swept area which is the circle defined by the blades revolution. With the speed of wind increasing with increase in elevation, maximum energy from the wind is harnessed by mounting the blades together with the hub on tall towers which are usually made of huge, tabular steel columns tapered at the top. The hub allows for flexibility in blade angles during changes in wind speeds by the use of large ball bearings. Turbines can have blades of about 30-50m long, with rotor blades of diameters about 60-100m.

6.1.2 Drivetrain

The gearbox, driveshaft and generator found inside the nacelle constitutes the drivetrain. Mechanical power is transferred to the generator by the driveshaft driven by the rotor blades to produce electricity. The gearbox transforms slow rotations of the blades into faster rotations suitable for the operation of the generator, ranging between 1200rpm-1800rpm (Busby, 2012).

In generating electricity from the generator, electrons flow through magnets inside a coil of wire called windings. The electrons in the windings are put into motion as the driveshaft spins the magnet creating a magnetic field as electric current passes through them. These generators fall into two classes namely; induction and permanent-magnet generators.

6.1.3 Yaw System

Yaw can be defined as the angle of rotation of the nacelle around its vertical axis. The yaw system ensures that the rotor axis is aligned with the wind direction, the system is connected to the tower and nacelle and can be used for power regulation above acceptable wind speeds. The system is made of the drives, bearings and brakes. They can either be of the;

Passive system; an example is an autonomous yawing of a turbine with a downward rotor or windvanes at upward rotor turbines

Active system; an example is a fantail or yaw drives driven by external energy.

6.1.4 Tower and Foundation

The static stability and dynamic behaviour of the entire wind turbine mostly depends on the tower and foundation. The structural design of the tower can either be soft or stiff. Stiff design structure implies that the first natural bending frequency of the tower is above the exciting rotor speed, which is the corresponding rotational frequency. On the contrary, the soft design implies that the first natural bending frequency of the tower is below the rotational frequency of the rated speed.

The foundation prevents the mast from sinking into the soil by loads from the turbines weight and vertical components of tensile forces, they are mostly made from concrete blocks. Self-supporting towers have flat centre foundation designs, measured to prevent turbines from tilting over mainly caused by gap joints. If not self-supported, the separate foundations are needed.

6.1.5 Control system and grid connection

The control system is responsible for monitoring the turbine conditions done by recording the entire systems performance, detecting faults and alerting operators when maintenance is needed and also by either slowing down or stopping the rotor in the rise of a hazardous condition.

6.2 Design parameters for Wind power system

The design parameters to be considered in predicting a wind power system include; the wind speed at that instant, V, and the swept area, A. The amount of power yielded by a turbine is also depended on the air density,ρ, an important design factor. The available energy, E, can be calculated from the relation,

$$E = {}^{1}\!/_{2} * \rho * A * V^{3} * t$$

$where\ t = time\ in\ sec$

And the power calculated as;

$$P = {}^{1}\!/_{2} * \rho * A * V^{3}$$

The air density,ρ, can be approximated depending on the project site by using the location`s elevation above sea level, the air temperature or the standard sea level atmospheric pressure. The swept area, A, dependent on the blade length can also be altered. The turbine's rotor efficiency is defined by its coefficient of power,C_p, given by the ratio of the total power available in the wind to the amount of power that the rotor actually produces. Therefore, the extracted power from the rotor is calculated as;

$$Extracted\ power = {}^{1}\!/_{2} * \rho * A * V^{3} * C_p$$

This available power is subject to *Betz limit,* which states that no wind turbine can convert more than about 59% of the wind's kinetic energy, therefore C_p has to be multiplied by a factor of 0.59 to get the actual value.

The amount of power produced by the rotor can then be determined from power curves.

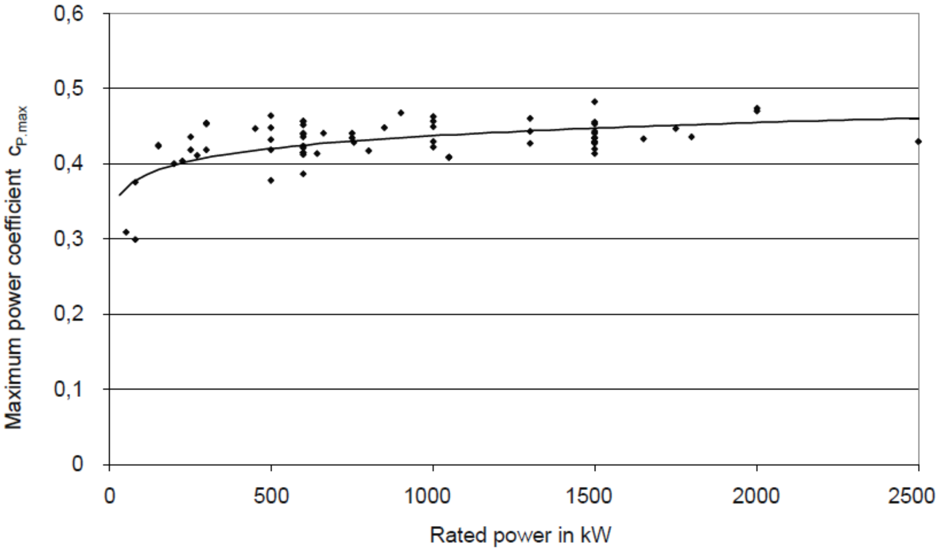


Figure 29: Power curve measurements of maximum power coefficient vs. rated power (Gasch & Twele, 2012)

The forces on the blade are to be taken into considering by considering the aerodynamic drag and lift forces on it. The blade should be designed in a way such that it obtains its best performance which occurs at an angle of attack where the lift-to-drag ratio is maximum. The aerodynamic lift can be calculated by the following relation which when the lift coefficient is replaced by the drag coefficient, also gives the aerodynamic drag.

$$Lift = {}^{1}/_{2} * \rho * A_b * {V_r}^2 \; * C_L$$

Where:

$\rho = air\ density\ (kg/m^3)$
${V_r}^2 = speed\ of\ the\ relative\ wind\ approaching\ airfoil, (m/s\ )$
$A_b = surface\ area\ of\ the\ blade, (m^2)$
$C_L = lift\ coefficient\ of\ the\ airfoil$

6.3 Advantages and Disadvantages of Wind power

Table 3: Advantages and Disadvantages of Wind power

Advantages	Disadvantages
Clean source of fuel: the process of harnessing the energy does not pollute the environment	**Noise and visual pollution:** the high mounted masts and noise produced sometimes by the turbine blades causes pollution
Sustainable source of power: winds are caused by the heating of the atmosphere by the sun, the rotation of the earth and the earth surface irregularities. Therefore, as long as the sun produces heat and the wind blows, energy can be harnessed	**Unreliability:** the problem of intermittency and variability in production during periods of less wind can affects power production and market
Domestic source of energy: wind supply is in abundance, which has seen an increase of about 31% per year	**Long transmission grids:** most of the favourable sites for windfarms are located far from where the energy is needed, with this more transmission lines are needed
Cost-effective: it is one of the lowest-cost renewable energy technologies available today, with power prices offered by newly built wind farms averaging 2 cents per kilowatt-hour	**Danger to wildlife:** the high mounted windmills can pose danger to local wildlife, especially with the free movement of birds, sometimes causing their death by flying into spinning wind blades

7 ELECTRICAL ENERGY STORAGE

The increase in renewable sources of energy now has called for the need for energy storage systems which have shown efficiencies in dealing with the fluctuations in the output for instance in the hourly variations in demand and price (IEC, 2011). The EES systems are classified into Mechanical, Electrochemical, Chemical, Electrical and Thermal.

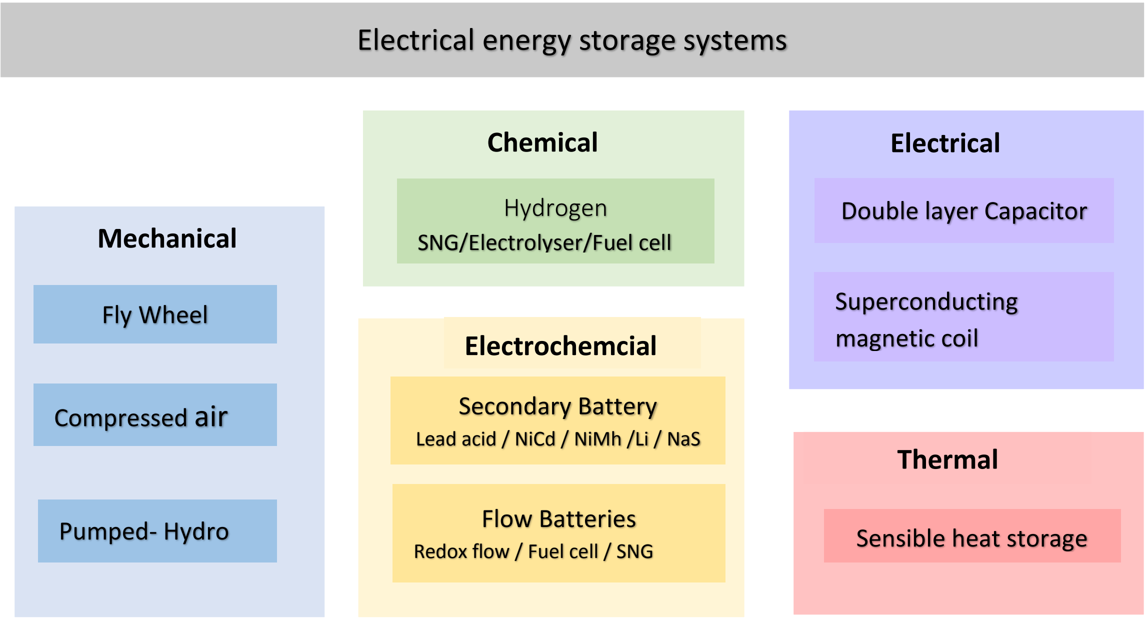


Figure 30: Electrical energy storage systems

Figure 30 above gives the examples of energy storage systems under the different classification. These storage systems can further be categorised into short discharge, medium and long discharge times.

Short discharge time: this discharge time ranges from seconds to minutes and has energy to power ratio less than 1.

Medium discharge time: the discharge rate ranges from minutes to hours and have discharge time is for a considerable number of hours with the energy to power ratio between 1 and 10

Long discharge time: storage systems with this discharging time ranges from days to months and have the energy to power ratio substantially more than 10

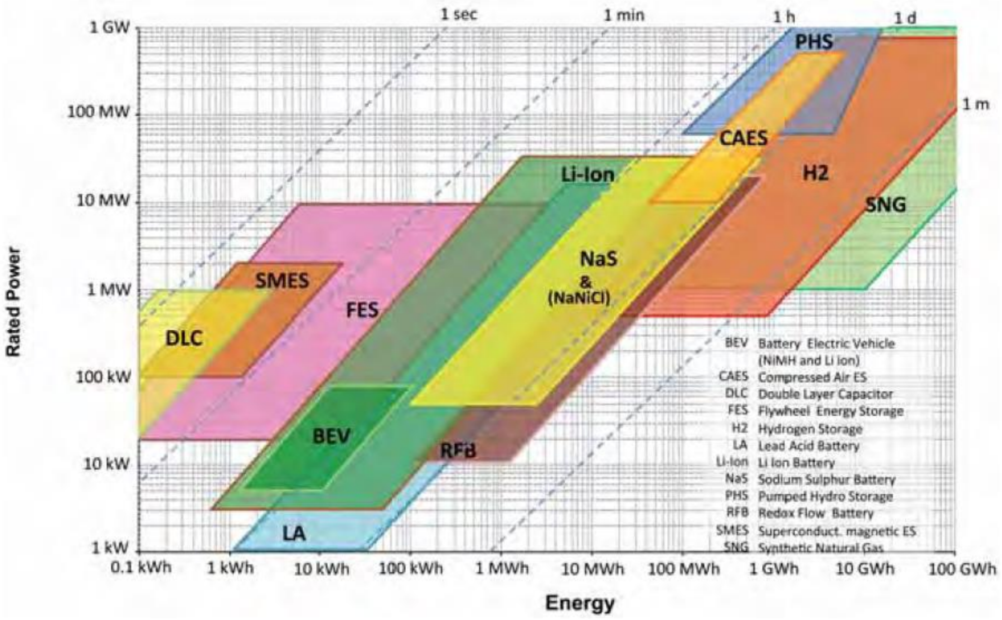


Figure 31: Comparison between rated power, energy content and discharge time for storage systems (IEC, 2011)

Comparison of the different types of storage systems in terms rated power, energy content and discharge time from Figure 31 shows that hydrogen (H2), synthetic natural gas (SNG), compressed air energy storage (CAES) and Pumped hydro storage (PHS) falls into the long discharge time category suitable for the balancing of power systems for a long period of time. However, the PSH system is common and has seen more development in recent years forming 97% of global storage capacity (REN21, 2016).

7.1 Benefits of Storage systems

The EES system plays important roles in that the unstable nature of renewable sources needs that the power supply be stabilized and these storage systems serve as storehouses to compensate for periods when one cannot depend on them for power generation. Secondly, due to variations in power demand the system scales down the price of energy generated for electricity by storing the energy generated at off-peak times when the price is lower, reserving it for use at peak times. Lastly, it retains and enhances the frequency and voltage thus improving the overall power quality.

8 LARGE SCALE ENERGY STORAGE AND BALANCING

The consequent challenge of the combination of more renewable power generation means new confronting concerns for the grid system namely frequency response, system power balancing, inconstancy of energy input and an upgrade of the energy market. One of the goals therefore is to provide large scale hydro balancing power to markets with high penetration of variable renewable production (Statkraft, 2015).

Norwegian Hydropower happens to be Europe’s renewable battery with close to about 50% of the reservoir capacity in Europe located there that is the Norwegian hydropower is considered to be the most cost-effective way to store energy (Statkraft, 2015).

The mechanism of pumped storage hydropower can be used in the storing of the power generated to balance the grid. Hydropower with reservoirs provides the required backup energy to sustain other renewables with intermittent service and ensure electricity supply in times when there is no wind or sun.

Global pumped storage capacity was estimated to be as high as 145 GW at year’s end, with approximately 2.5 GW added in 2015 (REN21, 2016). The IHA asserts that hydropower will continue to complement the increased penetration of variable renewables into the European power grid.

With the majority of the Pumped storage systems undertaken in the southern of Norway, this project investigates the potential for the implementation of PSH in Northern Norway, comparing the current patterns of water level fluctuation to the simulated patterns such as time periods, change frequency and rate, and to analyse which factors (e.g. Turbine capacity, free reservoir volumes) determine how much power can be balanced compared to how much is required.

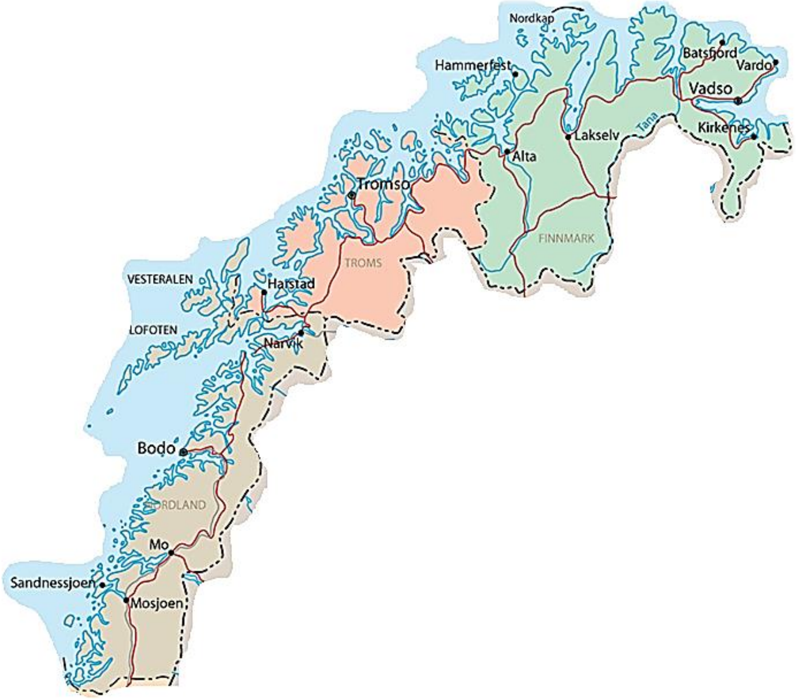


Figure 32: Map of Northern Norway

Data from the NVE estimates that hydropower potential in Norway stands at 214 TWh/year, with 33.8 TWh/year that can be generated from water bodies that have not been protected from development. The 2013 Joint Norwegian-German Declaration states that;

> *"Thanks to its natural endowments and previous investments, Norway possesses 50% of Europe's entire power storage capacities. Therefore, Norway is in a position to provide large-scale, cost-effective, and emission-free indirect storage to balance wind and solar generation in other countries."*

Owing to this, several research activities mostly carried out by SINTEF and CEDREN reveals that the potential for the deployment of Norway's hydropower for large-scale balancing of intermittent renewable energy is high. The focus mainly on reservoir pairs in the south-west of Norway as potential sites for PSH development (Harby , et al., 2013).

8.1 Demand for balancing power in the case of operation of renewable energy in the grid system of Northern Norway.

The main reason for the demand for balancing power in the operation any renewable energy any grid system is due to inconsistency in power supply due to fluctuations in the generation of power, in this case use of wind power. In CREDREN's HydroPeak project concerning the export of balance power from Norway, it is estimated that 20,000 MW of power can be produced by including projects in Northern Norway (Solvang, et al., 2012). If projects from Northern Norway are to be included as proposed, then there is the need to balance power from renewable energy source to make it feasible.

The figure below shows the data output of wind power production from a HydroBalance project by SINTEF showing the sharp fluctuations in the power production. The sharp fluctuations call for the need to phase out the irregularities by balancing.

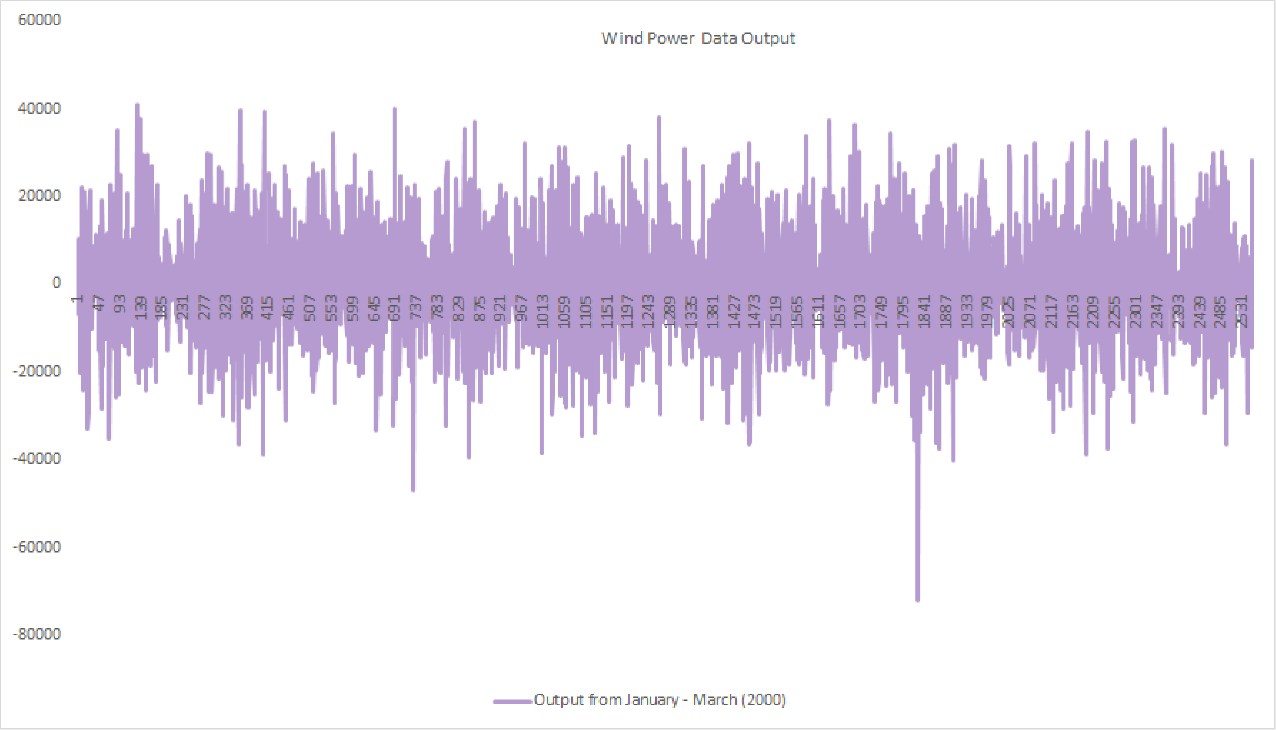
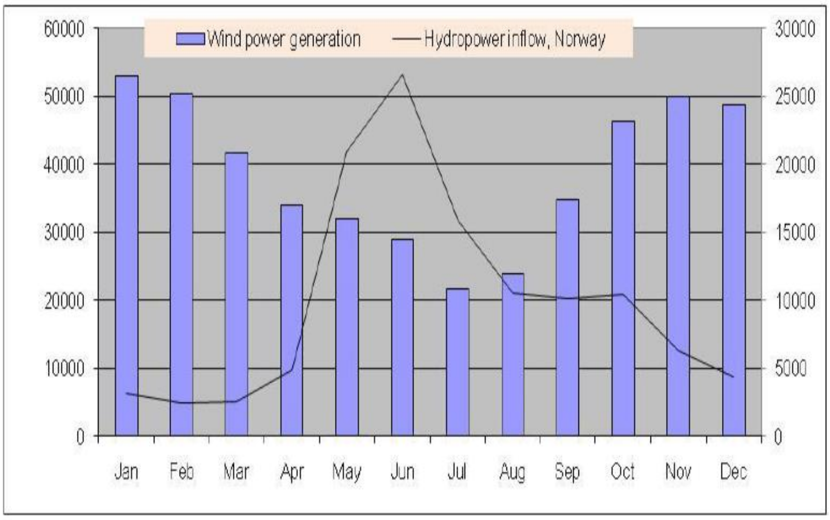


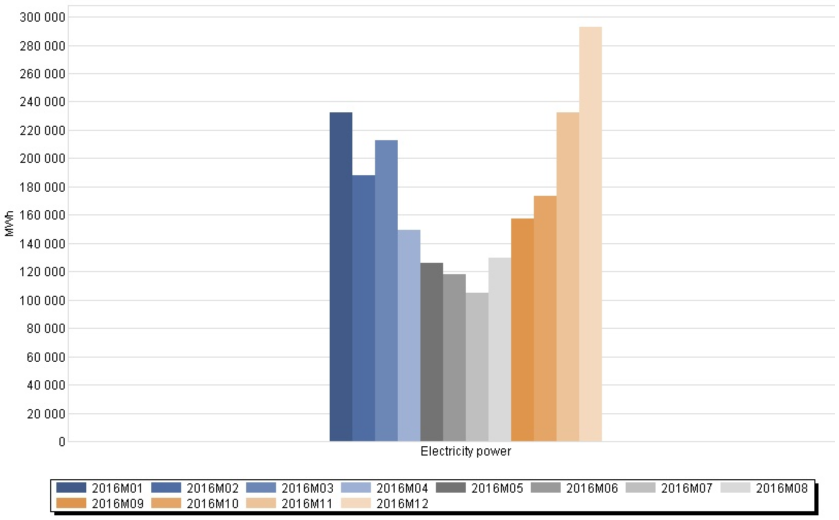
Figure 33: Wind power production fluctuations

8.1.1 Wind Power Balancing Function

Wind power operation can also serve as an optimal source in balancing hydropower production by PSH during seasons of low hydropower power inflow in dams. It happens that the peak of wind power generation, power production from hydropower is at its lowest. That it by utilising the energy from wind power, water can be pumped between reservoirs to compensate for the low hydropower production.



(a)



(b)

Figure 34: (a) production trend of wind and hydro power (source: CEDREN) (b) Annual electricity balance by wind power, 2016 (Statistics Norway, 2016)

9 POTENTIAL PUMPED STORAGE HYDRO-POWER SITES IN NORTH NORWAY

9.1 Hydrological data

Norway is situated in the northern temperate zone, the result of advective heat and condensation heat caused by moving cyclones along the polar front gives large part of the region perpetual change between warm and cold and between dry and humid weather (Hydrological data(Norden), 1970). Hydrological conditions in this Nordic region is characterised by;

Storage of the winter precipitation as snow, which is followed by a high rate of runoff during the snow melt period.

Lake storage

Groundwater storage

The northern part is characterised by runoff which decreases eastwards to about 300mm/yr, the mean annual runoff can be estimated to be 1200mm/yr. Most rivers in Norway belong to the nival regime, characterised spring flood caused by the melting of snow cover and a relatively high discharge during summer and autumn, whilst low discharge occurs during winter when the precipitation accumulates as snow.

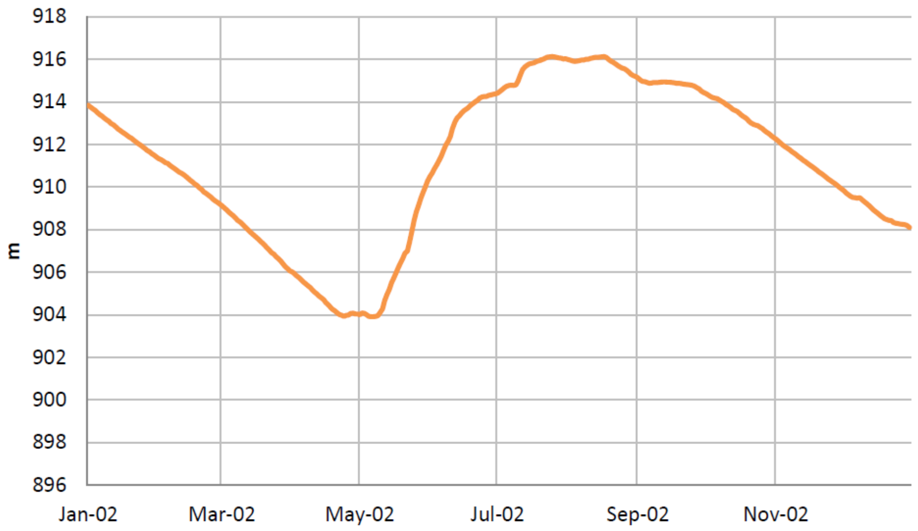


Figure 35: Annual pattern of water level in reservoir (Capo, 2012)

The water level fluctuations in hydropower reservoirs follow the runoff patterns since they are fed from these sources, in PSH reservoirs fluctuation is dependent on the designed discharge pattern of the power plant and the size of the reservoir, with HRWL and LRWL between 1cm/hr to 13cm/hr for upper reservoir. The analysis on water level fluctuations used in this project can be found in details in section 11.5. Water level fluctuation under 7 Days-Average Scenario.

SECTION C: PUMPED STORAGE HYDROPOWER IN NORTHERN NORWAY

Pumped storage hydropower in Norway is not new thing. However, in the North Norway sites, there is not even one operating pumped storage hydro-power plant[1]. Nordland and Troms has many potential sites. Following lists of possible sites have been undertaken based on the availability of the reservoirs and their geographical location.

All the reservoirs data's are collected from NVE official map site (atlas.nve.no, u.d.). For natural lakes which have been used as reservoirs have only HRWL value. For LRWL value, it is estimated to be less than 5 m from HRWL.

9.2 Nordland

There are altogether 17 projects which have been considered as possible site for future operation of pump storage hydropower stations in Nordland. Further details of the reservoirs and stations can be found in the Appendix D.1 and D.3.

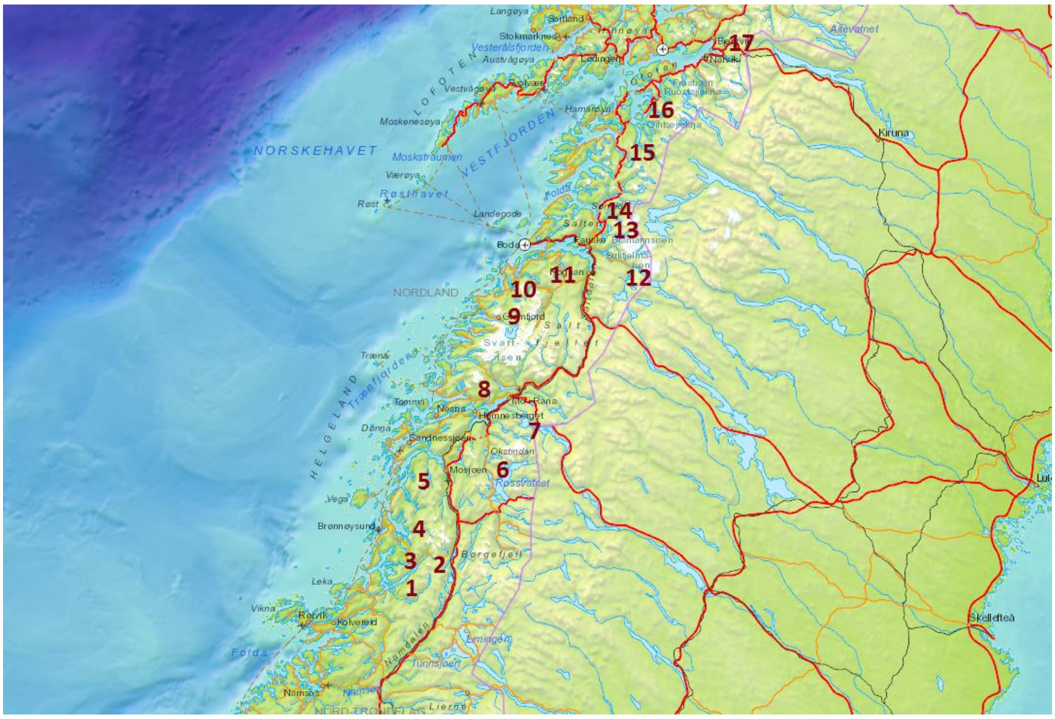


Figure 36: PSH projects on Nordland, Norway (atlas.nve.no, n.d.)

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[1] Facts collected for NVE data base for hydropower plant: http://nedlasting.nve.no/gis/

9.2.1 Kolsvik Bindal PSH Project

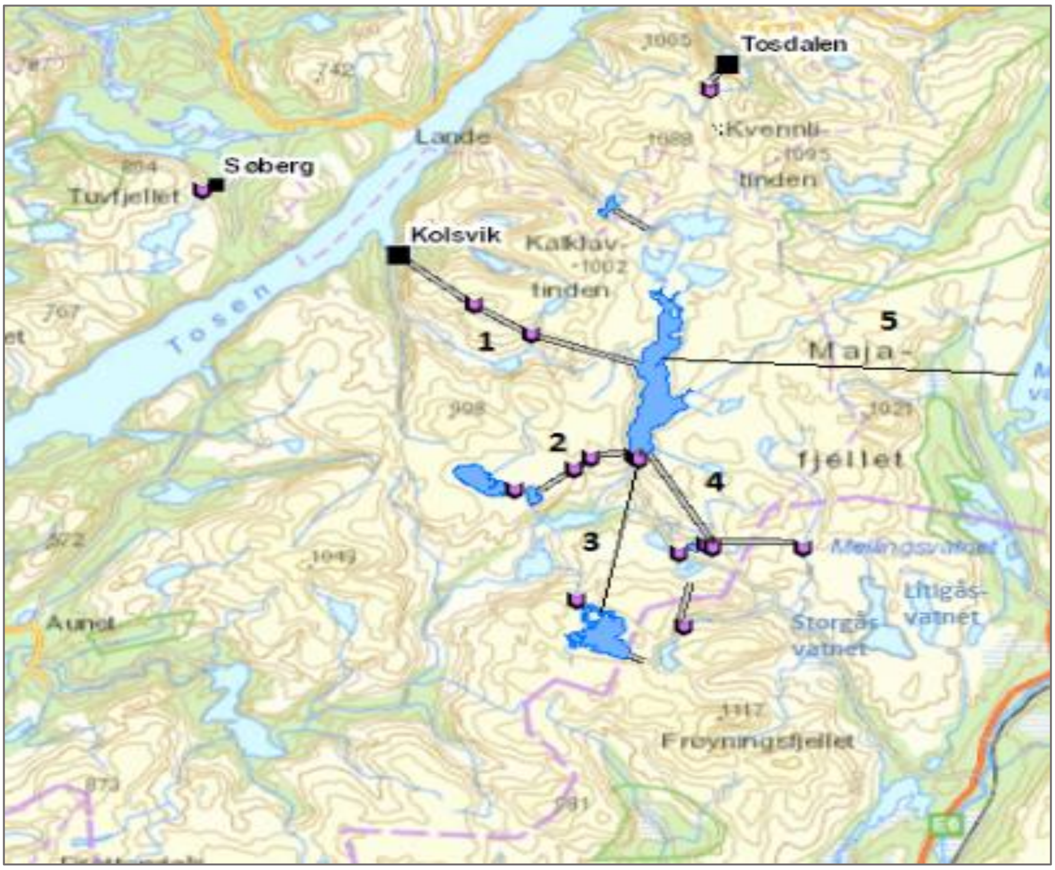

Figure 37: Kolsvik Bindal PSH Project (atlas.nve.no, n.d.)

Table 4: Hydrological data on Kolsvik Bindal PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2-3-4-5	Øvre Kalvvatnet	484	519	158	6.4849	Yes
2	Øvre ringvatn	608.6	613.6	7.6	1.48	Yes
2	Nedre ringvatnet	597.5	597	0.7	0.29	Yes
3	Kalvvatn	730	741	30.5	2.64	Yes
4	Nilsinetjern	515.3	521	1.3	0.22	Yes
5	Majavatnet	268	273	220	4.4387	No

9.2.2 Tosdalsvatnet PSH Project

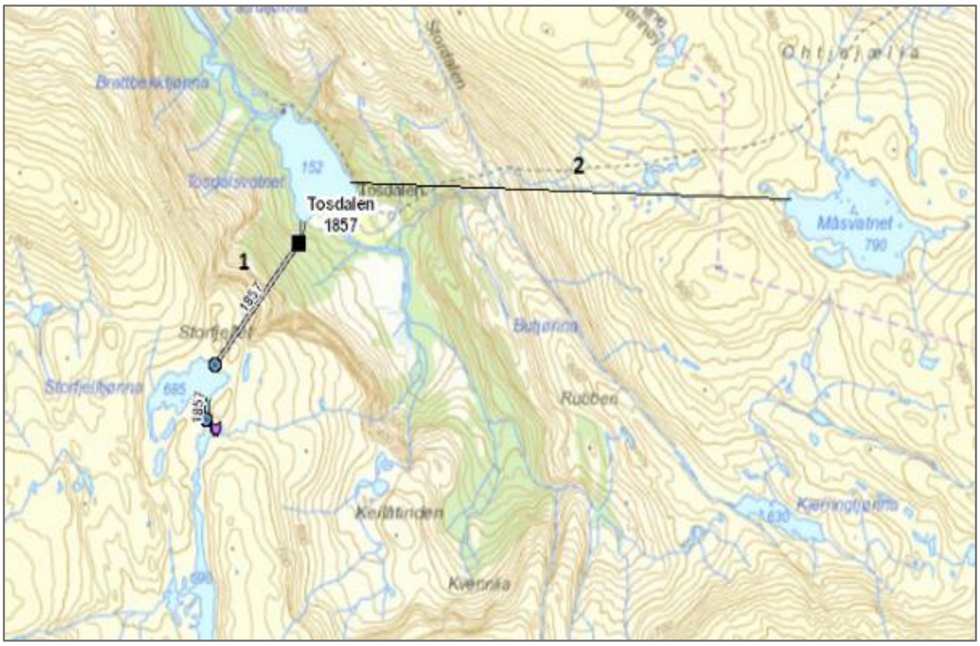

Figure 38: Tosdalsvatnet PSH Project (atlas.nve.no, n.d.)

Table 5: Hydrological data on Tosdalsvatnet PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Tosdalsvatnet	147	152	n/a	0.2403	No
1	Storfjelltjønna	680	685	n/a	0.1.98	No
2	Måsvatnet	785	790	0.3865	n/a	No

9.2.3 Soberg PSH Project

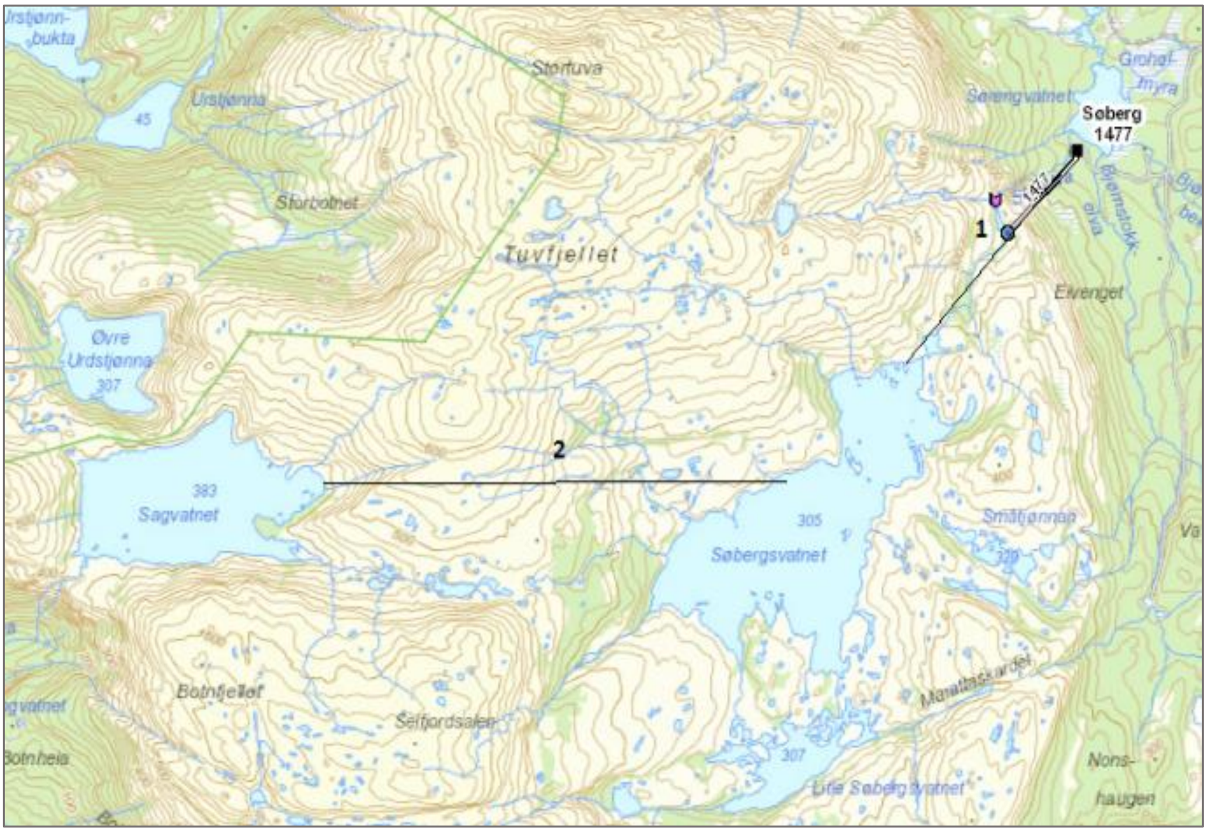

Figure 39: Soberg PSH Project (atlas.nve.no, n.d.)

Table 6: Hydrological data on Soberg PSH Project

Project related	**Reservoir**	**LRWL [m.o.h]**	**HRWL [m.o.h]**	**Volume [Mill.m^3]**	**Area [Km^2]**	**Regulated reservoir**
1	Sørengvatnet	25	30	n/a	0.1362	No
2	Søbergsvatnet	297	302	n/a	1.5286	No
2	Sagvatnet	377	382	n/a	0.9717	No
3	Øvre urdstjønna	301	306	n/a	0.3193	No

9.2.4 Langfjord PSH Project

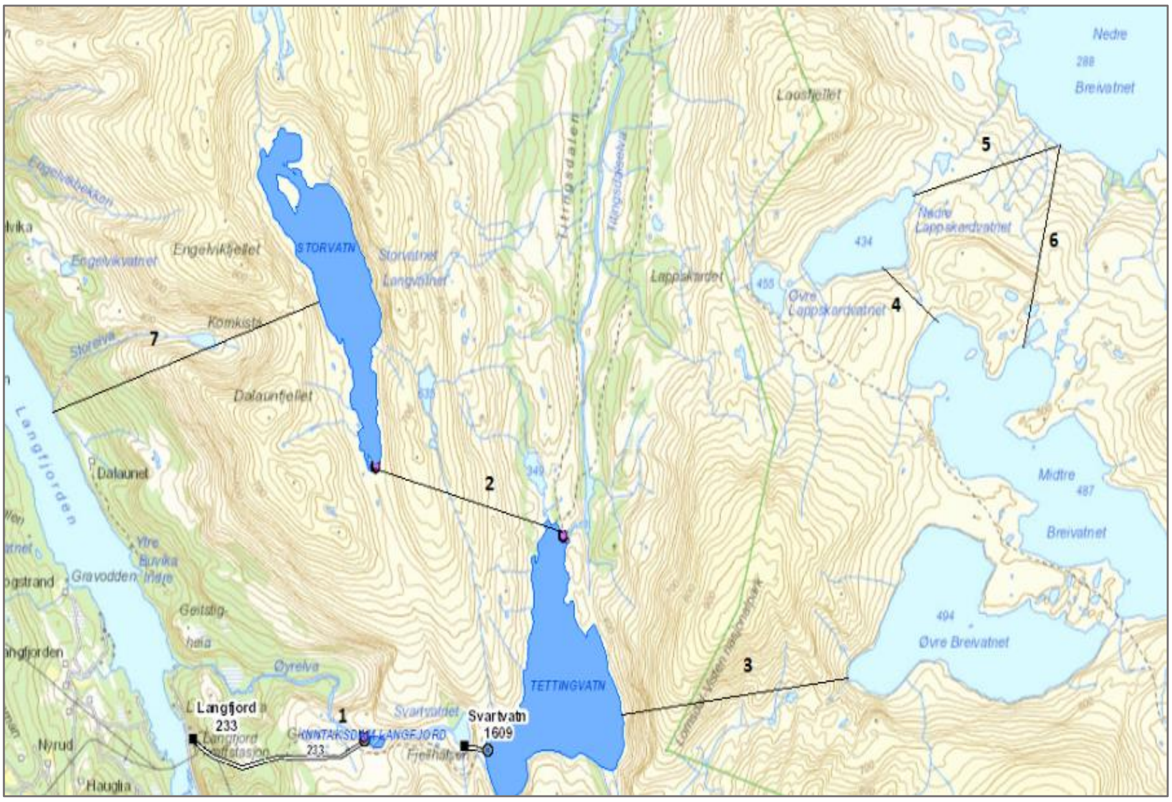

Figure 40: Langfjord PSH Project (atlas.nve.no, n.d.)

Table 7: Hydrological data on Langfjord PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2-3	Tettingvatn	322	343	18.4	1.19	Yes
2-7	Storvatn	555.5	559	3.2	0.92	Yes
4-6	Midtre Breivatnet	482	487	n/a	2.1952	No
3	Øvre breivatnet	489	494	n/a	1.5315	No
4-5	Nedre lappskardvatnet	429	434	n/a	0.399	No
5-6	Nedre breivatnet	483	288	n/a	2.1277	No

9.2.5 Grytåga PSH Project

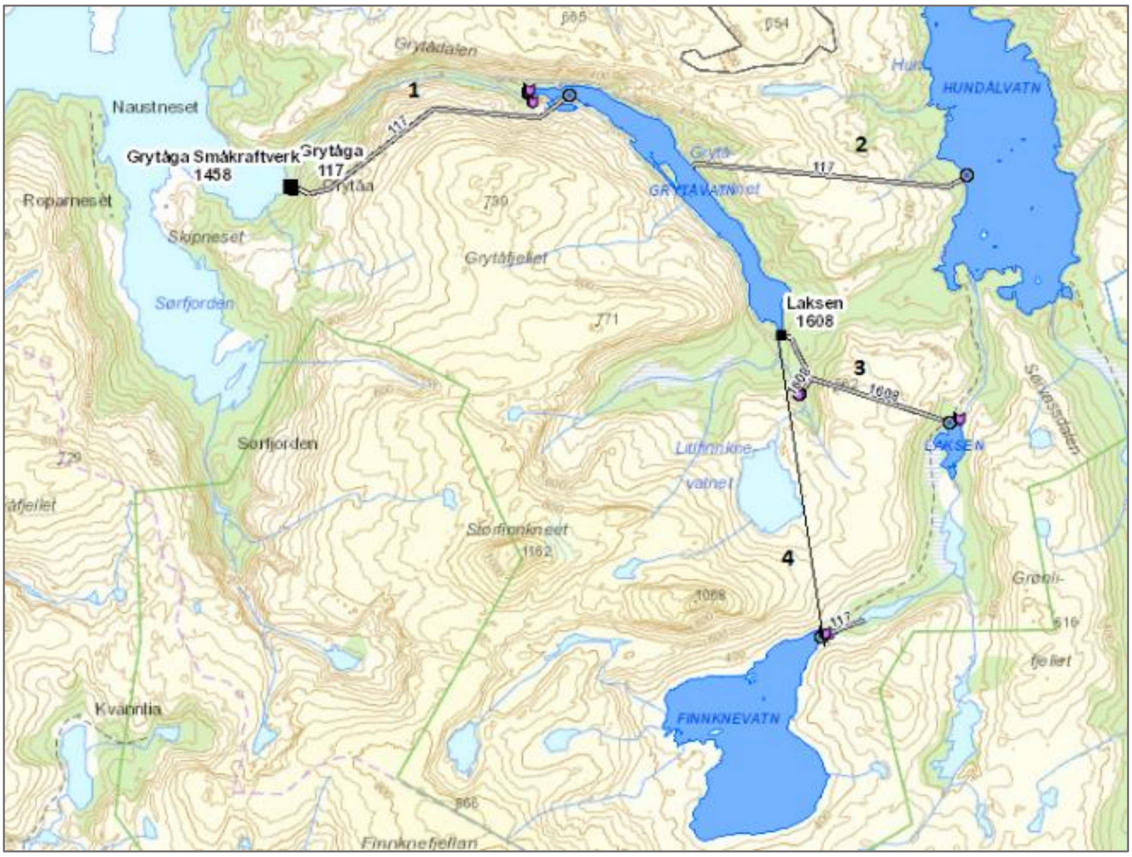

Figure 41: Grytåga PSH Project (atlas.nve.no, n.d.)

Table 8: Hydrological data on Grytåga PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2-3-4	Grytåvatn	172	198	26.5	1.49	Yes
2	Hundålvatnet	173.3	199	120	7.7679	Yes
3	Laksen	274.9	277.9	n/a	0.17	No
4	Finnknevatn	336	353	45	3.78	Yes

9.2.6 Røssåga PSH Project

Figure 42: Røssåga PSH Project (atlas.nve.no, n.d.)

Table 9: Hydrological data on Røssåga PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2	Stormyra	244.5	247.9	19	6.58	Yes
2-3	Bleikvatn	386	407.5	250	12.74	Yes
1-3	Tustervatn-Røsvatn	370.7	383.15	2309	218.05	Yes

9.2.7 Kjensvatn PSH Project

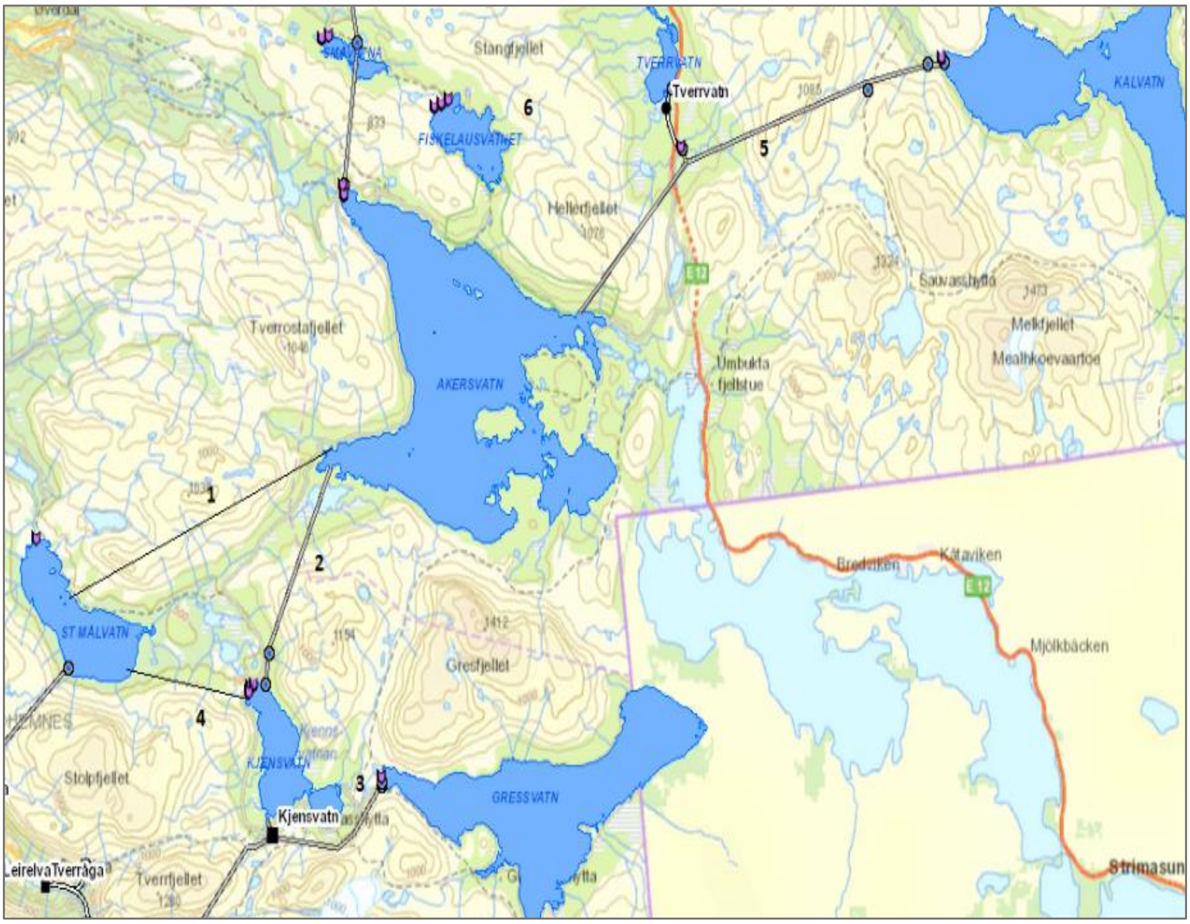

Figure 43: Kjensvatn PSH Project (atlas.nve.no, n.d.)

Table 10: Hydrological data on Kjensvatn PSH Project

Project related	**Reservoir**	**LRWL [m.o.h]**	**HRWL [m.o.h]**	**Volume [Mill.m^3]**	**Area [Km^2]**	**Regulated reservoir**
1-2-5-6	Akersvatn	480	523	1276	42.24	Yes
1-4	ST Målvatn	397	430	153	7.35	Yes
2-3-4	Kjensvatn	520	527	28	4.99	Yes
3	Gressvatn	582	598	314	22.6	Yes
5	Kalvatn	521	564	706	28.61	Yes

9.2.8 Fagervollan Mo i Rana PSH Project

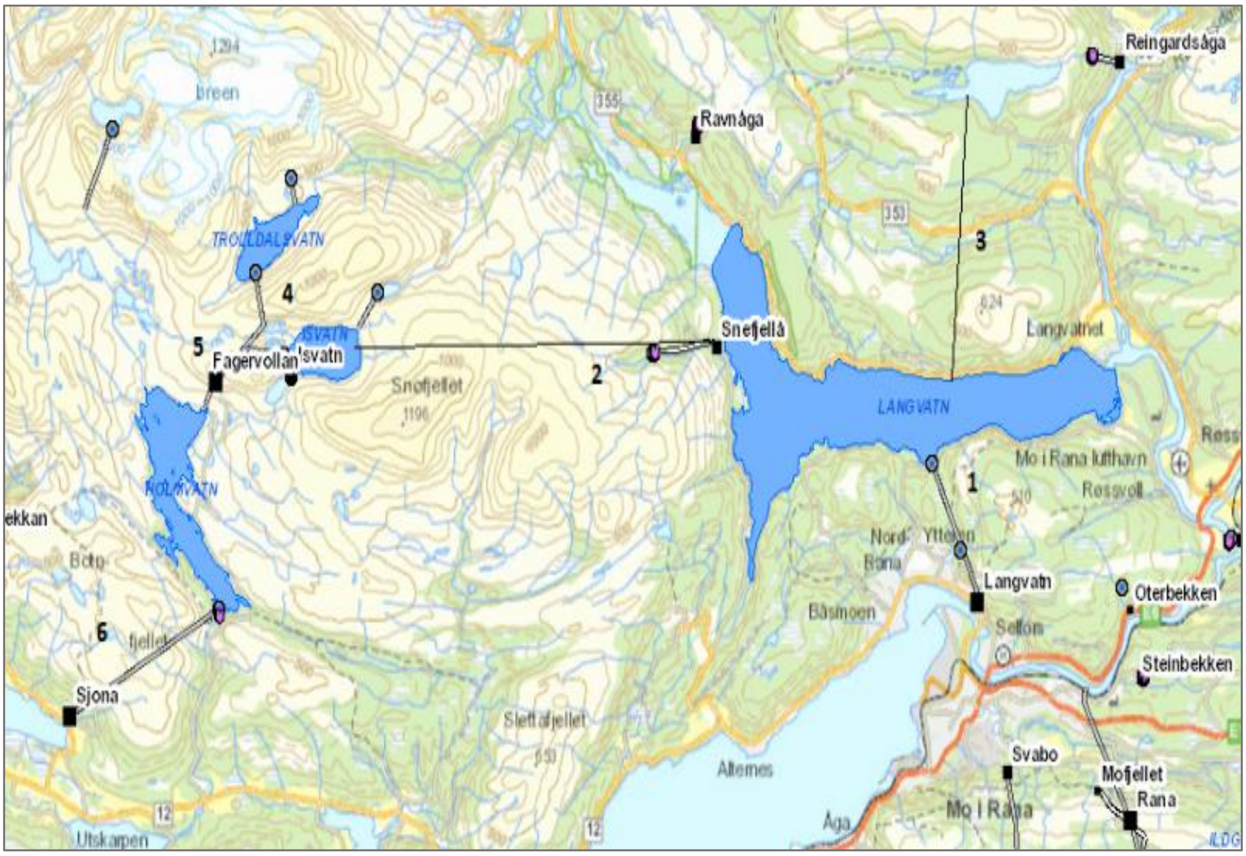

Figure 44: Fagervollan Mo i Rana PSH Project (atlas.nve.no, n.d.)

Table 11: Hydrological data on Fagervollan Mo i Rana PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2-3	Langvatnet	41	43.7	54	22.67	Yes
3	Reingardslivatnet	356	361	n/a	2.407	No
2-4	Isvatn	538.5	562.5	44	2.08	Yes
4-5	Trolldalsvatn	438.5	468.5	30	1.66	Yes
5-6	Holmvatn	254.3	275	72	4.84	Yes

9.2.9 Svartsen PSH Project

Figure 45: Svartsen PSH Project (atlas.nve.no, n.d.)

Table 12: Hydrological data on Svartsen PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2	Storglomvatn	460	585	3506	47.3	Yes
2-4	Fykanvatnet	90	92	2.8	1.22	Yes
3-5	Øv Navervatn	540	544.94	9	2.14	Yes
3-5	Nd Navervatn	464.44	468.36	8	2.06	Yes
5	Øv Glomvatn	473	495	22.8	1.24	Yes

9.2.10 Forså PSH Project

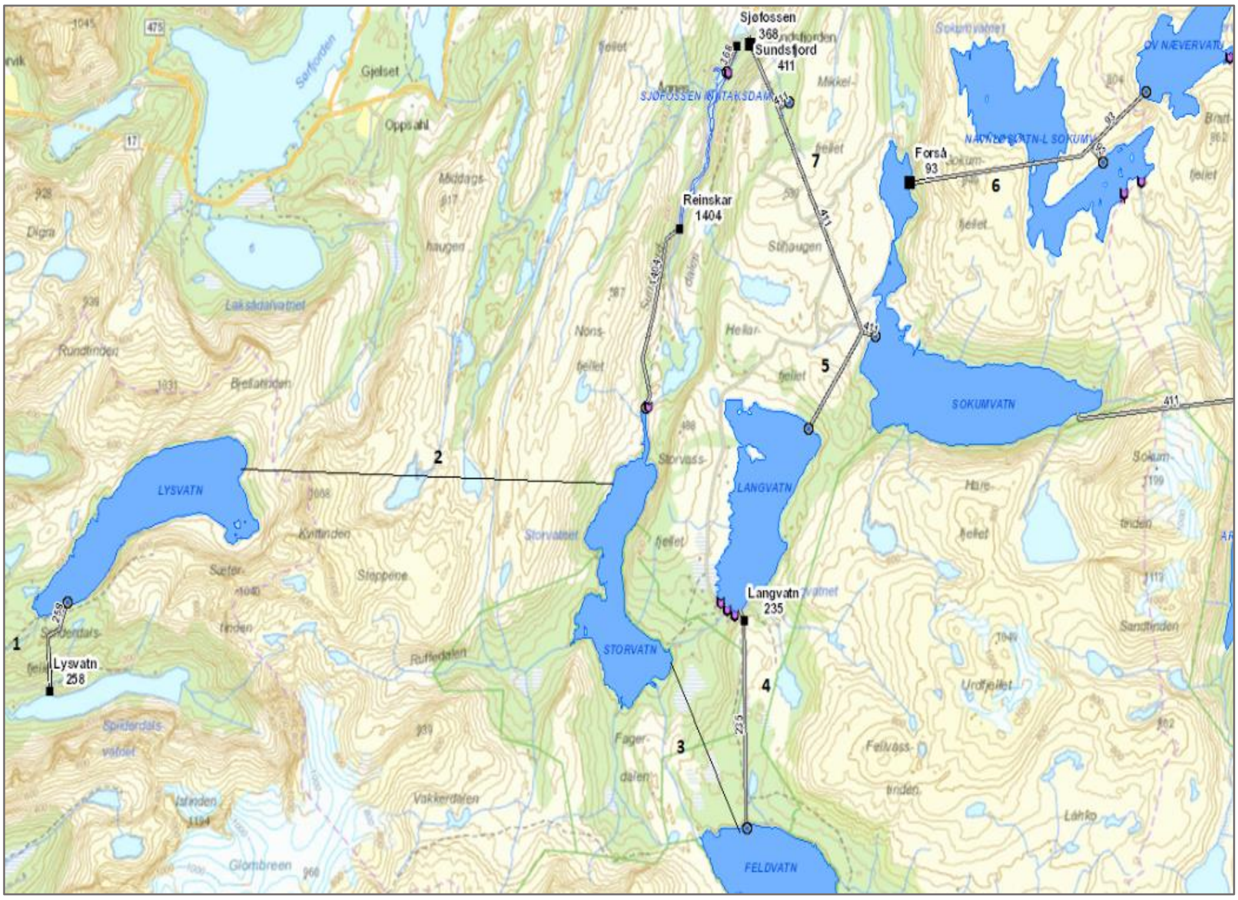

Figure 46: Svartsen PSH Project (atlas.nve.no, n.d.)

Table 13: Hydrological data on Forså PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-2	Lysvatn	361.65	371.65	28	4.5	Yes
2-3	Storvatn	184.1	187.6	10	3.3	Yes
3-4	Feldvatn	363.2	393.3	55.2	2.69	Yes
4-5	Landvatn	299.1	331.3	75.9	3.73	Yes
5-6-7	Sokumvatn	299.1	331.3	130.1	6.25	Yes
6	Navnløsvatn-L Sokumv	637.43	645	17.4	4.46	Yes
6	Øv Nævervatn	580	604	45.9	3.26	Yes

9.2.11 Oldereid PSH Project

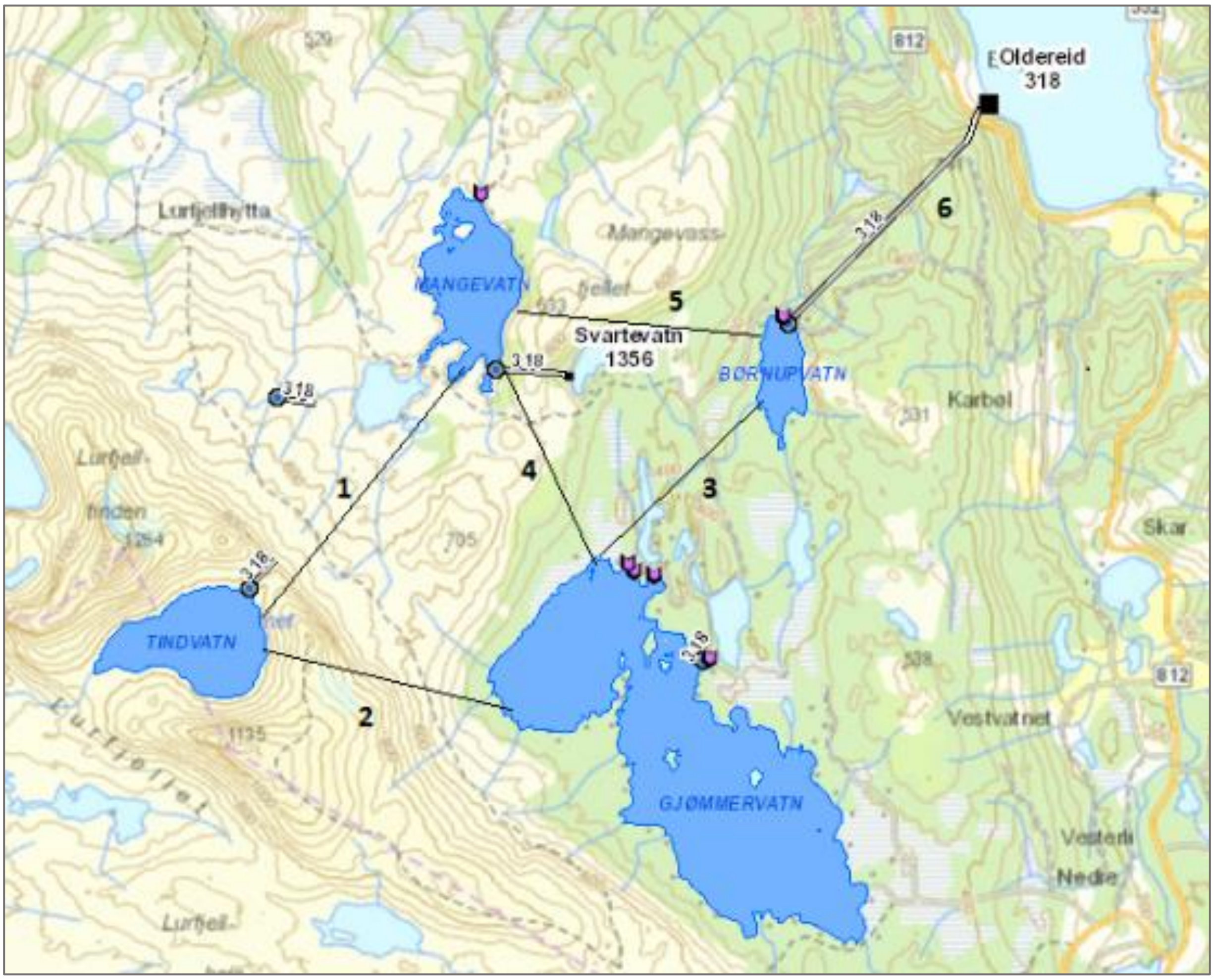

Figure 47: Oldereid PSH Project (atlas.nve.no, n.d.)

Table 14: Hydrological data on Oldereid PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-4-5	Mangevatn	466.33	473.03	6.7	1.31	Yes
1-2	Tindvatn	775.25	780.25	6.3	1.36	Yes
2-3-4	Glømmervatn	390.5	399.25	38	6.61	Yes
3-5-6	Børnupvatn	309.33	321.33	5	0.47	Yes

9.2.12 Lomi PSH Project

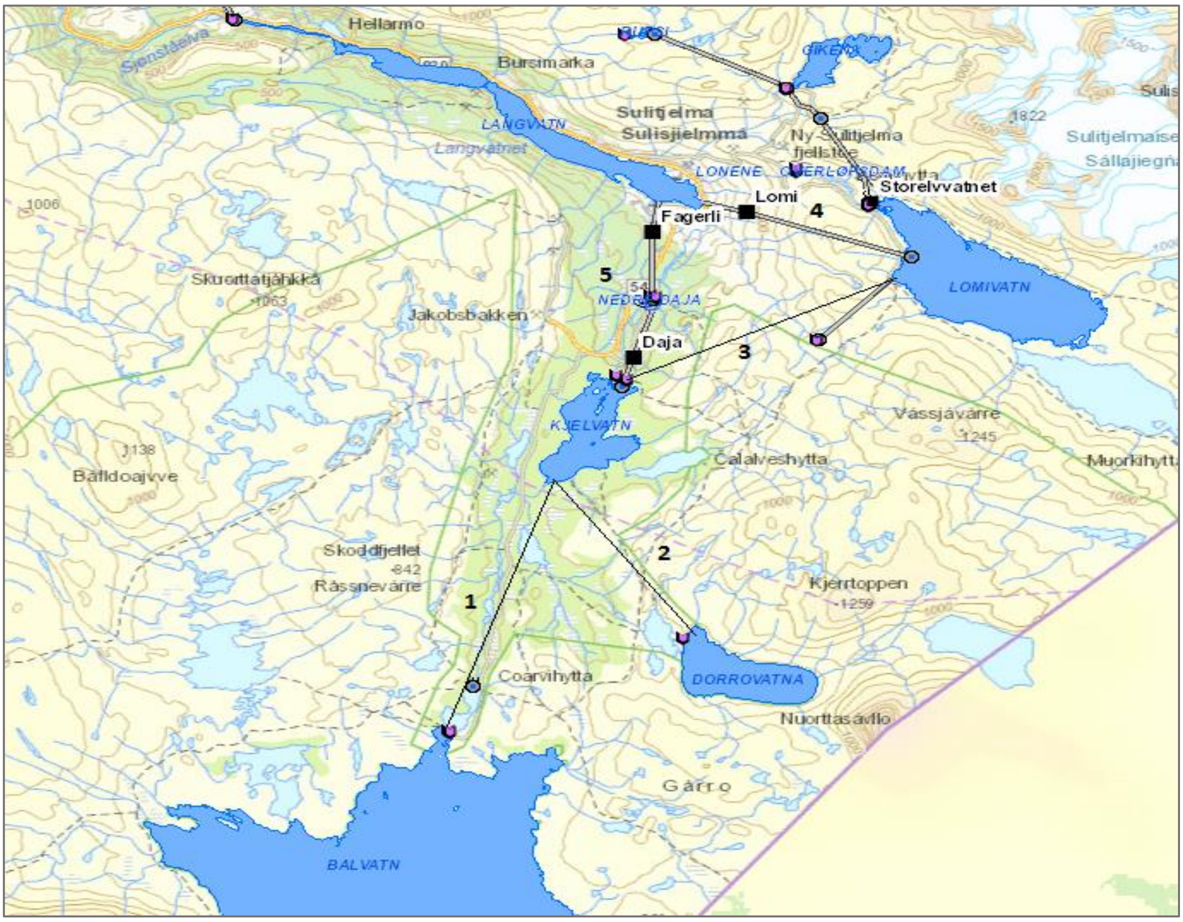

Figure 48: Lomi PSH Project (atlas.nve.no, n.d.)

Table 15: Hydrological data on Lomi PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Balvatn	589.91	597.31	292.3	40.84	Yes
2	Dorrovatna	670.48	674.48	16	4.26	Yes
1-2-3-5	Kjelvatn	496.1	509.5	8	3.81	Yes
3-4	Lomivatn	648.68	707.98	473	11.38	Yes
4-5	Langvatn	126	126.5	2.7	5.64	Yes

9.2.13 Siso PSH Project

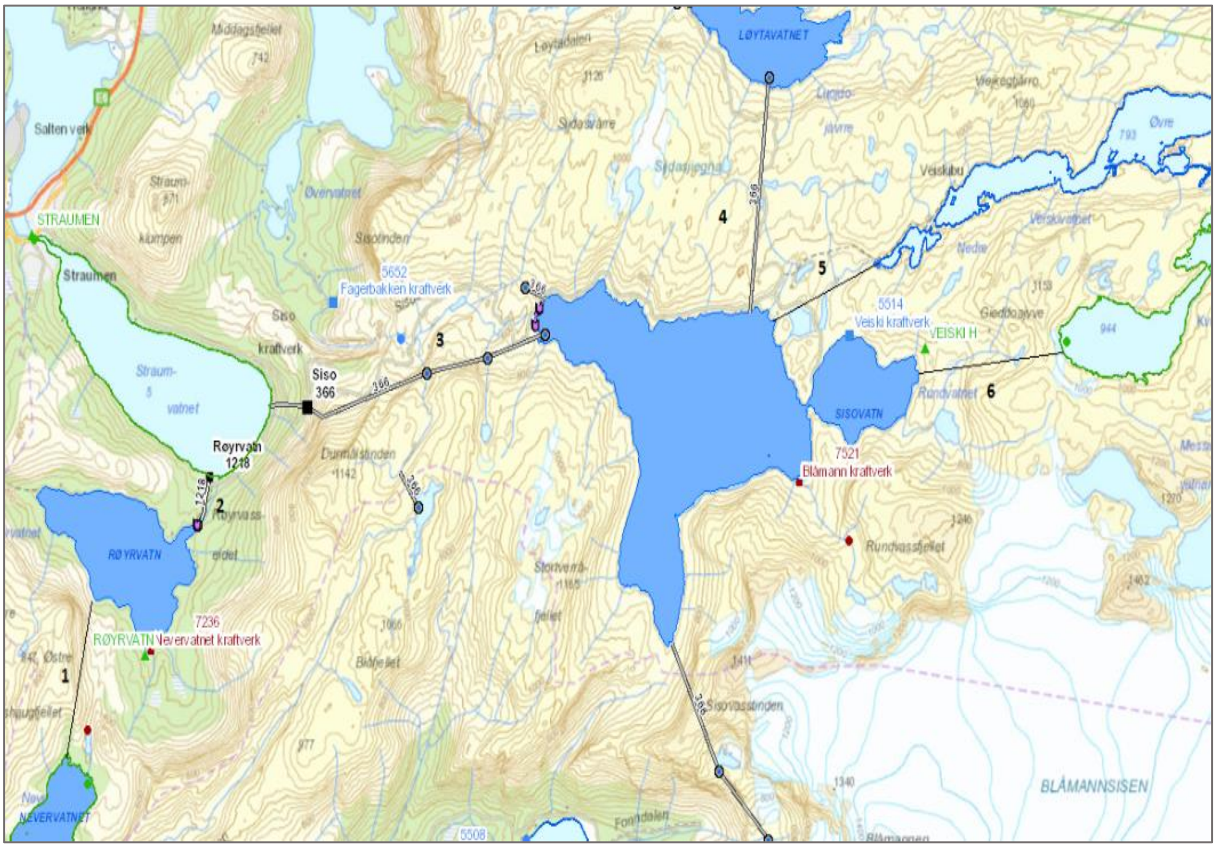

Figure 49: Siso PSH Project (atlas.nve.no, n.d.)

Table 16: Hydrological data on Siso PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Nevervatnet	398	408	n/a	1.57	No
1-2	Røyrvatn	111.2	115	14	4.01	Yes
2-3	Straumvatnet	4.5	5	n/a	6.77	No
3-4-5-6	Sisovatn	615	671	498.1	14.95	Yes
4	Løytavatnet	652.5	671	49	2.76	Yes
5	Øvre Veiskivatnet	792	793	n/a	3.84	No
6	Kvitvatnet	938	950	n/a	3.08	No

9.2.14 Lakshola PSH Project

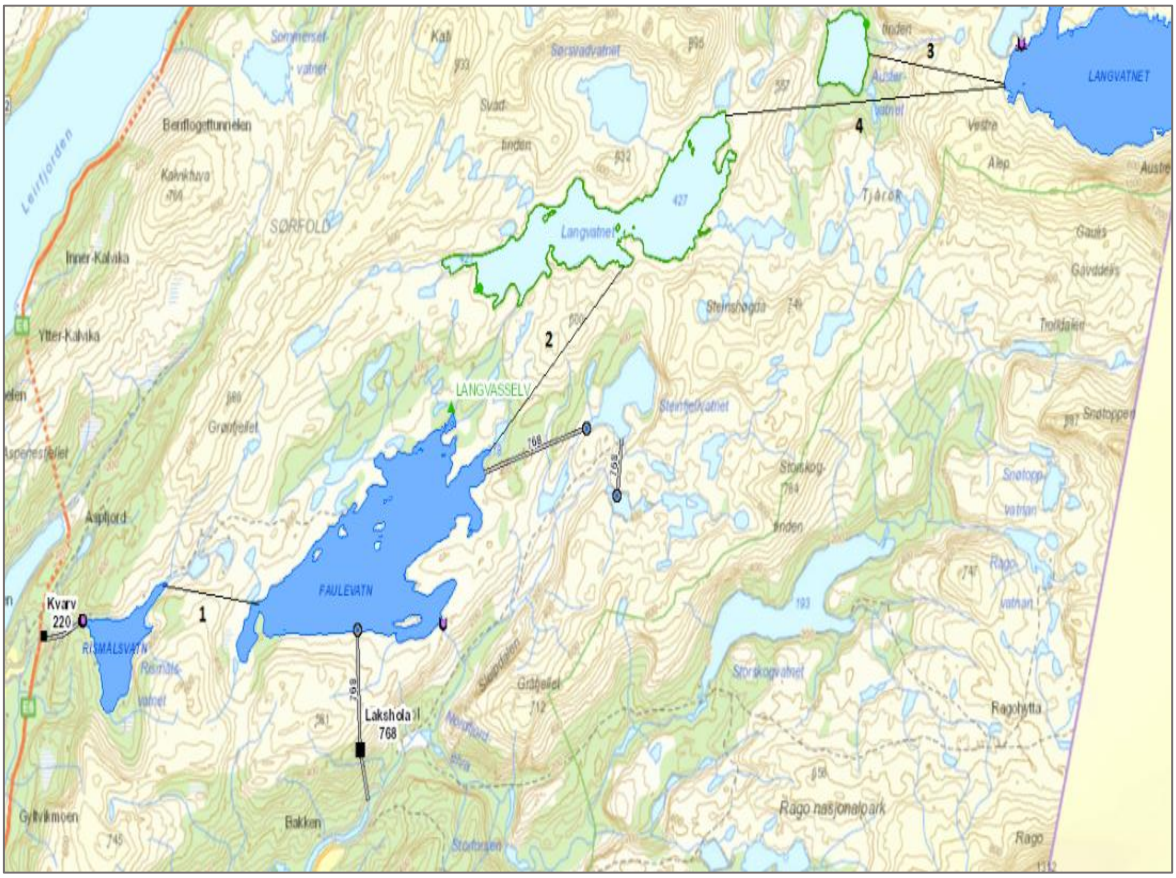

Figure 50: Lakshola PSH Project (atlas.nve.no, n.d.)

Table 17: Hydrological data on Lakshola PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Rismålsvatn	279.5	281.5	2.1	1.08	Yes
1-2	Faulevatn	314	317.5	24.5	7.25	Yes
2-4	Langvatnet svierppejavrre	418	427	n/a	5.26	No
3	Austervatnet	262.7	272.6	n/a	0.92	No
4	Langvatnet	545	622	528	13.98	Yes

9.2.15 Slunkajavrre PSH Project

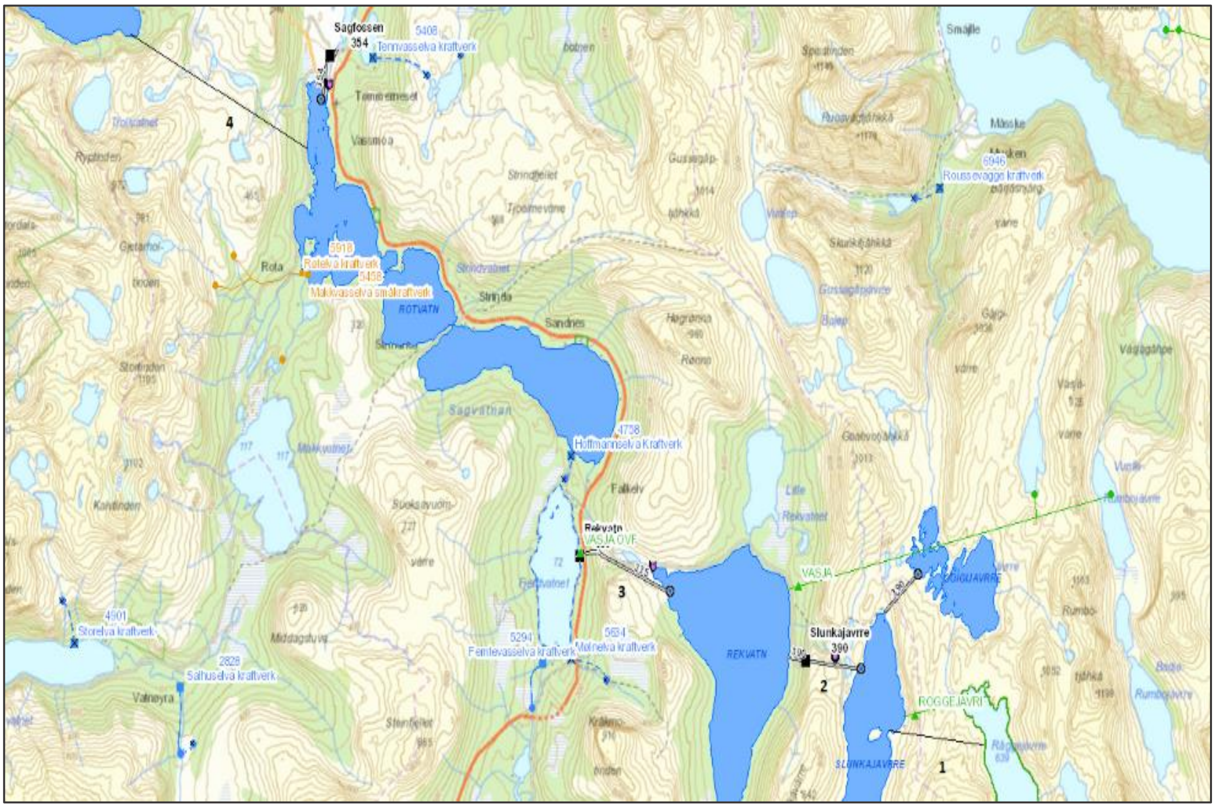

Figure 51: Slunkajavrre PSH Project (atlas.nve.no, n.d.)

Table 18: Hydrological data on Slunkajavrre PSH Project

Project related	**Reservoir**	**LRWL [m.o.h]**	**HRWL [m.o.h]**	**Volume [Mill.m^3]**	**Area [Km^2]**	**Regulated reservoir**
1	Roggejavri	624	639	n/a	1.97	No
1-2	Slunkajavrre	516.35	531.35	80	6.13	Yes
2-3	Rekvatn	271.75	283.75	77	7.39	Yes
4	Forsanvatnet	253.5	258.5	25	4.8	Yes
3	Fjendvatnet	72	73	n/a	2.26	No
4	Rotvatn	44.45	45.45	4	10.89	Yes

9.2.16 Sørfjord II PSH Project

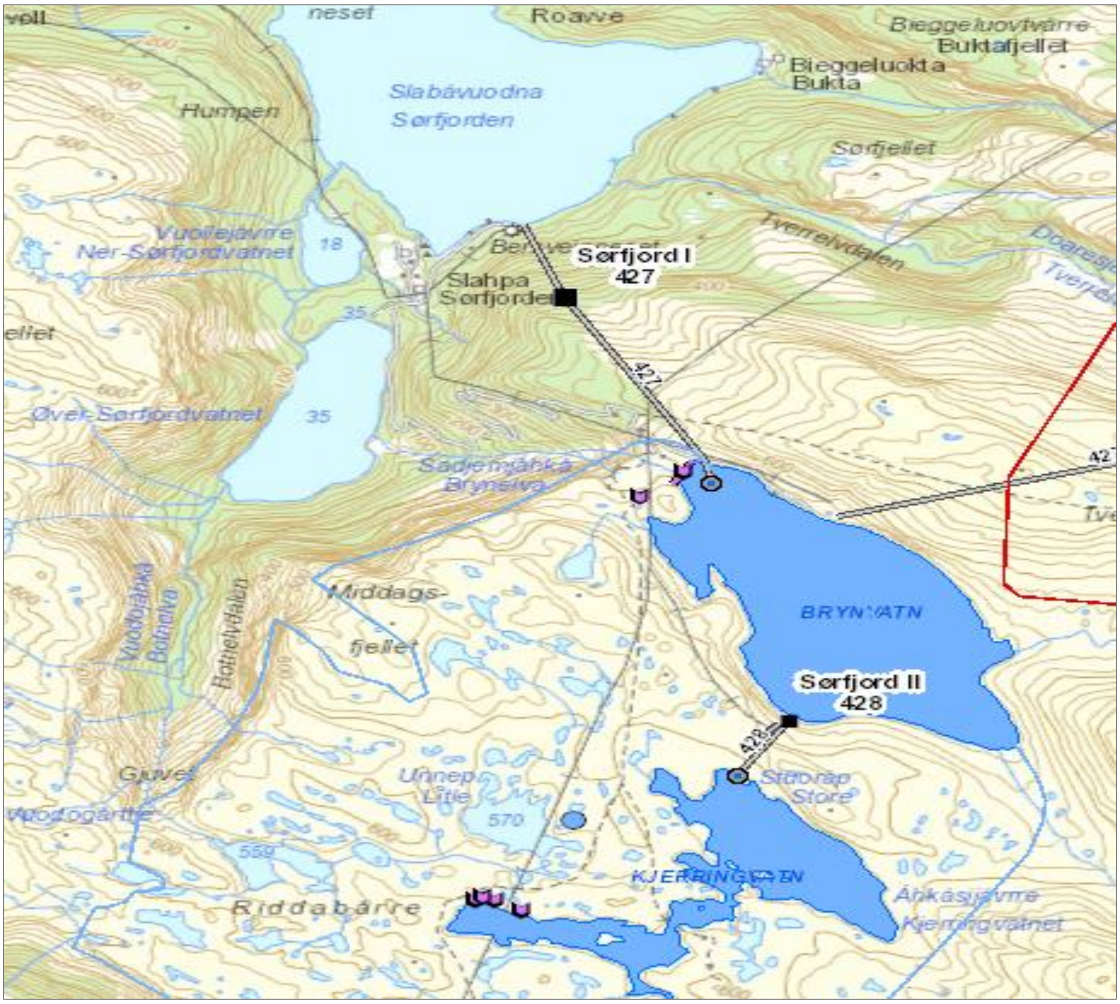

Figure 52: Sørfjord II PSH Project (atlas.nve.no, n.d.)

Table 19: Hydrological data on Sørfjord II PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Kjerringvatn	562	577.5	5.2	0.68	Yes
1	brynvatn	435	515	75	1.41	Yes

9.2.17 Nygård Narvik PSH Project

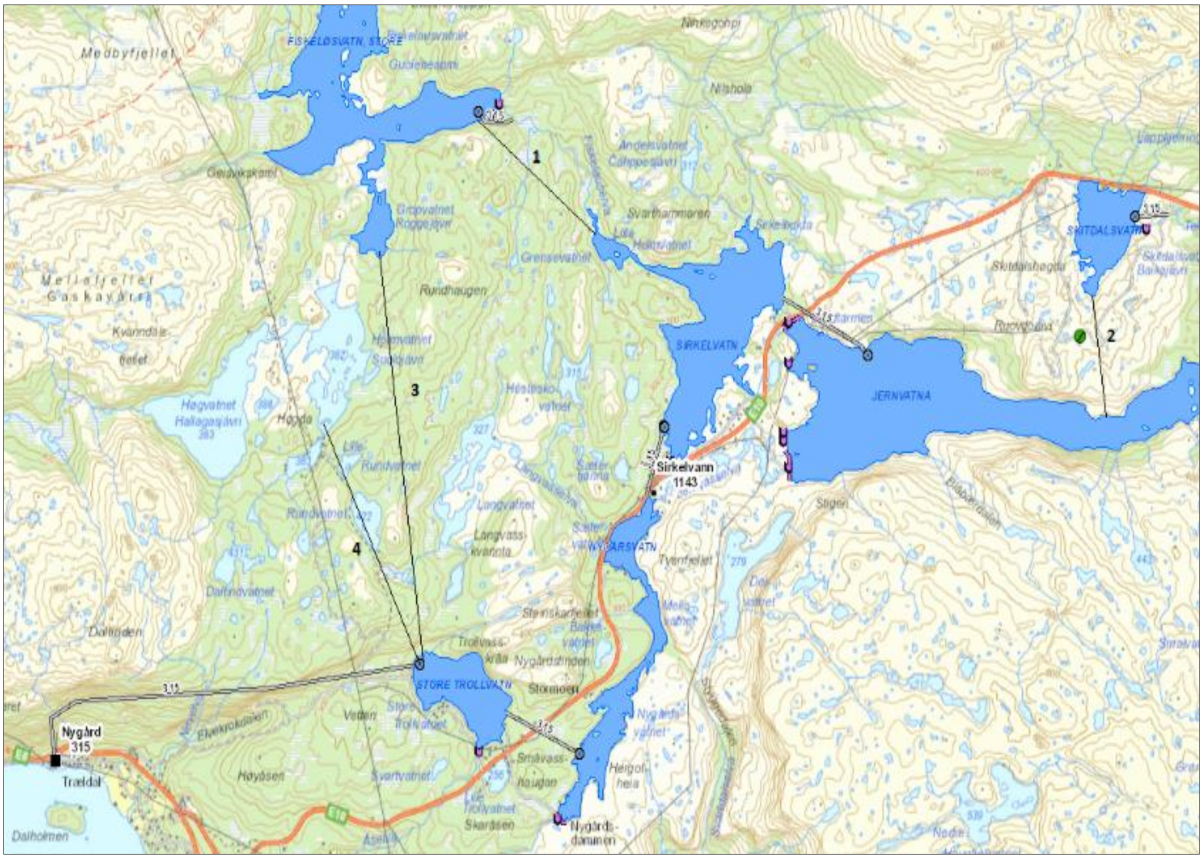

Figure 53: Nygård Narvik PSH Project (atlas.nve.no, n.d.)

Table 20: Hydrological data on Nygård Narvik PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1-3	Fiskeløsvatn	324.5	347.5	17.2	1.45	Yes
1	Sirkelvatn	256	273	13.5	1.22	Yes
2	Jernavatna	264.8	298.5	52.9	3.62	Yes
2	Skitdalsvatn	361	379	4.3	0.39	Yes
4	Høgvatnet	378	383	n/a	0.6789	No
3	Store trollvatn	250	259	2.5	0.43	Yes

9.3 Troms

In Troms area, only two sites have been taken into account which are shown below. Further details of the reservoir and station can be found in the Appendix D.1 and D.3.

9.3.1 Kvænangsbotn PSH Project

Figure 54: Kvænangsbotn PSH Project (atlas.nve.no, n.d.)

Table 21: Hydrological data on Kvænangsbotn PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Soikkajavrre	516.5	529	61.2	6.18	Yes
1-2	Abbujavrre	674	692	71.7	5.89	Yes
2-3	Lassajavrre	519	543	61.8	3.27	Yes
3	Småvatna	293.5	315	23.3	1.4	Yes

9.3.2 Bergsbotn PSH Project

Figure 55: Bergsbotn PSH Project (atlas.nve.no, n.d.)

Table 22: Hydrological data on Bergsbotn PSH Project

Project related	Reservoir	LRWL [m.o.h]	HRWL [m.o.h]	Volume [Mill.m^3]	Area [Km^2]	Regulated reservoir
1	Lappegamvatn	150.25	152.25	n/a	0.36	No
1-2-3	Øv Helvetesvatn	197.25	203.2	26.9	4.89	Yes
2	Ned Hestvatn	305.85	312.25	11.5	1.99	Yes
3-4	Store Hestvatn	349.5	360.5	20	1.96	Yes
4	Roaldsvatn	427.5	435.5	5.8	0.82	Yes

The further details of these projects (9.2-9.3) can be found in the Appendix D.3

10 HYPOTHESIS COST ESTIMATION ANALYSIS FOR PSH PROJECTS

The cost estimation of the hydro plant is based on prices presented by NVE on January 2015. (Norconsult, Januar 2015). The cost estimation covers three main topics: Civil, Mechanical and Electro technical. The methodology followed for the cost analysis estimation, is based on a work by Bruno Capo, under the topic "The potential for pumped storage Hydropower Development in Mid-Norway" (Capo, 2012).

For the cost estimation analysis for PSH projects, a model was developed in Excel®. The detailed results of the analysis is presented at Appendix D.4

10.1 Assumptions

- Any cost involving installation, construction and maintenance of dams, reservoirs/lakes are excluded
- Only the costs for civil work, mechanical and electrical equipment's are considered
- Wind power for electricity generation should be cheaper than hydropower
- Cost estimation is only the early phase of project to present the rough figure of the cost
- The maximum variation of water level in the lake should not exceed 14 cm/hour (Eivind Solvang, 2014, p. 16)
- The start level of reservoir is 100% and 0 for upper and lower reservoir respectively and there are no other inflow/discharge to/from the reservoirs.
- Power generation and pumping time per day is consider as 24 and 6 hours respectively
- The length of the tunnel is simply a distance between upper reservoir and lower reservoir
- The length of access tunnel and adit tunnel is consider as 800 m and 300 m respectively for all calculations
- The average velocity inside the tunnel is 2 m/s
- The overall efficiency of turbine is set up to 80%

10.2 Nordland PSH Projects

Table 23: Nordland PSH Projects estimated cost (NOK/kW)

Project No	Project name	Total estimated Maximum power [MW]	Estimated Max. Production [GWh]	Total estimated cost [NOK/kW]
1	Kolsvik Bindal	1221,66	376,8687	74290,52
2	Tosdalen	34,33	1,714613	19671,82
3	Soberg	31,2	1,5587	43848,76
4	Langfjord	249,72	20,58661	91400,71
5	Grytåga	183,62	36,48862	39389,88
6	Røssåga	6112,19	806,8024	9331,085
7	Kjensvatn	1603,8	543,971	20333,04
8	Fagervollan Mo i Rana	717,72	124,931	30094,16
9	Svartsen	6832,49	8264,116	18121,31
10	Forså	944,31	171,7191	35680
11	Oldereid	361,28	24,21211	31795,55
12	Lomi	2457,39	895,9834	13691,04
13	Siso	1464,79	734,8441	56315,94
14	Lakshola	902,8	650,6568	51123,63
15	Slunkajavrre	833,13	92,7517	64373,25
16	Sørfjord II	10,42	1,61538	10925,86
17	Nygård Narvik	42,55	8,447195	57568,32

10.3 Troms PSH Projects

Table 24: Troms PSH Projects estimated cost (NOK/kW)

Project No	Project name	Total estimated Maximum power [MW]	Estimated Max. Production [GWh]	Total estimated cost [NOK/kW]
1	Kvænangsbotn	442,69	88,08628	8993,866
2	Bergsbotn	175,52	14,19323	24719,36

10.4 Estimated Capacity of PSH in Northern Norway

From the above studies, it is clearly seen that Northern Norway has tremendous capacity of hydropower energy. An accumulated total maximum capacity[2] of approximately 25 GW can be produced in Northern Norway area with the production capacity of approximately 13 TWh. The total cost for the entire project amounts around 47000 million kroner with an average value of approximately 550 million kroner per each station.

A summary table of all the details calculation of the above topics can be found in Appendix D.1, D.2, D.4 and E.1.

11 CASE STUDY FOR PSH MODEL: ISVATN-LANGVATNET PSH

The choice of reservoir pair Isvatn-langvatnet was choose as they have very large altitude difference, short transportation distance and have similar reservoir volumes. This large altitude difference has high water head to generate the power. Isvatn-langvatnet PSH is a part of project 9.2.8 Fagervollan Mo i Rana PSH Project with maximum power capacity of approximately 208 MW costing around 526 million kroner. For more information: Appendix D.1,D.2,D.4 and E.1

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[2] when variation of water level in upper reservoir is 10 cm/hour

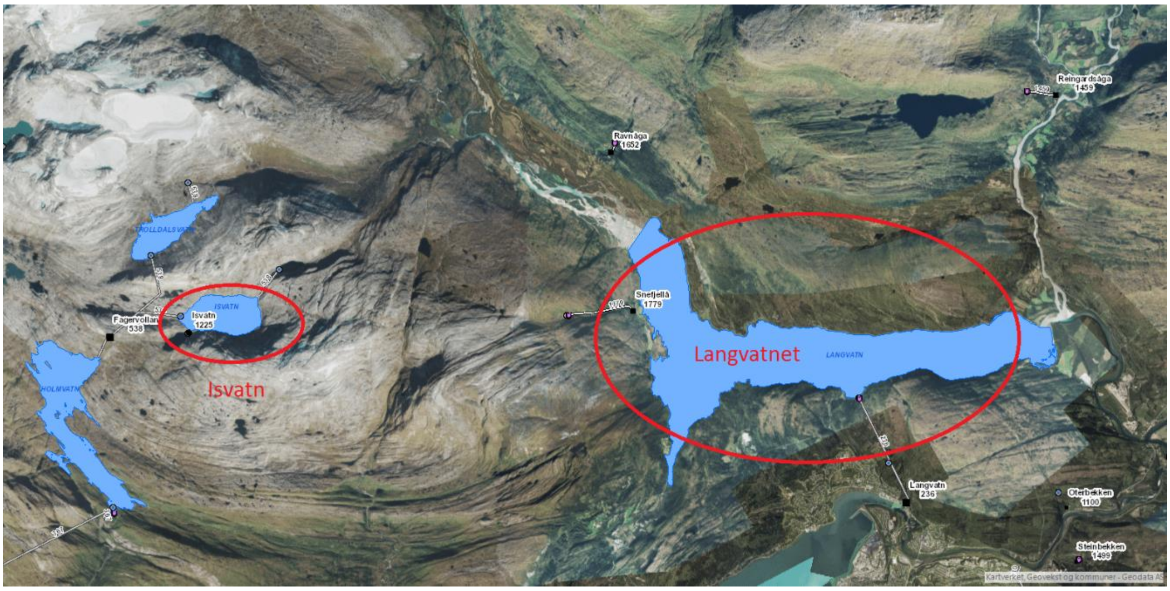

Figure 56: Isvatn-Langvatnet PSH (atlas.nve.no, n.d.)

11.1 Reservoir Characteristics

The following are reservoir data

Table 25: Reservoir Data

Project 10.1.8	**Upper**	**Lower**
Reservoirs	Isvatn	Langvatnet
Water course No.	772	745
Hydropower plant No.	538	236
Volumes	44	54 million m^3
HRWL	562,5	43,7 masl
LRWL	538,5	41 masl
HRWL-LRWL	24	2,7 m
Area	2,08	22,67 km^2
Effective area	1,83	20 km^2
Start level	100 %	0 %
Other inflow	0	0 m^3
Other discharge	0	0 m^3

11.2 Methodology for analysing the balancing of power

11.2.1 Pumped storage Hydropower Model

The potential PSH reservoirs screened in this work, from the estimated power outputs can be used for balancing power purposes taking into consideration the reservoir's Highest Regulated Water Levels (HRWL) and Lowest Regulated Water Levels (LRWL). In order to simulate the pumped storage operation or reservoir pairs, a model Pumped Storage Hydro (PSH) was developed in Excel® (Nie, et al., 2016)

The model calculates changes of water volume in the lower and upper reservoirs which operate under the principle of pumped storage hydropower. The principle of operation is that, water is pumped up the upper reservoir (electricity consumption, uptake of energy) or released through turbines into the lower reservoir (electricity generation, output of energy) (Nie, et al., 2016). The main output of the model are calculations of the differences in water volume, level and area in selected reservoirs pairs, under new potential energy storage scenarios with phases of pumping and generation. The model consists of three basic components;

- Current operation
- Balancing power operation
- Future operation

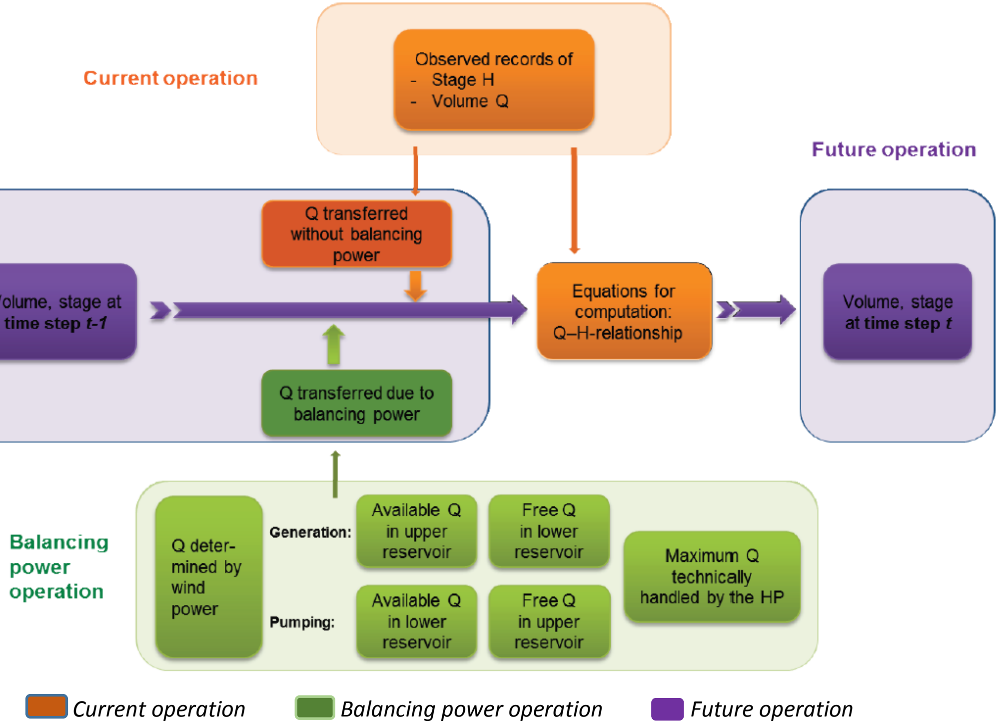

Figure 57: Scheme of the PSH model (Patocka, 2014)

A layout of the PSH operation scheme is shown above is simulated by integrating the current operation with the balancing power operation. Simulation of future operations are estimated based on the water volume transferred between both reservoirs.

By using the model, the water volumes which are moved between the upper and lower reservoirs are calculated in intervals of a day, the corresponding reservoir stages are calculated from the volumes by use of specific rating curves. Current operations are implemented using observed records of water volume and stage. In addition to these water volumes, the volumes transferred due to balancing power operation are accounted for by calculating the volumes corresponding to the required balancing power. In calculating this, the volume of water pumped up during electricity uptake into the upper reservoir and water volumes released into the lower reservoir during electricity generation are observed. The future operational scheme is obtained by summing up the water volumes of the current operation and the balancing power operation.

11.2.2 Principle of design for the balancing power scenarios

The design principle is that hydropower would compensate for shortfalls in meeting the required load conditions in electricity generation from renewable sources mainly wind power in this case. To compensate for the shortfalls, electricity will be generated from the hydropower plants during periods with little wind and in periods of strong winds, water will be pumped into the upper reservoir for storage purposes. Variations of volume and water level in reservoirs will depend on both market demands and wind power production.

In phasing out the variations to obtain a balanced system, two power balancing scenarios are established and these scenarios define the schedule for both generation and pumping phases. **7Days-Average** and the **Dev-Average scenario.**

11.2.3 7Days-Average Scenario

The 7Days-Average scenario is characterised by the presumption that hydropower will compensate for short term fluctuations of wind power generation up to one week. The one advantage of hydropower of been able to regulate its generation to meet short term energy demands makes it suitable for balancing any of such short-term variations. In computing under this scenario, the average of each data point of the available wind production data is calculated by starting three days before and three days afterwards on the considered point of time.

The difference between the weekly fluctuations and the daily fluctuations therefore represents the energy required to be balanced. That is when the fluctuations in the weekly production is greater than the fluctuations in the daily production of the wind power, then there is not enough energy. In that case, water has to be discharged from the upper reservoir into the lower reservoir to generate power. With the order reversed, energy will be in abundance and pumping is done to transfer water from the lower to the upper reservoir.

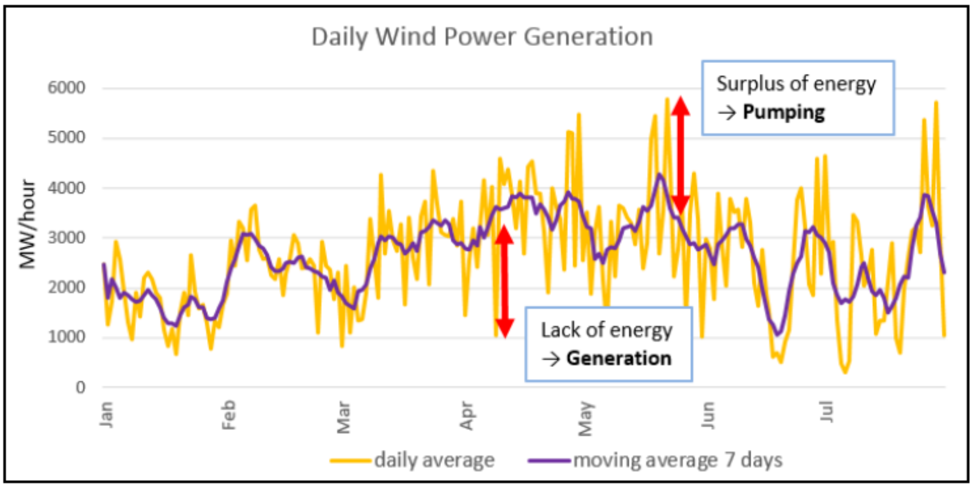

Figure 58: Generation and pumping phases for a 7 Days-Avg scenario. (Nie, et al., 2016)

11.2.4 Deviation Average Scenario

This second scenario assumes that hydropower balances the larger fluctuations in wind power production, while smaller fluctuations up to certain threshold can be compensated by the existing energy system (Nie, et al., 2016). In computing this, values representing high and low threshold values of the daily average production are defined plus or minus 25% of the average of the wind power production. Daily wind production values that fall below the predefined lower threshold value are considered to be times when electricity that to be produced by releasing water into the lower reservoir. Conversely, values above are considered to be times when water has to be pumped into the upper reservoir.

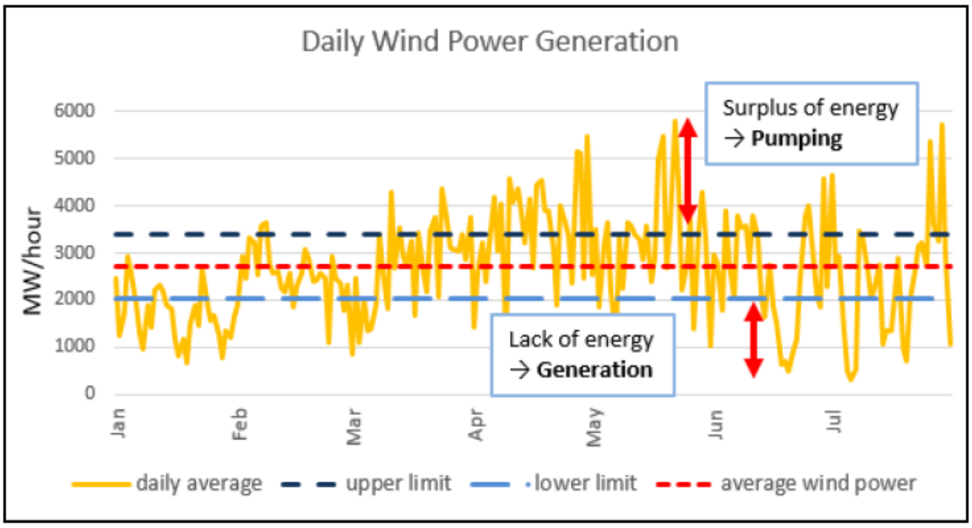

Figure 59: Generation and Pumping phases for a Dev-Avg Scenario (Nie, et al., 2016)

11.3 Assumptions

- For simulation, the following assumption were used;
- Reversible turbine is used for both electricity generation and pumping.
- The overall efficiency of turbine is set up to 80%

- The maximum power capacity of the PSH station is calculated when the variation of water level in upper reservoir is 10 cm/hour
- In PSH model, whenever the simulated stage exceeds the highest regulated water level (HRWL) or reaches below the lowest regulated water level (LRWL), the stage at HRWL or LRWL well be applied.
- Wind flow has no inter-annual variation, therefore the wind power from North Sea for 2000 is used as a referencing value for Balancing Power Operation
- The targeted balancing power is met when the difference between the balancing power demand and the output of pumped storage power station is less than 2.0 GW
- Simulation time interval is 1 hour

Due to the inaccessibility of required data for water level, the available daily water level data has been linearly interpolated in order to obtain hourly data which was crucial for operation of the PSH model. Similarly, for the volume data also the linear interpolation algorithm has been used, starting from LRWL value of the reservoirs.

11.4 Input parameters

The following values are the input parameters to run the model simulation along with the details of reservoir characteristics mentioned above in Table 25: Reservoir Data

Table 26: Input parameters

Power	**208.44 MW**
Pumping capacity	208.44 MW
Efficiency	80 %
Time-step	1 hour

11.5 Water level fluctuation under 7 Days-Average Scenario

Water level variation in the upper and lower reservoir can be studied under the following topics:

11.5.1 Seasonal trend

Upper reservoirs

- Seasonal trend for upper reservoirs has four periods
- A filling period (spring, receive water from melting of snow)
- High stage period (summer)
- Emptying period (autumn and winter)
- Low stage period (before the spring flood)

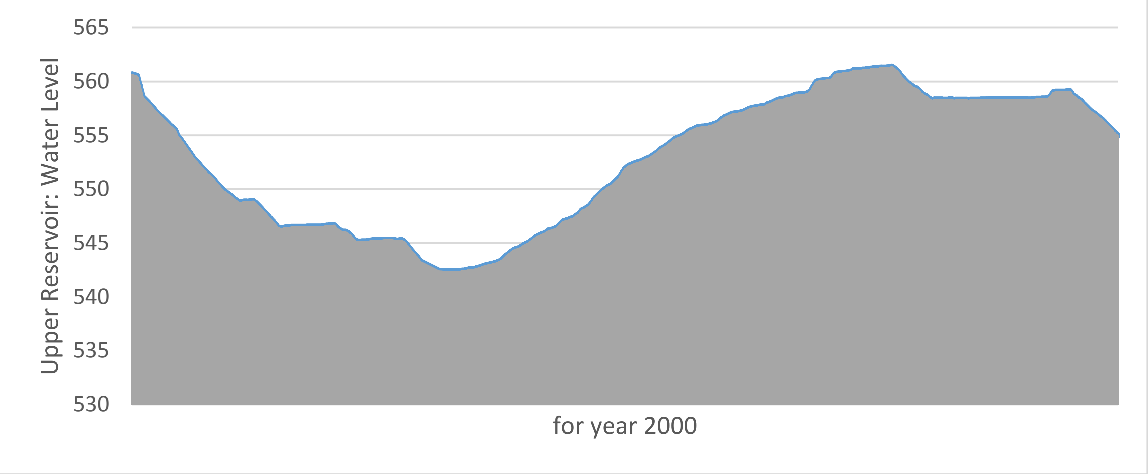

Figure 60: Upper Reservoir Water Level

Lower reservoirs

Seasonal trend for lower reservoirs is not quite clear as upper reservoir. The fluctuation occurs during whole year.

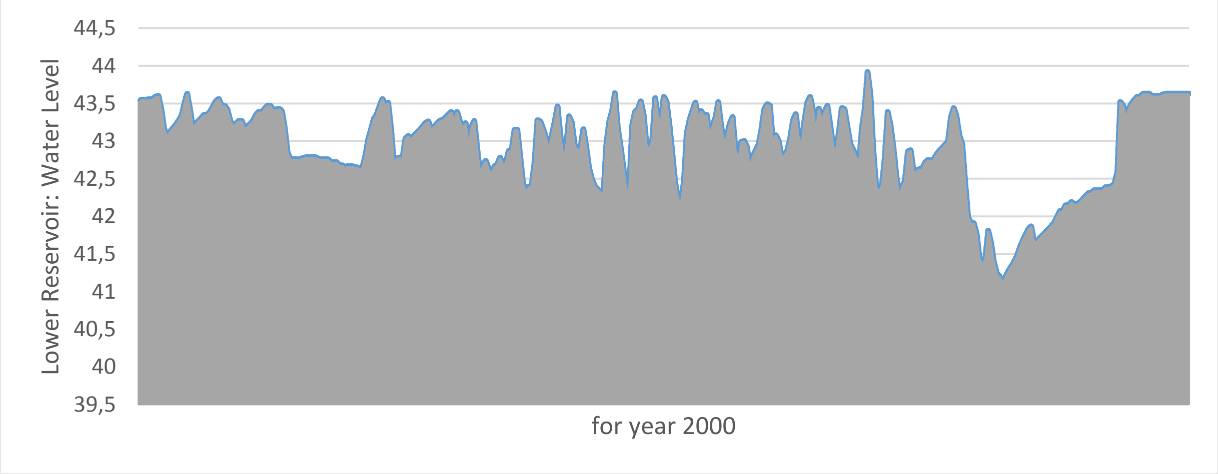

Figure 61: Lower Reservoir Water Level

11.5.2 Shor term Fluctuations

Short term stage fluctuation is determined by the hourly variation in the water level variation of the reservoirs. Filling and discharge induce an instant fluctuation of water level in the reservoirs. These fluctuations rely directly on the reservoirs characteristics and are obtained from the balancing power operation (Nie, et al., 2016). The actual and simulated water level of the upper and lower reservoir for year 2000 (Jan-April) are shown below:

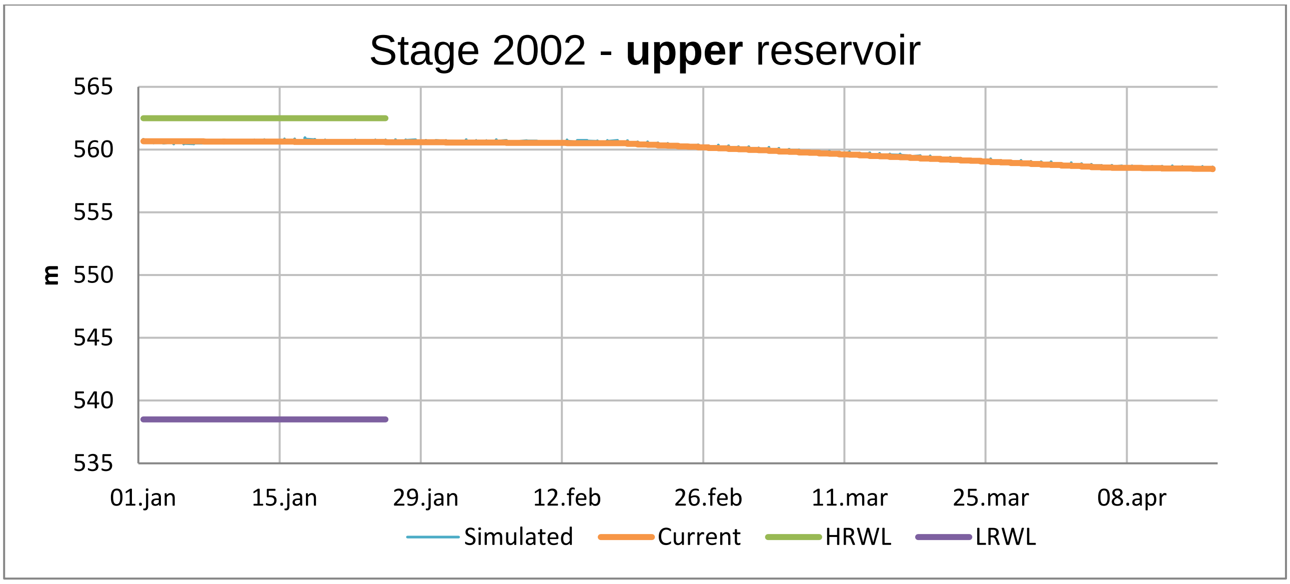

Figure 62: Water Level Variation of Upper Reservoir during 2000 (Jan-April) under 7 Days Avg scenario

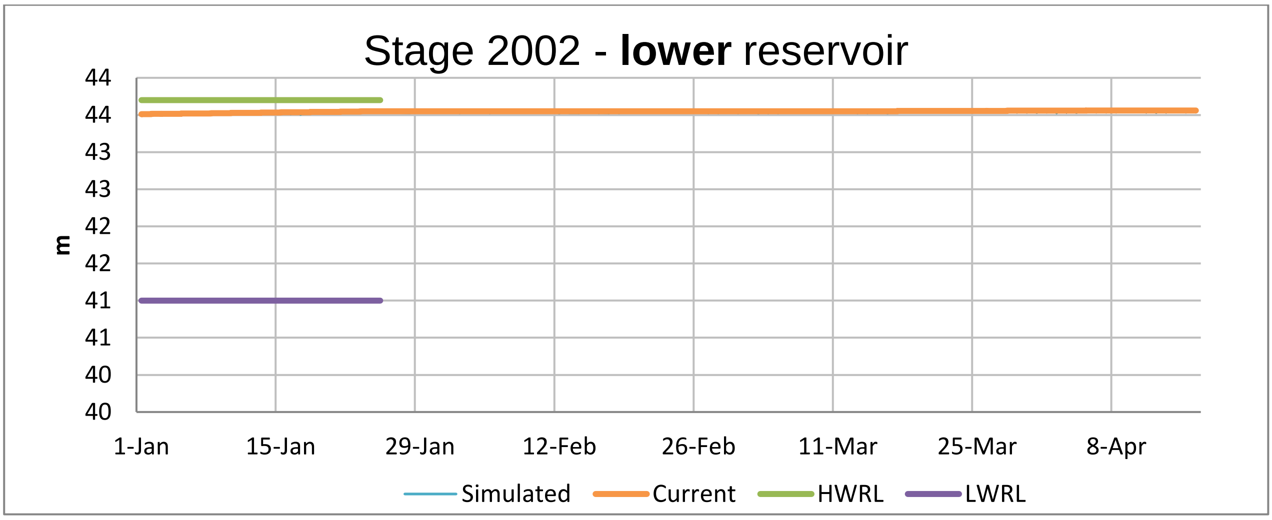

Figure 63: Water Level Variation of Lower Reservoir during 2000 (Jan-April) under 7 Days Avg scenario

11.5.3 Rate of stage change

The average monthly rate of stage change is shown in Figure 64 and Figure 65. The simulated variations of change in rates in both reservoirs is higher than the currents rate of change.

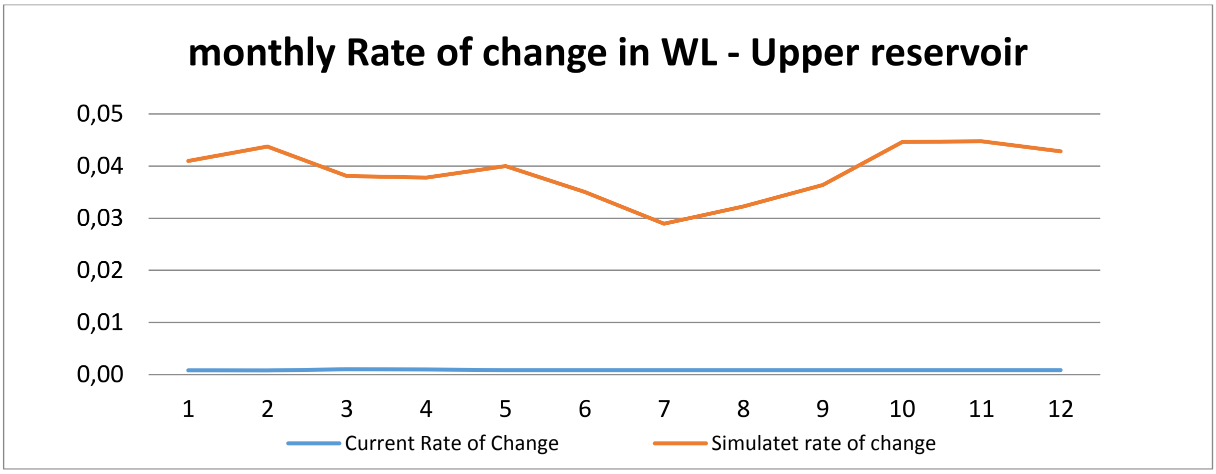

Figure 64: Monthly rate of change in water level - Upper Reservoir during 2000)

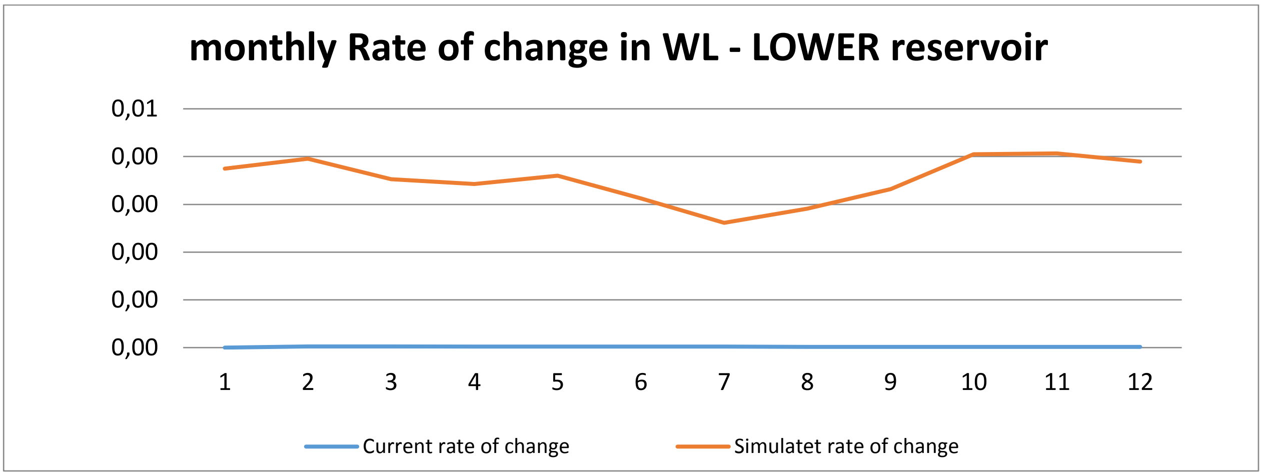

Figure 65: Monthly rate of change in water level - Lower Reservoir during 2000)

11.5.4 Reservoir emptying and filling

Reservoir emptying and filling are determined when the water level approach to its LRWL and HRWL. Figure 66 and Figure 67 shows the monthly average reservoirs emptying and filling stage for both reservoirs. It is clearly seen that the simulated LRWL and HRWL are reached during the whole year with 7 days average scenario for both reservoirs.

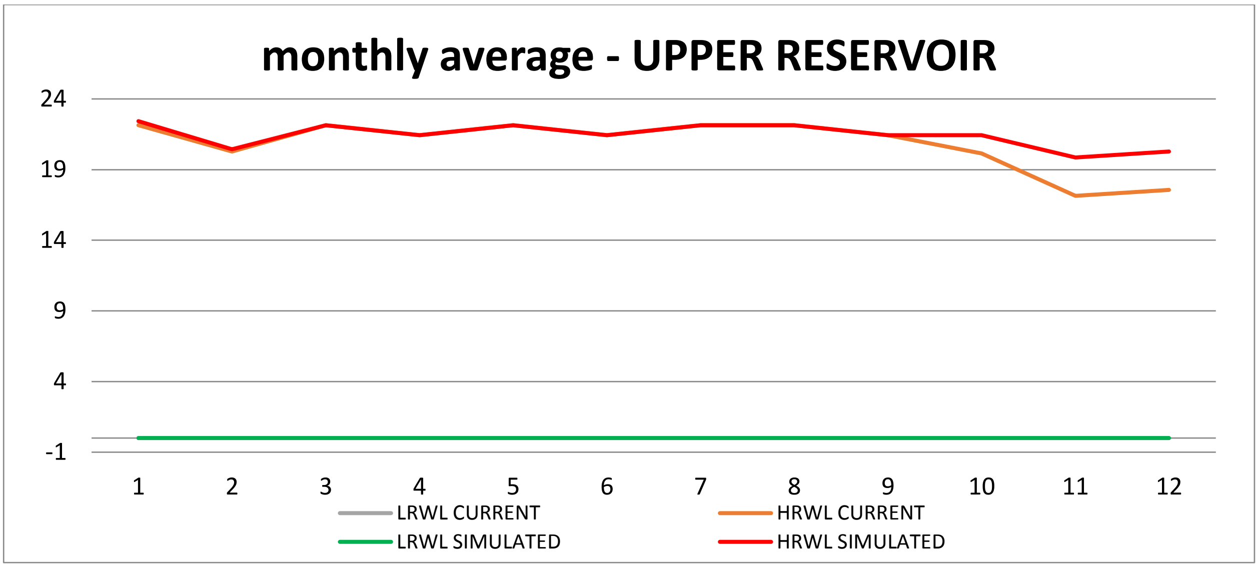

Figure 66: Monthly average Upper Reservoir

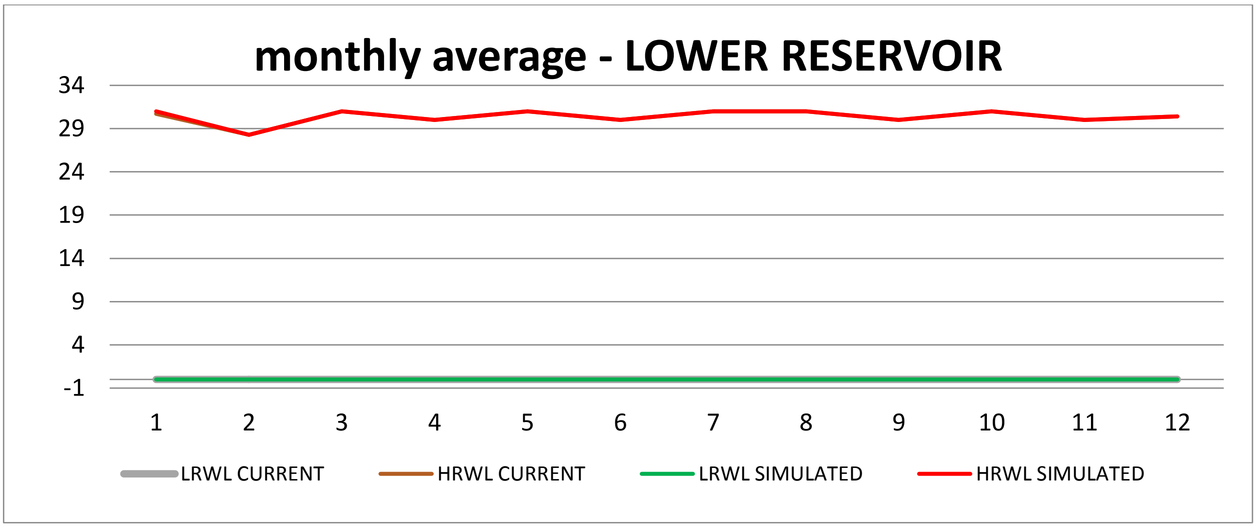

Figure 67: Monthly average Lower Reservoir

11.6 Balancing power operation with 7 Days Avg scenario

Under 7 Days Avg scenario[3], the balancing power demand (pumping and generation) can be provided at approximately 76 % of the time (Figure 68).

Considering both generation and pumping, the free or available volume in the lower reservoirs and the turbine capacity are the main limiting factors for providing balancing power. The main limiting factor is the turbine capacity, which is approximately 13 % (Figure 68). The free volume in the lower reservoir has limiting factor of 11 % of all days during electricity

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[3] The simulation is based on the electricity produced from wind turbines in the North Sea for the years 2000 (from 1st January to 16th April).

generation. This is related to the total live storage volume of the lower reservoir. While considering pumping only, there is no free upper reservoir' volume, which is limiting the balancing power provision, whereas the available water volumes in the lower reservoir is not limiting.

The free/available reservoir volumes do only limit the balancing power amount during generation, i.e. the HRWL of the lower reservoir and the LRWL of the upper reservoir are reached at times. However, there is no free volume in the upper reservoir during pumping.

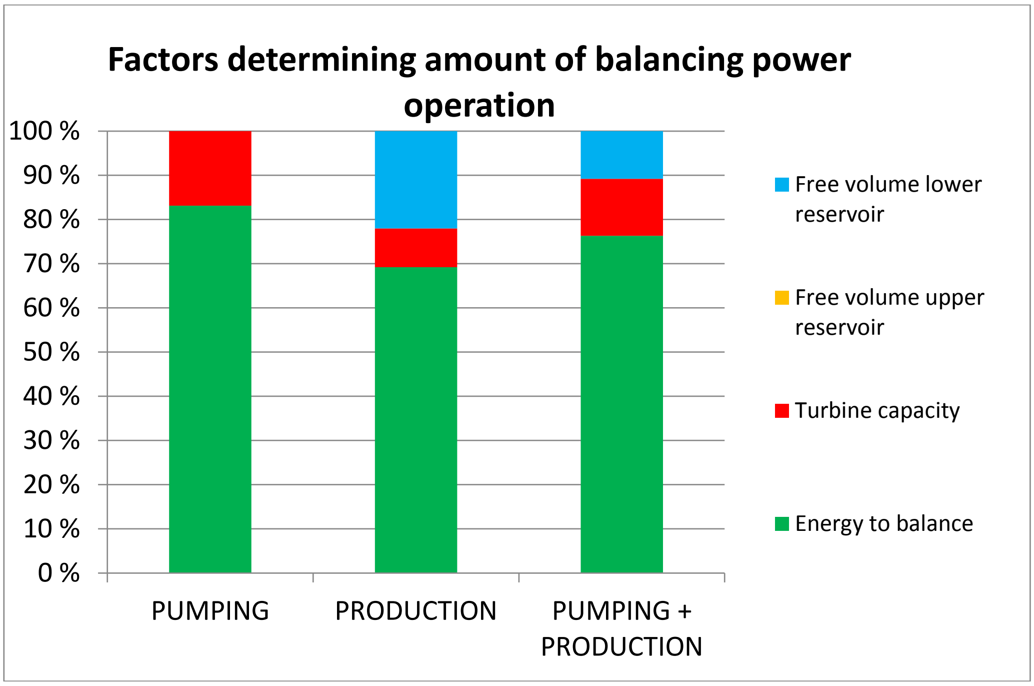

Figure 68: Factors determining the amount of Balancing power provision under 7 Days Avg scenario

Table 27: Cases meeting the required amount of balance power

	Energy to balance	**Turbine capacity**	**Free volume upper reservoir**	**Free volume lower reservoir**	**Hours of operation**
PUMPING					
Count	1017	206	0	0	1223
Percentage	83,2	16,8	0,0	0,0	100
PRODUCTION					
Count	812	103	0	258	1173
Percentage	69,2	8,8	0,0	22,0	100
PUMPING + PRODUCTION					
Count	1829	309	0	258	2396
Percentage	76,3	12,9	0,0	10,8	100

From the above Table 27, we can clearly see the hourly operation amount of pumping, production and pumping & production corresponding with energy to balance, turbine capacity and free upper/lower reservoir volumes.

Table 28: Numbers of case meeting the balance power

Number of cases meeting the required amount of balance power:	
Time period	2000
Total number of hours	2555
Deviation in GWh accepted	2,0
Share balancing power	0,010422
Number of hours with balancing demand	1
Number of hours with actual balancing operation	159

The number of hours with balancing demand is just 1 hour while the number of actual balancing operation is 159 hours (Table 28).

11.7 Balancing power demand

The number of days determining the balancing power demand can be increase or decrease mainly by two factors; turbine capacity and reservoirs volumes.

11.7.1 Increased share of capacity

Increasing the ratio of the required balancing power a single reservoir pair leads to lower percentages of days on which the balancing power demand can be met. When doubling the share of installed capacity, the percentages decreases from 76% to 67% (Figure 68 and Figure 69) mainly due to the turbine capacity increasingly limiting the balancing power provision, whereas the reservoir volumes are less significant. In order to achieve a situation in which the turbine capacity is no longer limiting the share of installed capacity has to be halved. (Eivind Solvang, 2014, p. 45)

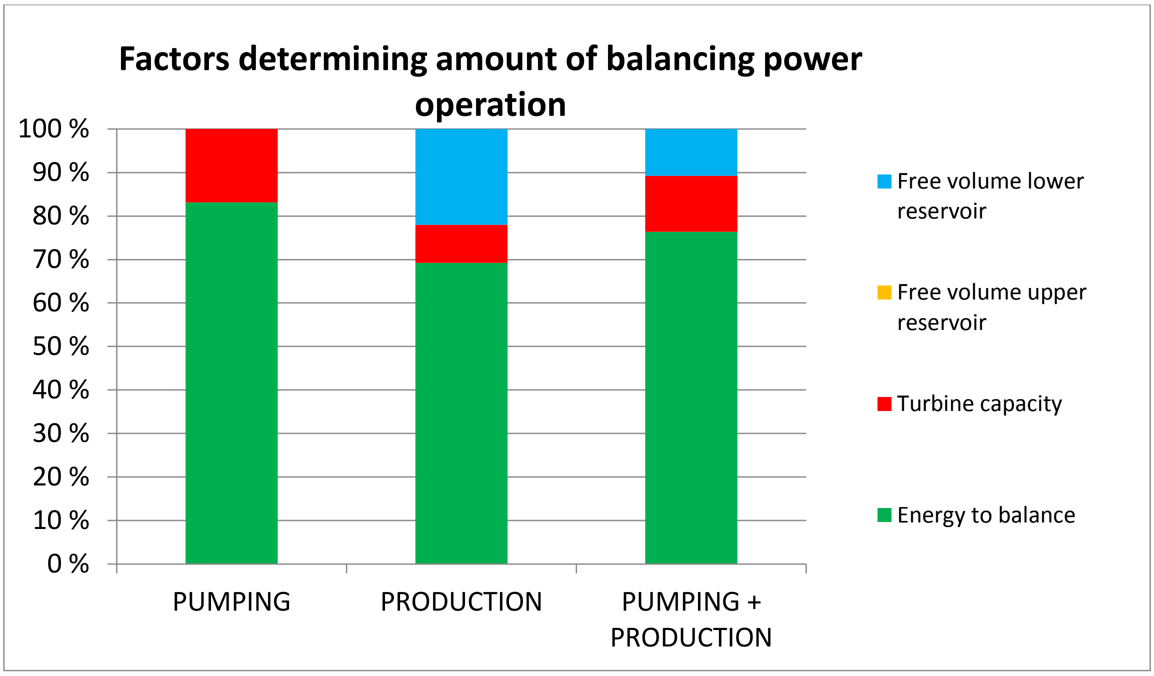

Figure 69: Doubled share of installed capacity. Factors determining the amount of balancing power provision

11.7.2 Altered threshold for balancing power demand

Decreasing the threshold determining the required balancing power above or below a certain amount of wind power generation leads to lower percentages of days on which the balancing power demand can be met, but the effect is not so strong. When halving the percentage of deviation from the average wind power generation the percentages of days decrease somewhat, mainly due to the turbine capacity increasingly limiting the balancing power provision. When doubling the threshold, the percentage of days the turbine capacity limits the balancing power provision diminishes, while the influence of the reservoir volumes remains about the same. (Eivind Solvang, 2014, p. 45)

11.8 Balancing power operation with Dev-Avg scenario

The simulation using the second scenario is not carried out in this report because of availability of only short period data for balancing power.

12 ENVIRONMENTAL IMPACTS OF HYDROPOWER AND PUMPED STORAGE HYDROPOWER

Hydropower and PSH in energy generation may not necessarily contribute to emissions in air pollution, however they have environmental impacts, dams, reservoirs and the operation of hydropower electric generators. The impacts do not only affect the area only covered by the dam and reservoir but goes beyond that. Norway has had a fair share of protests on the construction oh hydropower plants and an example is the case of the Alta river hydropower project which was supposed to be built in Finnmark. The operation of PSH on an existing hydropower plant has its unique environmental impacts. The Convention on Biological Diversity defines Environmental Impact Assessment (EIA) as;

"The process of evaluating the likely environmental impacts of a proposed project or development, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse."

The implementation of the PSH system and its impacts on the environment need to be fully assessed. Normal hydropower plants are operated based on the available water at a time following the natural seasonal flow of water at both peak and off-peak times, which cannot be said of PSH system. The fluctuations of water levels is controlled based on the demand for power to be balanced which does not follow a particular pattern. Rates of withdrawal or addition of water in reservoirs for a pumped hydro will vary mainly due to operation with relation to energy market and situation in the electricity grid, and it could also vary according to variation of water inflow, water demands and water availability in the region (Patocka, 2014).The nature and magnitude of impacts are highly site specific, vary significantly from one project to another and vary according to the biotopes in which projects are sited (Trussart, et al., 2002).

12.1 Environmental impacts in the operation of Hydro and PSH

The assessment of the possible environmental impacts in the operation of hydro and PSH hydropower in this project are not site specific but a general overview.

12.1.1 Physical impacts

Less predictable water level and discharge

Normal hydropower plants are built to follow the climatic conditions of a particular area in terms of precipitation. Most reservoirs of hydropower plants serve as storages of which their storage patterns (seasonal, yearly, etc.) is predictable based on annual inflow and outflow of water during the peak seasons especially in during autumn when there is the melting of snow and off peak seasons in spring. These patterns are predictable and any effects that comes with it are always prepared for beforehand.

This is not the case for reservoirs for PSH systems, serving as a form of storage to compensate for fluctuations in the energy demand, there is increased frequency of draining and filling of reservoir. This can range from hourly to weekly bases. The regulation of water in the reservoir implies a rise in fluctuation also in the water discharge. Such discharge patterns can cause huge differences in the water level, quality and temperature.

Increased Erosion and sedimentation

The increased rate of pumping and generation from both reservoirs increases the chances of erosion. Pumping and generation may not follow the natural flow velocity and site factors such as slope length and gradient, soil type and surface texture not favourable for such conditions of frequent draining and pumping will lead to the eroding of some amount of surface soil always. That is increased cycles of pumping and generation means increased rate of eroded materials which eventually will lead to increase sedimentation at the bottom of reservoirs reducing the total volume over a period of time.

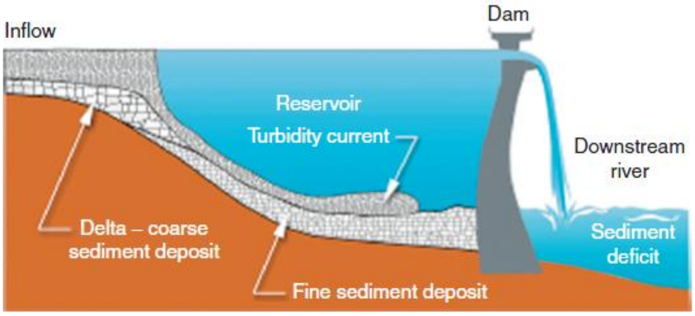

Figure 70: Schematic representation of reservoir sedimentation (Horlacher, et al., 2012)

Figure 70 above shows fine sediments moved by turbidity currents and coarse sediments from the bed of water body. The turbidity currents result in fine sediment transport in suspension (causing low visibility) in the reservoir. Problems associated with reservoir sedimentation are related to volume loss, the risk of obstruction of water intakes, abrasion of conduits and equipment, deterioration of water quality, and bed erosion (bed degradation) downstream of the dam (Horlacher, et al., 2012). Lakeshore erosion can be a key process in the destruction of habitat.

Changes in circulation patterns

Water bodies have their unique circulation patterns which are mostly influenced by factors such as topography, shape of basin and water density differences. Changes therefore occur when any is altered. The implementation of PSH on any water body or to any existing conventional hydropower plant leads to changes in the topography of the area. Pumping and generation mechanism in PSH also affects the water temperature (due to speed, volume and inlet and outlet conditions) and depth which affects the water density. This affects the thermal stratification which occurs when differences in density causes warm water lies above cooler waters which are denser.

Changes in water temperature and ice formation

The effects of pumping and generation which affects the thermal stratification also leads to the disturbance of the conditions favourable for the formation of ice on water bodies. The accelerated rate of inflows and outflows of water at different temperatures leads to constant mixing of the water causing the temperature and density to be unstable example in the formation of ice at temperatures below 3.9°C which occur at the surface when it is still. High water currents (>0.6ms^{-1}) hinders the formation of ice and in the case that ice forms, the frequent pumping and generation will lead to short duration of ice cover due to breakup.

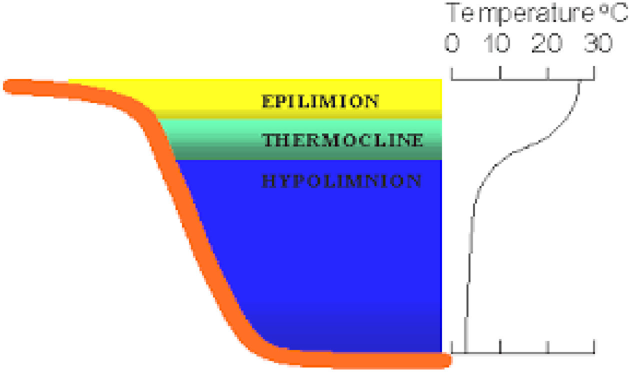

Figure 71: Thermal stratification of rivers (GWRC, 2009)

A shorter ice season may imply economic savings to hydropower facilities, whereas more frequent mid-winter break-ups may lead to increased frazil production and hence more frequent problems in a shorter season. (Gebre, et al., 2014) Hydro-peaking power plants may have a great impact on the water temperature in the river downstream from the outlet. For example, when the Grana power plant in the River Orkla was running with frequent starts and stops in July, August and September, the water temperature in the river downstream from the Grana power plant varied up to 6°C from one day to another. (Aas, et al., 2010)

Increased fluctuation water level of littoral zone

The topmost zone near the shore of a lake or pond is the *littoral zone*. This zone is the warmest since it is shallow and can absorb more of the Sun's heat. It sustains a fairly diverse community, which can include several species of algae (like diatoms), rooted and floating aquatic plants, grazing snails, clams, insects, crustaceans, fishes, and amphibians (UCMP, u.d.).

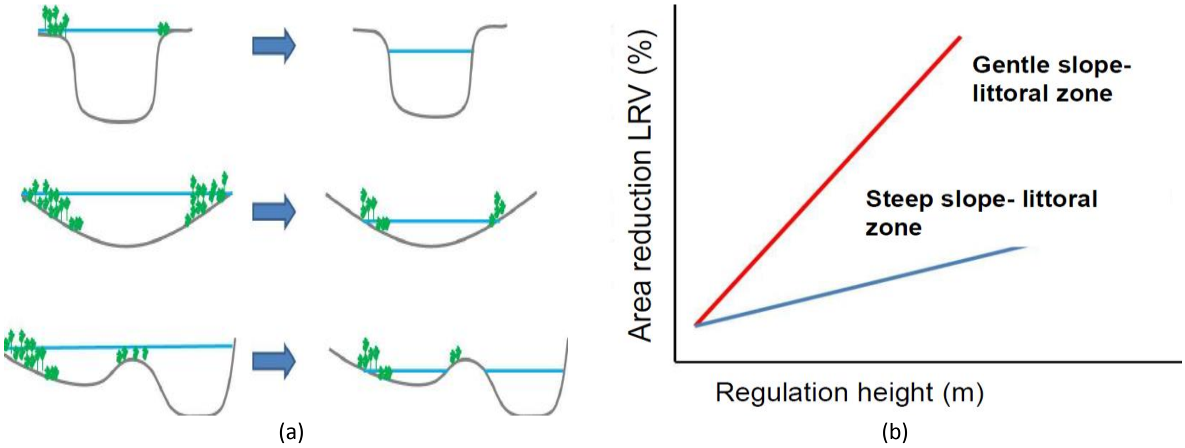

Figure 72: (a) effects of water fluctuations on littoral zones; (b) graph showing the intensity of water level fluctuations on slope intensity (Sundt-Hansen & Helland, u.d.)

Stability of reservoir banks

The rapid fluctuations in the water level between the HRWL and the LRWL has adverse effect on the stability of reservoir banks. With particular attention paid to bank slopes, most landslides are related to reservoir impounding and rapid drawdown (Chen & Huang, 2011). Research works carried out by Fujita resulted in the conclusion that the stability of reservoir banks is affected by water level fluctuations when rapid restoration of water to the HRWL occurs, rapid drawdown of water level and heavy rainfall. (H, 1977) These conditions trigger landslides which cannot be ignored when PSH system is under operation.

12.1.2 Biological Impacts

12.1.2.1.1 Higher risk of spreading of species

Migration patterns of aquatic species are affected by the constant pumping and generation. Changes in circulation patterns followed by migrating species may change their final destinations. Changes in water level, quality and temperature can also force migrating species to the find suitable conditions.

12.1.2.1.2 Impacts on biological production in littoral zone

Majority of aquatic species are affected by the accelerated change in water levels in the littoral zone. The littoral zone of a lake is the nearshore interface between the terrestrial ecosystem and the deeper pelagic zone. (Peters & Lodge , 2009)

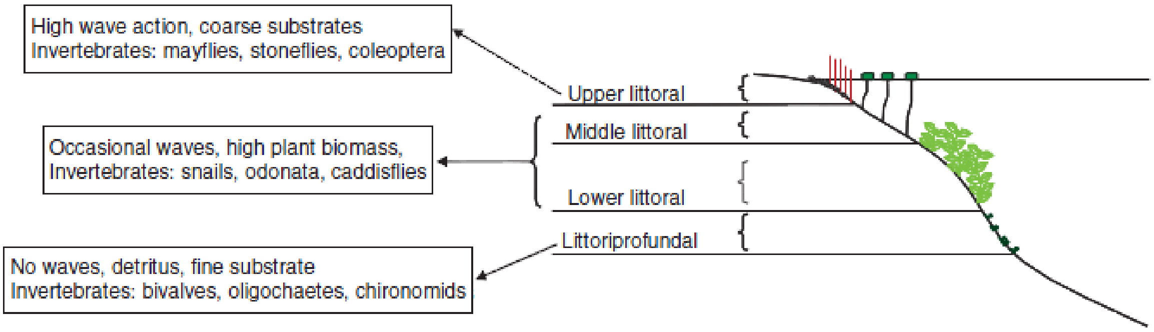

Figure 73: Habitation zones in the littoral zone (Peters & Lodge , 2009)

It is the warmest part of any lake because of the increase absorption of heat from the sun and serves as habitat for species such as invertebrates, algae and amongst others. The abundance of lakes in Norway means most of them will be used as reservoirs for the PSH operation leading to a rapid fluctuation of water levels in the littoral zone. Spawning of fishes which takes place in this zone means any change in the normal pattern decreases plants and aquatic population, physical structure of the zone and the nutrient dynamics also.

Studies carried out on the influence of fluctuating water levels in lakes revealed that Brown trout caught under such conditions were small and in poor conditions whilst those of moderate and slow water level fluctuations had limited effects on them (James & Graynoth, 2002).

12.1.2.1.3 Increased mortality for species

The changes in water level, quality and temperature have negative impacts on the aquatic life. A study revealed that sudden and strong reductions in water levels likely in PSH reservoirs affected Atlantic salmon populations in several Norwegian rivers, also rapid reductions in flow especially during pumping have either a direct mortality effect on fish owing to stranding or an indirect effect owing to desiccation or drift of the benthos (Aas, et al., 2010).

Aside the changed conditions of the water, the use of turbines for both pumping and generation can cause fish mortality. Fishes may be killed in the water intake, in the turbines or in the outflow runway from the turbines, one study has estimated a turbine mortality of 73% for smolts released into the intake at a power station in the River Orkla in Norway (Aas, et al., 2010).

13 RESULTS AND DISCUSSION

The study carried out on potential sites for PSH projects in Northern Norway has proven to be a success, the review revealed potential PSH projects that can be developed. Northern Norway, having no operational PSH system as at now has the potential to implement them.

From the review, a total of 84 pairs of reservoirs of potential PSH sites were identified. These constitute in total 19 different projects (17 from Nordland and 2 from Troms). These selections were made based on the availability of reservoirs and their geographical locations. When implemented, the PSH plants can produce an estimated capacity maximum energy of about 25 000 MW in total. The cost analysis of each station gives an overall approximation of the total amount needed for the development of energy plant. The total cost is therefore estimated to be about 47 billion kroner for the 19 projects identified.

The feasibility of the overall project is possible with the availability of wind power plants in the same region, with 5 wind power plants currently under operation with several others yet to be developed according to the records from NVE database. A total of 210 MW wind power capacity is currently generated from the operational plants, with projected values of 1500 MW of power to be generated from the projects which are under consideration. Aside balancing of power from these onshore wind power plants discussed above, offshore wind power plants can be used as well as international links such as the Nordlink cable from Germany or North Sea Link from the UK for the balance operation.

The study carried out on the Isvatn-Langvatn PSH project (9.2.8 Fagervollan Mo i Rana PSH Project), was chosen because of the wide difference in water head between the upstream and downstream reservoirs and the short transportation distance between them. A number of assumptions were made in running the model to simulate and study the balance operation scheme. Results gotten from the analysis using the PSH model were quite satisfactory despite the lack of accurate data.

The analysis of Isvatn-Langvatnet reservoir pairs however demonstrated to what extent the fluctuation of current patterns of water level, stage and water volume can be modified when balancing power operation is introduced. The analysis showed that the water level fluctuations are site-specific and water level variations depends on the characteristics of each reservoir pair (volume, area, location, and slope) as well as its installed capacity. The output differences did not vary much in our case due to the less accurate data and assumptions which were made.From Table 28, we see that the number of actual balancing operation is 159 hours for a total of 2555 hours for the year 2000 (1st Jan. to 16th April).

The number of actual balancing operation can be further adjusted with total turbine capacity and reservoirs characteristics which can be used for future operation of the PSH plant. Although these results are not based on accurate data values, it however gives an idea of what to expect from actual results on any of the identified PSH projects.

14 CONCLUSION

The target of the EU and the rest of the world that green energy will form a great percentage of energy sources in the world by 2030, will lead to more resources being put into the study and research of effective ways of harnessing renewable sources of energy including ways on how to store the energy produced. The work done in this thesis by identifying potential sites for PSH projects in Northern Norway is all aimed at meeting the targets set by EU curb the global rising temperatures. By the implementation of these PSH projects, as much renewable energy sources can be harnessed without any form of challenge on how to store the power generated. This paves the way for the full exploitation of renewable energy sources without boundaries.

The idea of the EU to make Norway the “Green Battery” will make the vision to be realized because Norway offered the favorable conditions needed without a doubt with the many lakes and regulated reservoirs which are located in different altitudes. These lakes can be directly used as reservoirs for hydro operation without the need for the construction of new dams, which will as a result reduce significantly the overall cost of the development of the hydro plants. There is also going to be a reduction of adverse impacts on the environment as compared to new constructions.

The 19 potential PSH projects identified in the Northern Counties of Nordland and Troms, if implemented will give a boost to the ones identified in Southern Norway. However, the 25 000 MW of power expected from operating the PSH scheme will not only make it possible without much developments also in the area of solar and especially in the case of Norway's wind energy. It should operate in parallel with these sources for maximum outcome. That is by incorporating with other source of energies, PSH will be able store and discharge energy when needed ensuring long term stability of grid and cost of the power.

The biggest challenge in the project was in the acquisition of the required data. Despite this however, simulation under 7 Day Average scenario was analysed and the amounts of total hours of balancing operation was determined. Since the reservoir pairs have almost same volume capacity, the free volume in lower reservoir is limiting balance power operation during production. Another important limiting factor is the turbine capacity. The simulation under Dev Avg scenario has not been carried out because of non-availability of data for smooth model analysis.

The PSH model ran on the Isvatn-Langvatnet reservoir pair leads to the conclusion that it can be taken into further consideration as it has gotten the capacity to operate PSH project in the future. The hypothesis cost analysis conducted also gives quick overview on the cost relating to the development of the plant, anticipating any further research and development.

However, there is the need for a much detailed research on all of the mentioned PSH sites, by using accurate and complete input data in the modelling process for more comprehensive and precise results before further developments can take place. The procedure, methodology and outcome of this report however can be a step ahead for researchers/students for more detailed study of PSH plants in future especially in Northern Norway.

15 SUGGESTIONS FOR FURTHER RESEARCH

The proposed PSH projects that has been listed are simply based on its geographic locations being the initial phase of the review. Detailed screening of the individual sites along with collection of the right data of the variation of water level (hourly data) and the environmental impacts of the specific sites needs to be considered. This will eliminate most assumptions made in other to get results.

In summary, the suggestions for further research are listed below;

- Use of complete and real initial water level fluctuation values for all the reservoirs and the reservoir-specific rating curves for determining its volumes as well as wind data for balancing power operation
- Modelling both balancing scenarios (7 Day-Avg and Dev Avg scenario) should be performed for better and compressive result
- Focus on impacts on environment and ecosystem in the area on accurate data
- Detailed topography of the reservoirs must be surveyed
- Construction and development of dams and reservoirs should be considered
- Technical characteristics and limitations should be included in the simulation (e.g. up & down ramping of PSH plant)
- Simulation performed with varieties of reservoirs pair having different capacities and characteristics

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APPENDIX

Appendix A Wind power in Norther Norway

A.1 Wind power plants in operation

Table A.1: List of Operational Wind Power Plants in Northern Norway

Case Title	Total Installed capacity (MW)	Turbine capacity (MW)	No. of turbines	County
Nygårdsfjellet	32.2	2.3	14	Nordland
Fakken	54	3	18	Troms
Havøygavlen	40.5	2.5 - 3	16	Finnmark
Raggovidda	45	3	15	Finnmark
Kjøllejord	39.1	2.3	17	Finnmark

A.2 Wind power plants under consideration

Table A.2: List of Wind power projects and their states in Nordlands. (Northern Norway)

Case Title	Developer	Case category	Status	Power MW	Expected production GWh	Area
Øyfjellet vindkraftverk	EOLUS VIND NORGE AS	2	V	330	990	Vefsn
Mosjøen vindkraftverk	FRED OLSEN RENEWABLES AS	3	V	305	915	Vefsn
Kalvvatnan vindkraftverk	FRED OLSEN RENEWABLES AS	3	V	225	675	Bindal
Sleneset vindkraftverk	NORD-NORSK VINDKRAFT AS	3	V	225	675	Lurøy
Andmyran vindkraftverk	ANDMYRAN VINDPARK AS	2	V	160	480	Andøy
Sørfjord vindkraftverk	Sørfjord Vindpark AS	2	V	90	270	Tysfjord
Skogvatnet	STATSKOG SF	3	V	80	240	Tysfjord
Ånstadblåheia	ÅNSTADBLÅHEIA VINDPARK AS	2	V	50	150	Sortland
Røst vindkraftverk	VINDKRAFT NORD AS	3	V	9	27	Røst
Hovden	ÅNSTADBLÅHEIA VINDPARK AS	3	V	9	27	Bø
Vardøya vindkraftverk	SOLVIND PROSJEKT AS	2	V	6	18	Træna
Træna vindkraftverk	RØDØY-LURØY KRAFTVERK AS	3	V	2.25	6.75	Træna

***Key:* *V = decided *U = planned *P2 = plan illustrated**

Table A.2: List of wind power projects and their states in Troms (Norther Norway)

Case Title	Developer	Case category	Status	Power MW	Expected production GWh	Area
Kvitfjell vindkraftverk	NORSK MILJØKRAFT TROMSØ AS	2	V	200	600	Tromsø
Raudfjell vindkraftverk	NORSK MILJØKRAFT RAUDFJELL AS	2	V	100	300	Tromsø
Maurneset vindkraftverk	VINDKRAFT NORD AS	1	P2	10	30	Nordreisa
Kroken vindkraftverk	FRED OLSEN RENEWABLES AS	1	P2	60	180	Tromsø
Rieppi vindkraftverk	TROMS KRAFT PRODUKSJON AS	3	V	80	240	Storfjord
Sandhaugen teststasjon	NORSK MILJØKRAFT FORSKNING & UTVIKLING AS	2	V	15	45	Tromsø

***Key:* *V = decided *U = planned *P2 = plan illustrated**

Appendix B Calculating formulas

Maximum Absorption capacity:

$$Maximum\ Absorption\ capacity\ [\frac{m^3}{s}] = \frac{(-Water\ level\ variation\ [m/hour])}{100} * \frac{Effective\ area}{3600}$$

$$Effective\ area\ [km^2] = Volumes/(HRWL - LRWL)$$

Maximum Power Generation:

$$Maximum\ Absorption\ capacity\ \left[\frac{liter}{sec}\right] = \left(Max\ Absorption\ capacity[\frac{m^3}{s}]\right) * 1000$$

$$Maximum\ Power\ Generation\ [MW] = \frac{9.81*efficiency*[(Max\ Absorption\ capacity)*1000]}{10\hat{}6}$$

Decrease in water level 1 day [m]:

$$Max.power\ generation\ [\frac{hours}{day}] = 24$$

$$Decrease\ in\ wate\ level\ D.1 = \frac{Water\ level\ variation}{100*Max.power\ generation}$$

Decrease in water level 3 day [m]:

$$Decrease\ in\ wate\ level\ D.3 = 3 * Decrease\ in\ wate\ level\ D.1$$

Decrease in water level 7 day [m]:

$$Decrease\ in\ wate\ level\ D.7 = 7 * Decrease\ in\ wate\ level\ D.1$$

Emptying upper reservoirs [days]:

$$Emptying\ upper\ reservoirs = start\ level\ \% * \frac{HRWL-LRWL}{(-Decrease\ in\ wate\ level\ D.1)}$$

Increase in water level in lower reservoirs [cm/h]:

$$Increase\ in\ water\ level\ in\ lower\ reservoirs = (-Water\ level\ variation) * \frac{upper\ effective\ area}{lower\ effective\ area}$$

Filling of lower reservoir [days]:

$$Max.power\ generation\ [\frac{hours}{day}] = 24$$

$$Filling\ of\ lower\ reservoir = \frac{(1-Start\ level\ )*(HRWL-LRWL)\cdot 100}{Increase\ in\ water\ level\ in\ lower\ reservoirs*Max.power\ generation}$$

Tunnel volume [m^3]:

$$Tunnel\ volume = \frac{(Tunnel\ cross\ section)*(Tunnel\ length)\cdot 1000}{10\text{^}6}$$

Station all Volume [m^3]:

$$Station\ all\ volume = 70 * (pressure\ head)^{0.5} * (Max\ absorption\ capacity)^{0.7} * 1^{0.1}$$

Total excavated [mil m^3]:

$$Tunnel\ excavated = Tunnel\ volume + \frac{Station\ all\ volume}{10^6}$$

Appendix C Cost Estimation

C.1 Civil work

Civil work includes the cost for construction and maintenance of the hydro plant structure. However, this report excludes the cost involving the construction and filling of dams and reservoirs.

Blasted tunnels

$Basic\ Price$ [kNOK/m] $= 106 * Tunnel\ crosssection + 9170$

$Miscellaneous\ and\ unforeseen = 10\%$

$Tunnel\ support = 22\%$

$Rigging\ and\ operation = 30\%$

$Correction\ factor\ for\ length =$ 0.0118*(tunnel length) ^2 – 0.0132* tunnel length + 0.9343

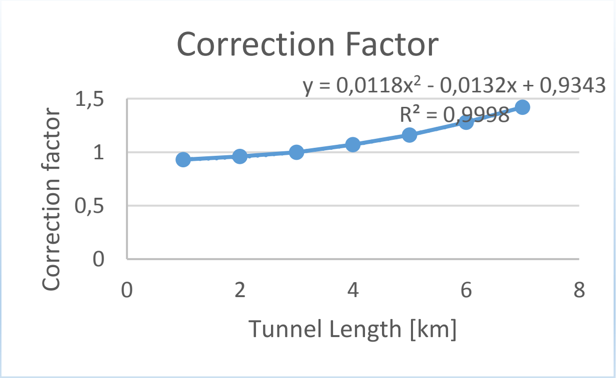


Figure C.1.a: Correction factor for Blasted tunnels

$Total\ cost = Basic\ Price * tunnel\ length * 1000 * Correction\ factor * (1 + 10\% + 22\% + 30\%)$

Drilled Tunnel

$Basic\ Price\ [\mathrm{kNOK/m}] = (0.1827 * Diameter\hat{}2 + 0.131 * Diameter + 5.62) * Tunnel\ Length * 10\hat{}6$
$Diameter = 2\sqrt{(tunnel\ cossection/\pi)}$
$tunnel\ crossection\ is\ 40\%\ smaller\ than\ balsting$
$Miscellaneous = 10\%$
$Inflation = 10\%$
$Correction\ factor = -0.0008 * (tunnel\ length)\hat{}3 - 0.025 * (tunnel\ length)\hat{}2 - 0.2834 * tunnel\ length + 1.9662$

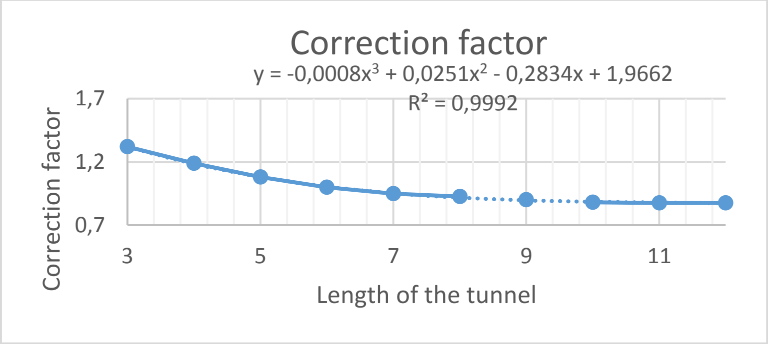


Figure C.1.b: Correction factor for Drilled tunnel

$Total\ cost = Basic\ price * Correction\ factor * (1 + 10\% + 10\%)$

Adit Tunnel

The tunnel cross-section is approximately 25 m^2
$Basic\ cost\ [NOK] = 24000 * Length$
If size of an Adit tunnel is less than 25 m^2, $Basic\ cost = 0$
$Collaring/portaling\ [NOk] = 210000$

Access Tunnel

$$Cost = (0.19 * Crosssection + 19) * length * 1000$$

Plug

$Plug\ length = 1/20 * Head$
Contractor costs for plugs are shown below:

Table C.1.a: Cost estimation analysis for contractor plugs

Head	Cost
80	(13.434*tunnel length+196.8) *1000*Plug length
150	(17.8* tunnel length +297) *1000* Plug length
300	(29.11* tunnel length +440) *1000* Plug length

Air cushion chamber

In calculating the cost for the air cushion chamber, the required air volume, rock volume and the length of the tunnel are considered as shown below;

$Required\ Air\ Volume = 1.2 * 17.2 * \text{tunnel length^(5/3)}$

$Rock\ Volume = 1.35 * Air\ Volume$

$TotalCost = Rock\ Volume * 420$

Under-ground water tunnel piercing

Cost for boring under-ground water tunnels depend

Table C.1.b: Cost estimation analysis for underground water tunnel piercing

Depth of Lake	Cross-section	Cost [kNOK]
20	15	1100
40	20	2400
60	70	4800

Under-ground power station

Table C.1.c: Cost estimation analysis for Under-ground power station

Under-ground works	Volume	Cost [NOK]
Blasting volume	78*(head)^0.5*(Discharge)^0.7*(number of unit) ^0.1	A = 300*Blasting volume
Concrete Volume	0.2*Blasting volume	B = 2500*Concrete Volume
Reinforcement	0.06*Concrete volume	C = 16000*Reinforcement
Formwork	2.1*Concrete volume	D = 1000*Formwork
Supporting work		E = 15%*A
Masonry and plastering work		F = 5%*(A + B)
Interior work		G = 15%*(B +C)
Unforeseen	10% of the above cost	H = 10%*(A + B +C + D + E + F +G)
Rigging and operation of the construction site	25% of the above work	I = 25%*(A + B +C + D + E + F + G + H)
HVAC (ventilation, water supply and sewer) sized plant		5000000
Electrical installations, lighting, heating, etc.		3000000

Transport Facilities

The estimation of total cost for temporary roads

$Maintenance\ cost = 10\%$

$Uncertainty\ cost = -50\%\ to + 100\%$

Table C.1.d: Cost estimation analysis for transport services

Terrain	High standard [NOK/m]	Low standard [NOK/m]
Easy terrain	1000	500
Normal terrain	1500	1000
Difficult terrain	2000	1500

C.2 Mechanical Work

Mechanical work includes the cost of all mechanical equipment. Depending on the type of turbine to be used and head of dam, the cost varies from one to another.

Pelton Turbine

2 jet horizontal cost estimation

Table C.2.a: Cost estimation analysis depending on head for 2 jet horizontal Pelton turbine

Head	Price [NOK/kW]
1000	1328.606*(Discharge)^(-0.511)
800	1644.645*(Discharge)^(-0.518)
600	2107.015*(Discharge)^(-0.509)

6 jet horizontal cost estimation

Table C.2.b: Cost estimation analysis depending on head for 6 jet horizontal Pelton turbine

Head	Price [NOK/kW]
1000	1874.804*(Discharge)^(-0.518)
800	2304.138*(Discharge)^(-0.522)
600	2898.381*(Discharge)^(-0.511)

Francis Turbine

Table C.2.c: Cost estimation analysis depending on head for Francis turbine

Head	Price [NOK/kW]
650	1035.785*(Discharge)^(-0.3044)
400	1442.1867*(Discharge)^(-0.323)
300	1655.0194*(Discharge)^(-0.3143)
200	2140.7817*(Discharge)^(-0.3149)
100	3130.2363*(Discharge)^(-0.3139)
50	5078.1598*(Discharge)^(-0.3334)

Kaplan Turbine

Table C.2.d: Cost estimation analysis depending on head for Kaplan turbine

Head	Price [NOK/kW]
30	9634.833*(Discharge)^(-0.299)
15	15484,286*(Discharge)^(-0.295)
10	27039.361*(Discharge)^(-0.327)

Condition to choose the type of turbine

Table C.2.e: Condition to choose the type of turbine

Turbine	Head [m]	Discharge [m^3/s]
Pelton	H ≥ 650	D ≤ 40
Francis	650 ≥ H ≥ 40	140 ≥ D ≥ 40
Kaplan	H ≤ 40	D ≥ 140

Turbine cost

$$Total\ cost = cost\ of\ turbine\ [NOK/kW] * Production\ [kW]$$

Pump turbine, estimation NVE

Factor = 1.25

Table C.2.f: Turbine cost

Head	Cost of turbine, Price [NOK/kW]
650	Factor*900.7*(Discharge)^(-0.3044)
400	Factor*1254*(Discharge)^(-0.323)
300	Factor*1439.1*(Discharge)^(-0.3143)
200	Factor*1784*(Discharge)^(-0.3149)
100	Factor*2407.9*(Discharge)^(-0.3139)
50	Factor*3906.3*(Discharge)^(-0.3334)

$$Turbine\ cost, NVE\ estimation = cost\ of\ turbine * Production$$

Adit gate

$$Size = 18$$

Table C.2.g: Adit gate

Head	Price [NOK]
30	242.5*(Size)^0.5219*1000
200	482.2*(Size)^0.5219*1000
600	717.9*(Size)^0.5219*1000

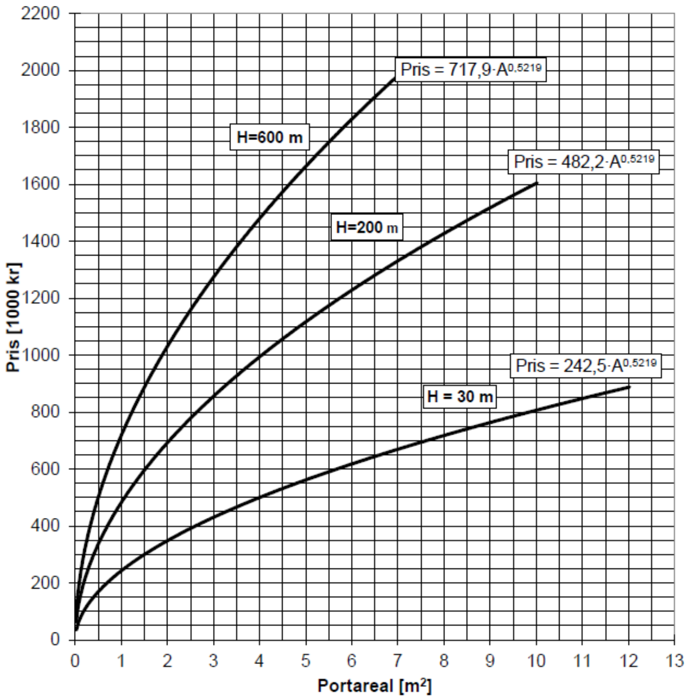


Figure C.2.a : Cost estimation analysis depending on Adit gate (Norconsult, Januar 2015, p. 186)

Gate

$$Size = tunnel\ length$$
$$depth\ of\ reservoir = 14$$

Roller

Table C.2.h: : Cost estimation of Roller

Head	Price [mil NOK]
10	0.3391*(size)^0.6779
20	0.5734*(size)^0.5857
40	0.6995*(size)^0.6428
60	1.5897 *(size)^0.4876
100	1.8524*(size)^0.5164

Slide

Table C.2.i: Cost estimation analysis on Slide

Head	Price [mil NOK]
10	0.6627*(size)^0,3644
20	0.938*(size)^0,3644
40	1.1494*(size)^0,3644
50	1.4849*(size)^0,3644
80	1.8794*(size)^0,3644
100	2.1018*(size)^0,3644

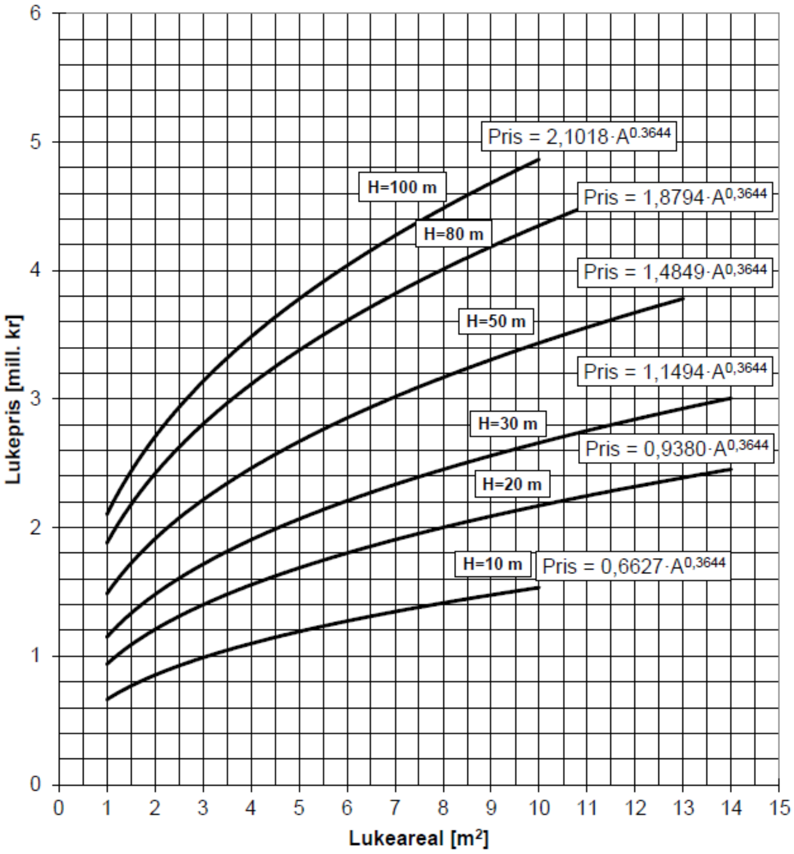


Figure C.2.b: Cost estimation analysis on Slide (Norconsult, Januar 2015, p. 184)

Segment

$$Cost\ [\text{mil NOK}] = 0.5414 * (size)\text{\textasciicircum}0.5415$$

Miscellaneous equipment

Table C.2.j: Cost estimation analysis depending on miscellaneous equipment

Head	Price [NOK/kW]
15	-61.336*LN(Discharge)+5579.79
50	471.51*(Discharge)^-0.2389
100	-38.795*LN(Discharge)+309.89
500	249.841*(Discharge)^-0.4108
1000	158.306*(Discharge)^-0.4385

C.3 Electro technical work

This chapter represent the cost related with components and systems of electro technical field.

Cost for electro-technical equipment with one generator

$$Power = production = 17.670\ [MW]$$

Table C.3.a: Cost for electro-technical equipment with one generator

N	cost
100	7.167*(Power)^0.6484
200	5.6427*(Power)^0.6549
300	4.9511*(Power)^0.659
500	4.2445*(Power)^0.6643
750	3.7905*(Power)^0.6686
1000	3.5161*(Power)^0.67164
1500	3.1863*(Power)^0.6758

Cost for electro-technical equipment with two generators

$$Power = production/2 = 8.835\ [MW]$$

Table C.3.b: Cost for electro-technical equipment with two generator

N	Cost
100	14.205*(Power)^0.63
200	11.138*(Power)^0.6437
300	9.7434*(Power)^0.6467
500	8.3161*(Power)^0.6507
750	7.3974*(Power)^0.654
1000	6.8411*(Power)^0.6563
1500	6.1716*(Power)^0.6596

Appendix D PHS Sites and Estimated power and cost

D.1 Nordland

Kolsvik Bindal PSH Project

Estimated power production:
Estimated total cost of the Kolsvik Bindal PSH project:

Table D.1.a: Estimated power and cost on Kolsvik Bindal

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Øvre Kalvvatnet		9.601	519	1.13142	510.77	1706.477139

2	Øvre ringvatn	Øvre Kalvvatnet	4.609	129.6	0.282528	42.94	5871.96817
3	Kalvvatn	Øvre Kalvvatnet	6.887	257	0.56026	155.34	2960.632321
4	Nilsinetjern	Øvre Kalvvatnet	4.863	37	0.08066	1.84	61898.11367
5	Øvre Kalvvatnet	Majavatnet	13.885	519	1.13142	510.77	1853.328291

Tosdalen PSH Project

Estimated power production:
Estimated total cost of the Kolsvik Bindal PSH project:

Table D.1.b: Estimated power and cost on Tosdalen

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Storfjelltjønna	Tosdalsvatnet	0.978	538	1.17284	23.48	6235.747657
2	Måsvatnet	Tosdalsvatnet	3.012	643	1.40174	10.85	13436.06749

Soberg PSH Project

Table D.1.c: Estimated power and cost on Soberg

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Søbergsvatnet	Sørengvatnet	1.673	277	0.60386	12.09	10642.64188
2	Sagvatnet	Søbergsvatnet	2.757	357	0.77826	15.58	9279.272808
3	Sagvatnet	Øvre urdstjønna	0.334	81	0.17658	3.53	23926.8465

Langfjord PSH Project

Estimated power production:
Estimated total cost of the Kolsvik Bindal PSH project:

Table D.1.d: Estimated power and cost on Langfjord

Project No.	Upstream reservoir	Downstream reservoir	Length of the	Max head [m]	EEKKV [kWh/m^3]	Maximum	Cost [kr/kW]

			tunnel [km]			Power [MW]	
1	Tettingvatn		1.492	343	0.74774	65.52	3653.157354
2	Storvatn	Tettingvatn	1.726	237	0.51666	47.24	4653.835504
3	Øvre breivatnet	Tettingvatn	2.073	172	0.37496	7.51	15490.78902
4	Midtre Breivatnet	Nedre lappskardvatnet	0.843	58	0.12644	2.53	35460.10934
5	Nedre lappskardvatnet	Nedre breivatnet	1.342	151	0.32918	6.59	16129.65127
6	Midtre Breivatnet	Nedre breivatnet	1.695	204	0.44472	8.9	13284.02465
7	Storvatn		2.506	559	1.21862	111.43	2729.147103

Grytåga PSH Project

Estimated power production:
Estimated total cost of the Kolsvik Bindal PSH project:

Table D.1.e: Estimated power and cost on Grytåga

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Grytåvatn		3.578	198	0.43164	43.99	5137.435674
2	Hundålvatnet	Grytåvatn	3.859	27	0.05886	27.48	14481.98939
3	Laksen	Grytåvatn	2.684	105.9	0.230862	7.7	16286.99518
4	Finnknevatn	Grytåvatn	4.24	181	0.39458	104.45	3483.460977

Røssåga PSH Project

Table D.1.f: Estimated power and cost on Røssåga

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Tustervatn-Røsvatn	Stormyra	7.759	138.65	0.302257	5605.72	1247.329985
2	Bleikvatn	Stormyra	3.375	163	0.35534	413.19	2203.385018
3	Bleikvatn	Tustervatn-Røsvatn	5.651	36.8	0.080224	93.28	5880.369806

Kjensvatn PSH Project

Table D.1.g: Estimated power and cost on Kjensvatn

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Akersvatn	ST Målvatn	10.082	126	0.27468	815.1	2193.462101
2	Kjensvatn	Akersvatn	6.402	47	0.10246	40.98	7646.975191
3	Gressvatn	Kjensvatn	4.875	78	0.17004	333.7	2742.483107
4	Kjensvatn	ST Målvatn	4.235	130	0.2834	113.36	3734.739677
5	Kalvatn	Akersvatn	15.013	84	0.18312	300.66	4015.380612

Fargervollan Mo I Rana PSH Project

Table D.1.h: Estimated power and cost on Fargervollan Mo I Rana

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Langvatnet		3.326	43.7	0.095266	190.53	3770.206854
2	Isvatn	Langvatnet	11.074	521.5	1.13687	208.44	2523.109674
3	Reingardslivatnet	Langvatnet	6.091	320	0.6976	13.96	11374.93113
4	Isvatn	Trolldalsvatn	1.969	124	0.27032	49.56	4932.583798
5	Trolldalsvatn	Holmvatn	3.688	214.2	0.466956	46.7	4980.090496
6	Holmvatn		4.906	275	0.5995	208.53	2513.240898

Svartsen PSH Project

Table D.1.i: Estimated power and cost on Svartsen

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Storglomvatn		8.069	585	1.2753	3576.96	957.8490928
2	Storglomvatn Øv	Fykanvatnet	5.008	495	1.0791	3026.66	1014.107272
3	Navervatn Nd	Nd Navervatn	0.767	80.5	0.17549	31.97	5659.110892
4	Navervatn Øv	Fykanvatnet	1.263	378.36	0.8248248	168.33	2305.84887
5	Navervatn	Øv Glomvatn	2.779	71.94	0.1568292	28.57	8184.394427

Forså PSH Project

Table D.1.j: Estimated power and cost on Forså

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Lysvatn		1.82	371.65	0.810197	226.86	2073.978848
2	Lysvatn	Storvatn	7.059	187.55	0.408859	114.48	3542.199188
3	Feldvatn	Storvatn	3.16	209.2	0.456056	83.63	3739.284428
4	Feldvatn	Landvatn	3.345	94.2	0.205356	37.66	6123.704475
5	Landvatn	Sokumvatn	1.98	32.2	0.070196	16.55	15542.00156
6	Navnløsvatn-L Sokumv	Sokumvatn	3.819	345.9	0.754062	173.33	2547.165452
7	Sokumvatn		5.475	331.3	0.722234	291.8	2111.663254

Oldereid PSH Project

Table D.1.k: Estimated power and cost on Oldereid

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Tindvatn	Mangevatn	3.431	313.92	0.6843456	86.23	3519.236052
2	Tindvatn	Glømmervatn	2.911	389.75	0.849655	107.06	3034.276923
3	Glømmervatn	Børnupvatn	2.384	89.92	0.1960256	85.13	4048.22112
4	Mangevatn	Glømmervatn	2.525	82.53	0.1799154	17.99	9182.225403
5	Mangevatn	Børnupvatn	3.006	163.7	0.356866	35.69	5694.173536
6	Børnupvatn		3.207	321.33	0.7004994	29.18	6317.413397

Lomi PSH Project

Table D.1.l: Estimated power and cost on Lomi

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Balvatn	Kjelvatn	8.438	101.21	0.2206378	871.52	2183.314117
2	Dorrovatna	Kjelvatn	5.746	178.38	0.3888684	155.55	3127.736987
3	Lomivatn	Kjelvatn	8.124	211.88	0.4618984	368.43	2465.265038
4	Lomivatn	Langvatn	5.707	581.98	1.2687164	1011.99	1162.264652
5	Kjelvatn	Langvatn	5.785	383.5	0.83603	49.9	4752.46371

Siso PSH Project

Table D.1.m: Estimated power and cost on Siso

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Nevervatnet	Røyrvatn	2.791	296.8	0.647024	6.48	18551.90734
2	Røyrvatn	Straumvatnet	0.885	110.5	0.24089	88.75	3803.848039
3	Sisovatn	Straumvatnet	5.83	666.5	1.45297	1292.35	1067.713614
4	Løytavatnet	Sisovatn	3.708	56	0.12208	32.33	7680.288716
5	Øvre Veiskivatnet	Sisovatn	2.532	178	0.38804	38.81	5309.663671
6	Kvitvatnet	Sisovatn	3.073	335	0.7303	6.07	19902.51464

Lakshola PSH Project

Table D.1.n: Estimated power and cost on Lakshola

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Faulevatn	Rismålsvatn	2.402	38	0.08284	57.99	5936.35615
2	Langvatnet svierppejavrre	Faulevatn	4.36	113	0.24634	2.74	41043.89373
3	Langvatnet	Austervatnet	3.536	359.3	0.783274	537.11	1558.395876
4	Langvatnet	Langvatnet svierppejavrre	6.661	204	0.44472	304.96	2584.980195

Slunkajavrre PSH Project

Table D.1.o: Estimated power and cost on Slunkajavrre

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Roggejavri	Slunkajavrre	2.583	122.65	0.267377	1.78	54910.81087
2	Slunkajavrre	Rekvatn	1.749	259.6	0.565928	301.83	1977.52533
3	Rekvatn	Fjendvatnet	2.257	211.75	0.461615	296.2	2348.807698
4	Forsanvatnet	Rotvatn	4.507	214.05	0.466629	233.32	2551.126722

Sørfjord PSH Project

Table D.1.p: Estimated power and cost on Sørfjord

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Kjerringvatn	brynvatn	0.4289	142.5	0.31065	10.42	1095.8594

Nygård PSH Project

Table D.1.q: Estimated power and cost on Nygård

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Fiskeløsvatn	Sirkelvatn	1.681	91.5	0.19947	14.91	9538.097854
2	Skitdalsvatn	Jernavatna	1.276	114.2	0.248956	5.95	17855.68838
3	Fiskeløsvatn	Store trollvatn	3.608	97.5	0.21255	15.89	10167.6749
4	Høgvatnet Høgvatnet	Store trollvatn	2.357	133	0.28994	5.8	20006.85547

D.2 Troms

Kænangsbotn PSH Project

Table D.2.r: Estimated power and cost on Kænangsbotn

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Abbujavrre	Soikkajavrre	5.567	175.5	0.38259	152.4	3147.437697
2	Abbujavrre	Lassajavrre	3.166	173	0.37714	150.23	2986.908212
3	Lassajavrre	Småvatna	1.865	249.5	0.54391	140.06	2859.51977

Bergsbotn PSH Project

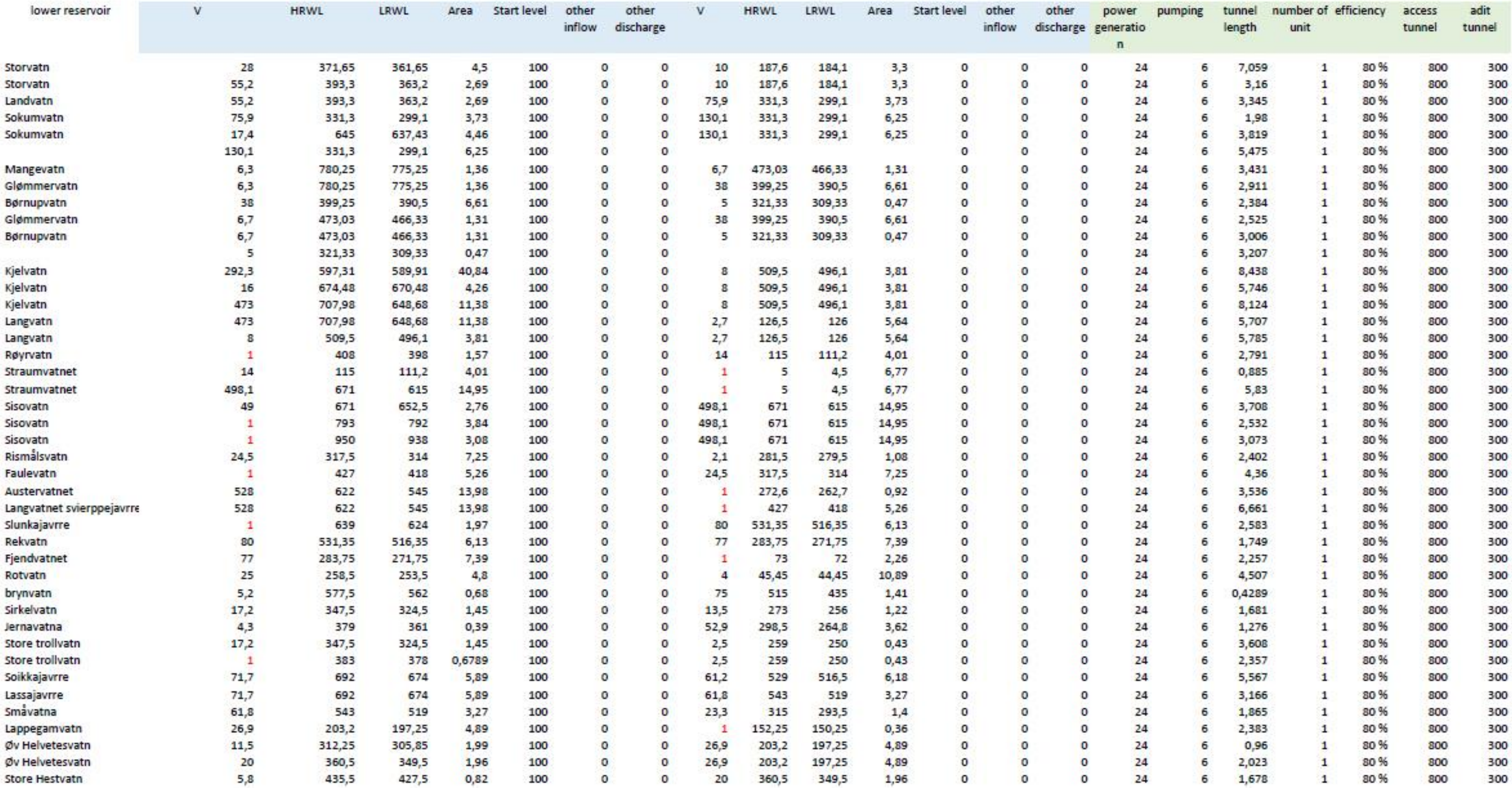
Table D.2.s: Estimated power and cost on Bergsbotn

Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Max head [m]	EEKKV [kWh/m^3]	Maximum Power [MW]	Cost [kr/kW]
1	Øv Helvetesvatn	Lappegamvatn	2.383	52.95	0.115431	52.18	5692.273815

2	Ned Hestvatn	Øv Helvetesvatn	0.96	115	0.2507	45.04	4789.102394
3	Store Hestvatn	Øv Helvetesvatn	2.023	163.25	0.355885	64.71	4080.953867
4	Roaldsvatn	Store Hestvatn	1.678	86	0.18748	13.59	10157.03264

D.3 Summary of Reservoir pair data

lower reservoir	V	HRWL	LRWL	Area	Start level	other inflow	other discharge	V	HRWL	LRWL	Area	Start level	other inflow	other discharge	power generation	pumping	tunnel length	number of unit	efficiency	access tunnel	adit tunnel
	158	519	484	6,4849	100	0	0					0	0	0	24	6	9,601	1	80 %	800	300
Øvre Kalvvatnet	7,6	613,6	608,6	6,4849	100	0	0	158	519	484	6,4849	0	0	0	24	6	4,609	1	80 %	800	300
Øvre Kalvvatnet	30,5	741	730	2,64	100	0	0	158	519	484	6,4849	0	0	0	24	6	6,887	1	80 %	800	300
Øvre Kalvvatnet	1,3	521	515,3	0,22	100	0	0	158	519	484	6,4849	0	0	0	24	6	4,863	1	80 %	800	300
Majavatnet	158	519	484	6,4849	100	0	0	220	273		4,4387	0	0	0	24	6	13,885	1	80 %	800	300
Tosdalsvatnet	1	685	680	0,198	100	0	0	0,2403	152	147	1	0	0	0	24	6	0,978	1	80 %	800	300
Tosdalsvatnet	0,3865	790	785	1	100	0	0	0,2403	152	147	1	0	0	0	24	6	3,012	1	80 %	800	300
Sørengvatnet	1	302	297	1	100	0	0	1	30	25	1	0	0	0	24	6	1,673	1	80 %	800	300
Søbergsvatnet	1	382	377	1	100	0	0	1	30	25	1	0	0	0	24	6	2,757	1	80 %	800	300
Øvre urdstjønna	1	382	377	1	100	0	0	1	306	301	1	0	0	0	24	6	0,334	1	80 %	800	300
	18,4	343	322	1,19	100	0	0					0	0	0	24	6	1,492	1	80 %	800	300
Tettingvatn	3,2	559	555,5	0,9	100	0	0	18,4	343	322	1,19	0	0	0	24	6	1,726	1	80 %	800	300
Tettingvatn	1	494	489	1,5315	100	0	0	18,4	343	322	1,19	0	0	0	24	6	2,073	1	80 %	800	300
Nedre lappskardvatnet	1	487	482	2,1952	100	0	0	1	434	429	0,399	0	0	0	24	6	0,843	1	80 %	800	300
Nedre breivatnet	1	434	429	0,399	100	0	0	1	288	283	2,1277	0	0	0	24	6	1,342	1	80 %	800	300
Nedre breivatnet	1	487	482	2,1277	100	0	0	1	288	283	2,1277	0	0	0	24	6	1,695	1	80 %	800	300
	3,2	559	555,5	0,92	100	0	0					0	0	0	24	6	2,506	1	80 %	800	300
	26,5	198	172	1,49	100	0	0					0	0	0	24	6	3,578	1	80 %	800	300
Grytåvatn	120	199	173,3	7,7679	100	0	0	26,5	198	172	1,49	0	0	0	24	6	3,859	1	80 %	800	300
Grytåvatn	1	277,9	274,9	0,17	100	0	0	26,5	198	172	1,49	0	0	0	24	6	2,684	1	80 %	800	300
Grytåvatn	45	353	336	3,78	100	0	0	26,5	198	172	1,49	0	0	0	24	6	4,24	1	80 %	800	300
Stormyra	2309	383,15	370,7	218,05	100	0	0	19	247,9	244,5	6,58	0	0	0	24	6	7,759	1	80 %	800	300
Stormyra	250	407,5	386	12,74	100	0	0	19	247,9	244,5	6,58	0	0	0	24	6	3,375	1	80 %	800	300
Tustervatn-Røsvatn	250	407,5	386	12,74	100	0	0	2309	383,15	370,7	218,05	0	0	0	24	6	5,651	1	80 %	800	300
ST Målvatn	1276	523	480	42,24	100	0	0	153	430	397	7,35	0	0	0	24	6	10,082	1	80 %	800	300
Akersvatn	28	527	520	4,99	100	0	0	1276	523	480	42,24	0	0	0	24	6	6,402	1	80 %	800	300
Kjensvatn	314	598	582	22,6	100	0	0	28	527	520	4,99	0	0	0	24	6	4,875	1	80 %	800	300
ST Målvatn	28	527	520	4,99	100	0	0	153	430	397	7,35	0	0	0	24	6	4,235	1	80 %	800	300
Akersvatn	706	564	521	28,61	100	0	0	1276	523	480	42,24	0	0	0	24	6	15,013	1	80 %	800	300
	54	43,7	41	22,67	100	0	0					0	0	0	24	6	3,326	1	80 %	800	300
Langvatnet	44	562,5	538,5	2,08	100	0	0	54	43,7	41	22,67	0	0	0	24	6	11,074	1	80 %	800	300
Langvatnet	1	361	356	2,407	100	0	0	54	43,7	41	22,67	0	0	0	24	6	6,091	1	80 %	800	300
Trolldalsvatn	44	562,5	538,5	2,08	100	0	0	30	468,5	438,5	1,66	0	0	0	24	6	1,969	1	80 %	800	300
Holmvatn	30	468,5	438,5	1,66	100	0	0	72	275	254,3	4,84	0	0	0	24	6	3,688	1	80 %	800	300
	72	275	254,3	4,84	100	0	0					0	0	0	24	6	4,906	1	80 %	800	300
	3506	585	460	47,3	100	0	0					0	0	0	24	6	8,069	1	80 %	800	300
Fykanvatnet	3506	585	460	47,3	100	0	0	2,8	92	90	1,22	0	0	0	24	6	5,008	1	80 %	800	300
Nd Navervatn	9	544,94	540	2,14	100	0	0	8	468,36	464,44	2,06	0	0	0	24	6	0,767	1	80 %	800	300
Fykanvatnet	8	468,36	464,44	2,06	100	0	0	2,8	92	90	1,22	0	0	0	24	6	1,263	1	80 %	800	300
Øv Glomvatn	9	544,94	540	2,14	100	0	0	22,8	495	473	1,24	0	0	0	24	6	2,779	1	80 %	800	300
	28	371,65	361,65	4,5	100	0	0					0	0	0	24	6	1,82	1	80 %	800	300

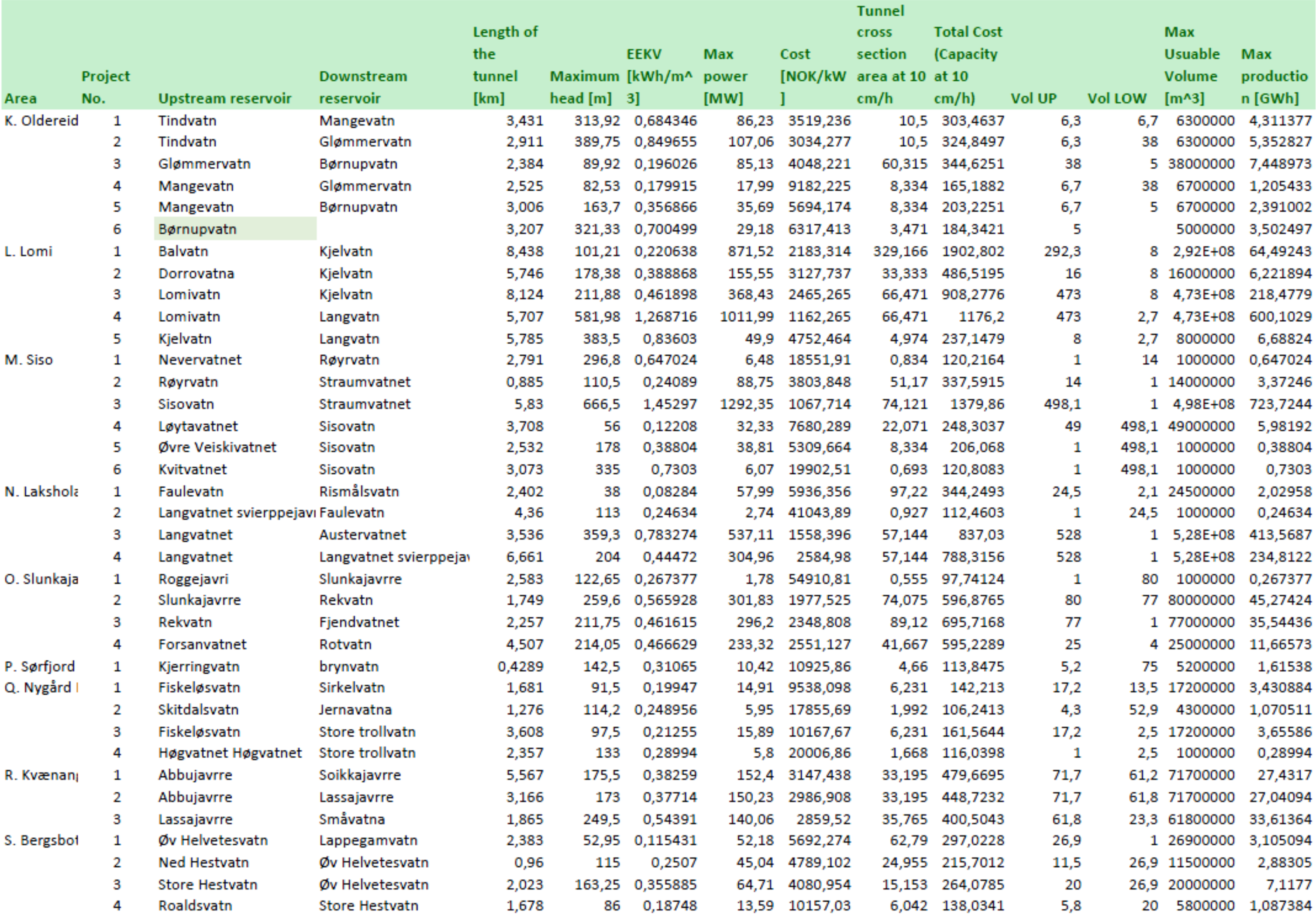


lower reservoir	V	HRWL	LRWL	Area	Start level	other inflow	other discharge	V	HRWL	LRWL	Area	Start level	other inflow	other discharge	power generation	pumping	tunnel length	number of unit	efficiency	access tunnel	adit tunnel
Storvatn	28	371,65	361,65	4,5	100	0	0	10	187,6	184,1	3,3	0	0	0	24	6	7,059	1	80 %	800	300
Storvatn	55,2	393,3	363,2	2,69	100	0	0	10	187,6	184,1	3,3	0	0	0	24	6	3,16	1	80 %	800	300
Landvatn	55,2	393,3	363,2	2,69	100	0	0	75,9	331,3	299,1	3,73	0	0	0	24	6	3,345	1	80 %	800	300
Sokumvatn	75,9	331,3	299,1	3,73	100	0	0	130,1	331,3	299,1	6,25	0	0	0	24	6	1,98	1	80 %	800	300
Sokumvatn	17,4	645	637,43	4,46	100	0	0	130,1	331,3	299,1	6,25	0	0	0	24	6	3,819	1	80 %	800	300
	130,1	331,3	299,1	6,25	100	0	0					0	0	0	24	6	5,475	1	80 %	800	300
Mangevatn	6,3	780,25	775,25	1,36	100	0	0	6,7	473,03	466,33	1,31	0	0	0	24	6	3,431	1	80 %	800	300
Glømmervatn	6,3	780,25	775,25	1,36	100	0	0	38	399,25	390,5	6,61	0	0	0	24	6	2,911	1	80 %	800	300
Børnupvatn	38	399,25	390,5	6,61	100	0	0	5	321,33	309,33	0,47	0	0	0	24	6	2,384	1	80 %	800	300
Glømmervatn	6,7	473,03	466,33	1,31	100	0	0	38	399,25	390,5	6,61	0	0	0	24	6	2,525	1	80 %	800	300
Børnupvatn	6,7	473,03	466,33	1,31	100	0	0	5	321,33	309,33	0,47	0	0	0	24	6	3,006	1	80 %	800	300
	5	321,33	309,33	0,47	100	0	0					0	0	0	24	6	3,207	1	80 %	800	300
Kjelvatn	292,3	597,31	589,91	40,84	100	0	0	8	509,5	496,1	3,81	0	0	0	24	6	8,438	1	80 %	800	300
Kjelvatn	16	674,48	670,48	4,26	100	0	0	8	509,5	496,1	3,81	0	0	0	24	6	5,746	1	80 %	800	300
Kjelvatn	473	707,98	648,68	11,38	100	0	0	8	509,5	496,1	3,81	0	0	0	24	6	8,124	1	80 %	800	300
Langvatn	473	707,98	648,68	11,38	100	0	0	2,7	126,5	126	5,64	0	0	0	24	6	5,707	1	80 %	800	300
Langvatn	8	509,5	496,1	3,81	100	0	0	2,7	126,5	126	5,64	0	0	0	24	6	5,785	1	80 %	800	300
Røyrvatn	1	408	398	1,57	100	0	0	14	115	111,2	4,01	0	0	0	24	6	2,791	1	80 %	800	300
Straumvatnet	14	115	111,2	4,01	100	0	0	1	5	4,5	6,77	0	0	0	24	6	0,885	1	80 %	800	300
Straumvatnet	498,1	671	615	14,95	100	0	0	1	5	4,5	6,77	0	0	0	24	6	5,83	1	80 %	800	300
Sisovatn	49	671	652,5	2,76	100	0	0	498,1	671	615	14,95	0	0	0	24	6	3,708	1	80 %	800	300
Sisovatn	1	793	792	3,84	100	0	0	498,1	671	615	14,95	0	0	0	24	6	2,532	1	80 %	800	300
Sisovatn	1	950	938	3,08	100	0	0	498,1	671	615	14,95	0	0	0	24	6	3,073	1	80 %	800	300
Rismålsvatn	24,5	317,5	314	7,25	100	0	0	2,1	281,5	279,5	1,08	0	0	0	24	6	2,402	1	80 %	800	300
Faulevatn	1	427	418	5,26	100	0	0	24,5	317,5	314	7,25	0	0	0	24	6	4,36	1	80 %	800	300
Austervatnet	528	622	545	13,98	100	0	0	1	272,6	262,7	0,92	0	0	0	24	6	3,536	1	80 %	800	300
Langvatnet svierppejavrre	528	622	545	13,98	100	0	0	1	427	418	5,26	0	0	0	24	6	6,661	1	80 %	800	300
Slunkajavrre	1	639	624	1,97	100	0	0	80	531,35	516,35	6,13	0	0	0	24	6	2,583	1	80 %	800	300
Rekvatn	80	531,35	516,35	6,13	100	0	0	77	283,75	271,75	7,39	0	0	0	24	6	1,749	1	80 %	800	300
Fjendvatnet	77	283,75	271,75	7,39	100	0	0	1	73	72	2,26	0	0	0	24	6	2,257	1	80 %	800	300
Rotvatn	25	258,5	253,5	4,8	100	0	0	4	45,45	44,45	10,89	0	0	0	24	6	4,507	1	80 %	800	300
brynvatn	5,2	577,5	562	0,68	100	0	0	75	515	435	1,41	0	0	0	24	6	0,4289	1	80 %	800	300
Sirkelvatn	17,2	347,5	324,5	1,45	100	0	0	13,5	273	256	1,22	0	0	0	24	6	1,681	1	80 %	800	300
Jernavatna	4,3	379	361	0,39	100	0	0	52,9	298,5	264,8	3,62	0	0	0	24	6	1,276	1	80 %	800	300
Store trollvatn	17,2	347,5	324,5	1,45	100	0	0	2,5	259	250	0,43	0	0	0	24	6	3,608	1	80 %	800	300
Store trollvatn	1	383	378	0,6789	100	0	0	2,5	259	250	0,43	0	0	0	24	6	2,357	1	80 %	800	300
Soikkajavrre	71,7	692	674	5,89	100	0	0	61,2	529	516,5	6,18	0	0	0	24	6	5,567	1	80 %	800	300
Lassajavrre	71,7	692	674	5,89	100	0	0	61,8	543	519	3,27	0	0	0	24	6	3,166	1	80 %	800	300
Småvatna	61,8	543	519	3,27	100	0	0	23,3	315	293,5	1,4	0	0	0	24	6	1,865	1	80 %	800	300
Lappegamvatn	26,9	203,2	197,25	4,89	100	0	0	1	152,25	150,25	0,36	0	0	0	24	6	2,383	1	80 %	800	300
Øv Helvetesvatn	11,5	312,25	305,85	1,99	100	0	0	26,9	203,2	197,25	4,89	0	0	0	24	6	0,96	1	80 %	800	300
Øv Helvetesvatn	20	360,5	349,5	1,96	100	0	0	26,9	203,2	197,25	4,89	0	0	0	24	6	2,023	1	80 %	800	300
Store Hestvatn	5,8	435,5	427,5	0,82	100	0	0	20	360,5	349,5	1,96	0	0	0	24	6	1,678	1	80 %	800	300

Figure D.3: Summary of Reservoirs pair data

D.4 Features of PSH stations

Area	Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Maximum head [m]	EEKV [kWh/m^3]	Max power [MW]	Cost [NOK/kW]	Tunnel cross section area at 10 cm/h	Total Cost (Capacity at 10 cm/h)	Vol UP	Vol LOW	Max Usuable Volume [m^3]	Max production [GWh]
A. Kolsvik E	1	Øvre Kalvvatnet		9,601	519	1,13142	510,77	1706,477	37,62	871,6173	158		1,58E+08	178,7644
	2	Øvre ringvatn	Øvre Kalvvatnet	4,609	129,6	0,282528	42,94	5871,968	12,666	252,1423	7,6	158	7600000	2,147213
	3	Kalvvatn	Øvre Kalvvatnet	6,887	257	0,56026	155,34	2960,632	23,106	459,9046	30,5	158	30500000	17,08793
	4	Nilsinetjern	Øvre Kalvvatnet	4,863	37	0,08066	1,84	61898,11	1,902	113,8925	1,3	158	1300000	0,104858
	5	Øvre Kalvvatnet	Majavatnet	13,885	519	1,13142	510,77	1853,328	37,62	946,6245	158	220	1,58E+08	178,7644
B. Tosdaler	1	Storfjelltjønna	Tosdalsvatnet	0,978	538	1,17284	23,48	6235,748	1,668	146,4154	1	0,2403	1000000	1,17284
	2	Måsvatnet	Tosdalsvatnet	3,012	643	1,40174	10,85	13436,07	0,645	145,7813	0,3865	0,2403	386500	0,541773
C. Soberg	1	Søbergsvatnet	Sørengvatnet	1,673	277	0,60386	12,09	10642,64	1,668	128,6695	1	1	1000000	0,60386
	2	Sagvatnet	Søbergsvatnet	2,757	357	0,77826	15,58	9279,273	1,668	144,5711	1	1	1000000	0,77826
	3	Sagvatnet	Øvre urdstjønna	0,334	81	0,17658	3,53	23926,85	1,668	84,46177	1	1	1000000	0,17658
D. Langfjor	1	Tettingvatn		1,492	343	0,74774	65,52	3653,157	7,302	239,3549	18,4		18400000	13,75842
	2	Storvatn	Tettingvatn	1,726	237	0,51666	47,24	4653,836	7,62	219,8472	3,2	18,4	3200000	1,653312
	3	Øvre breivatnet	Tettingvatn	2,073	172	0,37496	7,51	15490,79	1,668	116,3358	1	18,4	1000000	0,37496
	4	Midtre Breivatnet	Nedre lappskardvatnet	0,843	58	0,12644	2,53	35460,11	1,668	89,71408	1	1	1000000	0,12644
	5	Nedre lappskardvatnet	Nedre breivatnet	1,342	151	0,32918	6,59	16129,65	1,668	106,2944	1	1	1000000	0,32918
	6	Midtre Breivatnet	Nedre breivatnet	1,695	204	0,44472	8,9	13284,02	1,668	118,2278	1	1	1000000	0,44472
	7	Storvatn		2,506	559	1,21862	111,43	2729,147	7,62	304,1089	3,2		3200000	3,899584
E. Grytåga	1	Grytåvatn		3,578	198	0,43164	43,99	5137,436	8,493	225,9958	26,5		26500000	11,43846
	2	Hundålvatnet	Grytåvatn	3,859	27	0,05886	27,48	14481,99	38,91	397,9651	120	26,5	1,2E+08	7,0632
	3	Laksen	Grytåvatn	2,684	105,9	0,230862	7,7	16287	2,778	125,4099	1	26,5	1000000	0,230862
	4	Finnknevatn	Grytåvatn	4,24	181	0,39458	104,45	3483,461	22,059	363,8475	45	26,5	45000000	17,7561
F. Øvre Røs	1	Tustervatn-Røsvatn	Stormyra	7,759	138,65	0,302257	5605,72	1247,33	1545,516	6992,183	2309	19	2,31E+09	697,9114
	2	Bleikvatn	Stormyra	3,375	163	0,35534	413,19	2203,385	96,9	910,4167	250	19	2,5E+08	88,835
	3	Bleikvatn	Tustervatn-Røsvatn	5,651	36,8	0,080224	93,28	5880,37	96,9	548,5209	250	2309	2,5E+08	20,056
G. Kjensvat	1	Akersvatn	ST Målvatn	10,082	126	0,27468	815,1	2193,462	247,287	1787,891	1276	153	1,28E+09	350,4917
	2	Kjensvatn	Akersvatn	6,402	47	0,10246	40,98	7646,975	33,333	313,373	28	1276	28000000	2,86888
	3	Gressvatn	Kjensvatn	4,875	78	0,17004	333,7	2742,483	163,542	915,1666	314	28	3,14E+08	53,39256
	4	Kjensvatn	ST Målvatn	4,235	130	0,2834	113,36	3734,74	33,333	423,3701	28	153	28000000	7,9352
	5	Kalvatn	Akersvatn	15,013	84	0,18312	300,66	4015,381	136,821	1207,264	706	1276	7,06E+08	129,2827
H. Fagervol	1	Langvatnet		3,326	43,7	0,095266	190,53	3770,207	166,668	718,3375	54		54000000	5,144364
	2	Isvatn	Langvatnet	11,074	521,5	1,13687	208,44	2523,11	15,279	525,917	44	54	44000000	50,02228
	3	Reingardslivatnet	Langvatnet	6,091	320	0,6976	13,96	11374,93	1,668	158,794	1	54	1000000	0,6976
	4	Isvatn	Trolldalsvatn	1,969	124	0,27032	49,56	4932,584	15,279	244,4589	44	30	44000000	11,89408
	5	Trolldalsvatn	Holmvatn	3,688	214,2	0,466956	46,7	4980,09	8,334	232,5702	30	72	30000000	14,00868
	6	Holmvatn		4,906	275	0,5995	208,53	2513,241	28,986	524,0861	72		72000000	43,164
I. Svartsen	1	Storglomvatn		8,069	585	1,2753	3576,96	957,8491	233,733	3426,188	3506		3,51E+09	4471,202
	2	Storglomvatn	Fykanvatnet	5,008	495	1,0791	3026,66	1014,107	233,733	3069,358	3506	2,8	3,51E+09	3783,325
	3	Øv Navervatn	Nd Navervatn	0,767	80,5	0,17549	31,97	5659,111	25,305	180,9218	9	8	9000000	1,57941
	4	Nd Navervatn	Fykanvatnet	1,263	378,36	0,824825	168,33	2305,849	28,345	388,1435	8	2,8	8000000	6,598598
	5	Øv Navervatn	Øv Glomvatn	2,779	71,94	0,156829	28,57	8184,394	15,183	233,8281	9	22,8	9000000	1,411463
J. Forså	1	Lysvatn		1,82	371,65	0,810197	226,86	2073,979	38,89	470,5028	28		28000000	22,68552
	2	Lysvatn	Storvatn	7,059	187,55	0,408859	114,48	3542,199	23,334	405,511	28	10	28000000	11,44805
	3	Feldvatn	Storvatn	3,16	209,2	0,456056	83,63	3739,284	15,282	312,7164	55,2	10	55200000	25,17429
	4	Feldvatn	Landvatn	3,345	94,2	0,205356	37,66	6123,704	15,282	230,6187	55,2	75,9	55200000	11,33565
	5	Landvatn	Sokumvatn	1,98	32,2	0,070196	16,55	15542	19,644	257,2201	75,9	130,1	75900000	5,327876
	6	Navnløsvatn-L Sokumv	Sokumvatn	3,819	345,9	0,754062	173,33	2547,165	19,155	441,5002	17,4	130,1	17400000	13,12068
	7	Sokumvatn		5,475	331,3	0,722234	291,8	2111,663	33,669	616,1833	130,1		1,3E+08	93,96264

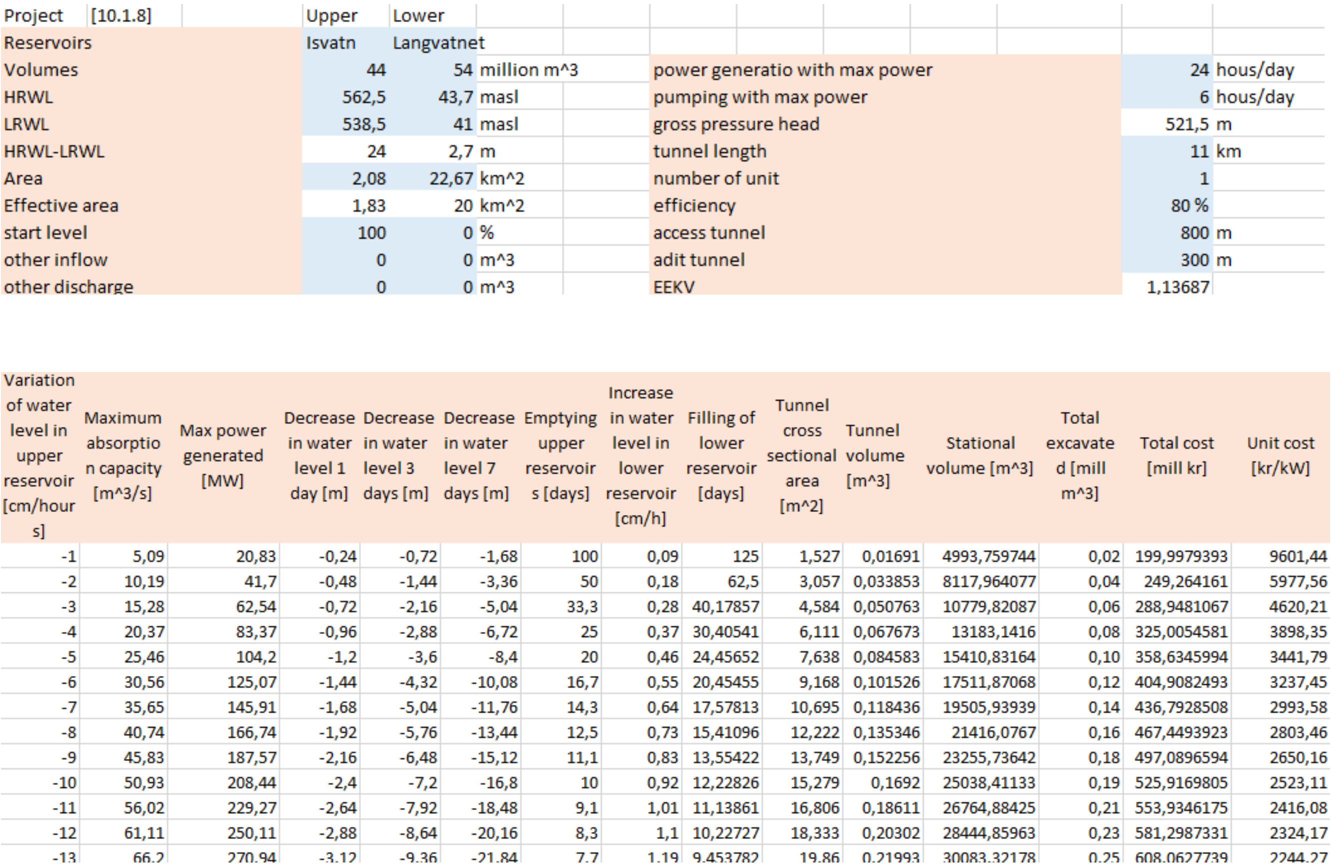


Area	Project No.	Upstream reservoir	Downstream reservoir	Length of the tunnel [km]	Maximum head [m]	EEKV [kWh/m^3]	Max power [MW]	Cost [NOK/kW]	Tunnel cross section area at 10 cm/h	Total Cost (Capacity at 10 cm/h)	Vol UP	Vol LOW	Max Usuable Volume [m^3]	Max production [GWh]
K. Oldereid	1	Tindvatn	Mangevatn	3,431	313,92	0,684346	86,23	3519,236	10,5	303,4637	6,3	6,7	6300000	4,311377
	2	Tindvatn	Glømmervatn	2,911	389,75	0,849655	107,06	3034,277	10,5	324,8497	6,3	38	6300000	5,352827
	3	Glømmervatn	Børnupvatn	2,384	89,92	0,196026	85,13	4048,221	60,315	344,6251	38	5	38000000	7,448973
	4	Mangevatn	Glømmervatn	2,525	82,53	0,179915	17,99	9182,225	8,334	165,1882	6,7	38	6700000	1,205433
	5	Mangevatn	Børnupvatn	3,006	163,7	0,356866	35,69	5694,174	8,334	203,2251	6,7	5	6700000	2,391002
	6	Børnupvatn		3,207	321,33	0,700499	29,18	6317,413	3,471	184,3421	5		5000000	3,502497
L. Lomi	1	Balvatn	Kjelvatn	8,438	101,21	0,220638	871,52	2183,314	329,166	1902,802	292,3	8	2,92E+08	64,49243
	2	Dorrovatna	Kjelvatn	5,746	178,38	0,388868	155,55	3127,737	33,333	486,5195	16	8	16000000	6,221894
	3	Lomivatn	Kjelvatn	8,124	211,88	0,461898	368,43	2465,265	66,471	908,2776	473	8	4,73E+08	218,4779
	4	Lomivatn	Langvatn	5,707	581,98	1,268716	1011,99	1162,265	66,471	1176,2	473	2,7	4,73E+08	600,1029
	5	Kjelvatn	Langvatn	5,785	383,5	0,83603	49,9	4752,464	4,974	237,1479	8	2,7	8000000	6,68824
M. Siso	1	Nevervatnet	Røyrvatn	2,791	296,8	0,647024	6,48	18551,91	0,834	120,2164	1	14	1000000	0,647024
	2	Røyrvatn	Straumvatnet	0,885	110,5	0,24089	88,75	3803,848	51,17	337,5915	14	1	14000000	3,37246
	3	Sisovatn	Straumvatnet	5,83	666,5	1,45297	1292,35	1067,714	74,121	1379,86	498,1	1	4,98E+08	723,7244
	4	Løytavatnet	Sisovatn	3,708	56	0,12208	32,33	7680,289	22,071	248,3037	49	498,1	49000000	5,98192
	5	Øvre Veiskivatnet	Sisovatn	2,532	178	0,38804	38,81	5309,664	8,334	206,068	1	498,1	1000000	0,38804
	6	Kvitvatnet	Sisovatn	3,073	335	0,7303	6,07	19902,51	0,693	120,8083	1	498,1	1000000	0,7303
N. Lakshol	1	Faulevatn	Rismålsvatn	2,402	38	0,08284	57,99	5936,356	97,22	344,2493	24,5	2,1	24500000	2,02958
	2	Langvatnet svierppejav	Faulevatn	4,36	113	0,24634	2,74	41043,89	0,927	112,4603	1	24,5	1000000	0,24634
	3	Langvatnet	Austervatnet	3,536	359,3	0,783274	537,11	1558,396	57,144	837,03	528	1	5,28E+08	413,5687
	4	Langvatnet	Langvatnet svierppeja	6,661	204	0,44472	304,96	2584,98	57,144	788,3156	528	1	5,28E+08	234,8122
O. Slunkaja	1	Roggejavri	Slunkajavrre	2,583	122,65	0,267377	1,78	54910,81	0,555	97,74124	1	80	1000000	0,267377
	2	Slunkajavrre	Rekvatn	1,749	259,6	0,565928	301,83	1977,525	74,075	596,8765	80	77	80000000	45,27424
	3	Rekvatn	Fjendvatnet	2,257	211,75	0,461615	296,2	2348,808	89,12	695,7168	77	1	77000000	35,54436
	4	Forsanvatnet	Rotvatn	4,507	214,05	0,466629	233,32	2551,127	41,667	595,2289	25	4	25000000	11,66573
P. Sørfjord	1	Kjerringvatn	brynvatn	0,4289	142,5	0,31065	10,42	10925,86	4,66	113,8475	5,2	75	5200000	1,61538
Q. Nygård	1	Fiskeløsvatn	Sirkelvatn	1,681	91,5	0,19947	14,91	9538,098	6,231	142,213	17,2	13,5	17200000	3,430884
	2	Skitdalsvatn	Jernavatna	1,276	114,2	0,248956	5,95	17855,69	1,992	106,2413	4,3	52,9	4300000	1,070511
	3	Fiskeløsvatn	Store trollvatn	3,608	97,5	0,21255	15,89	10167,67	6,231	161,5644	17,2	2,5	17200000	3,65586
	4	Høgvatnet Høgvatnet	Store trollvatn	2,357	133	0,28994	5,8	20006,86	1,668	116,0398	1	2,5	1000000	0,28994
R. Kvænan	1	Abbujavrre	Soikkajavrre	5,567	175,5	0,38259	152,4	3147,438	33,195	479,6695	71,7	61,2	71700000	27,4317
	2	Abbujavrre	Lassajavrre	3,166	173	0,37714	150,23	2986,908	33,195	448,7232	71,7	61,8	71700000	27,04094
	3	Lassajavrre	Småvatna	1,865	249,5	0,54391	140,06	2859,52	35,765	400,5043	61,8	23,3	61800000	33,61364
S. Bergsbo	1	Øv Helvetesvatn	Lappegamvatn	2,383	52,95	0,115431	52,18	5692,274	62,79	297,0228	26,9	1	26900000	3,105094
	2	Ned Hestvatn	Øv Helvetesvatn	0,96	115	0,2507	45,04	4789,102	24,955	215,7012	11,5	26,9	11500000	2,88305
	3	Store Hestvatn	Øv Helvetesvatn	2,023	163,25	0,355885	64,71	4080,954	15,153	264,0785	20	26,9	20000000	7,1177
	4	Roaldsvatn	Store Hestvatn	1,678	86	0,18748	13,59	10157,03	6,042	138,0341	5,8	20	5800000	1,087384

Figure D.4: Features of PSH stations

Appendix E PSH station Cost Analysis

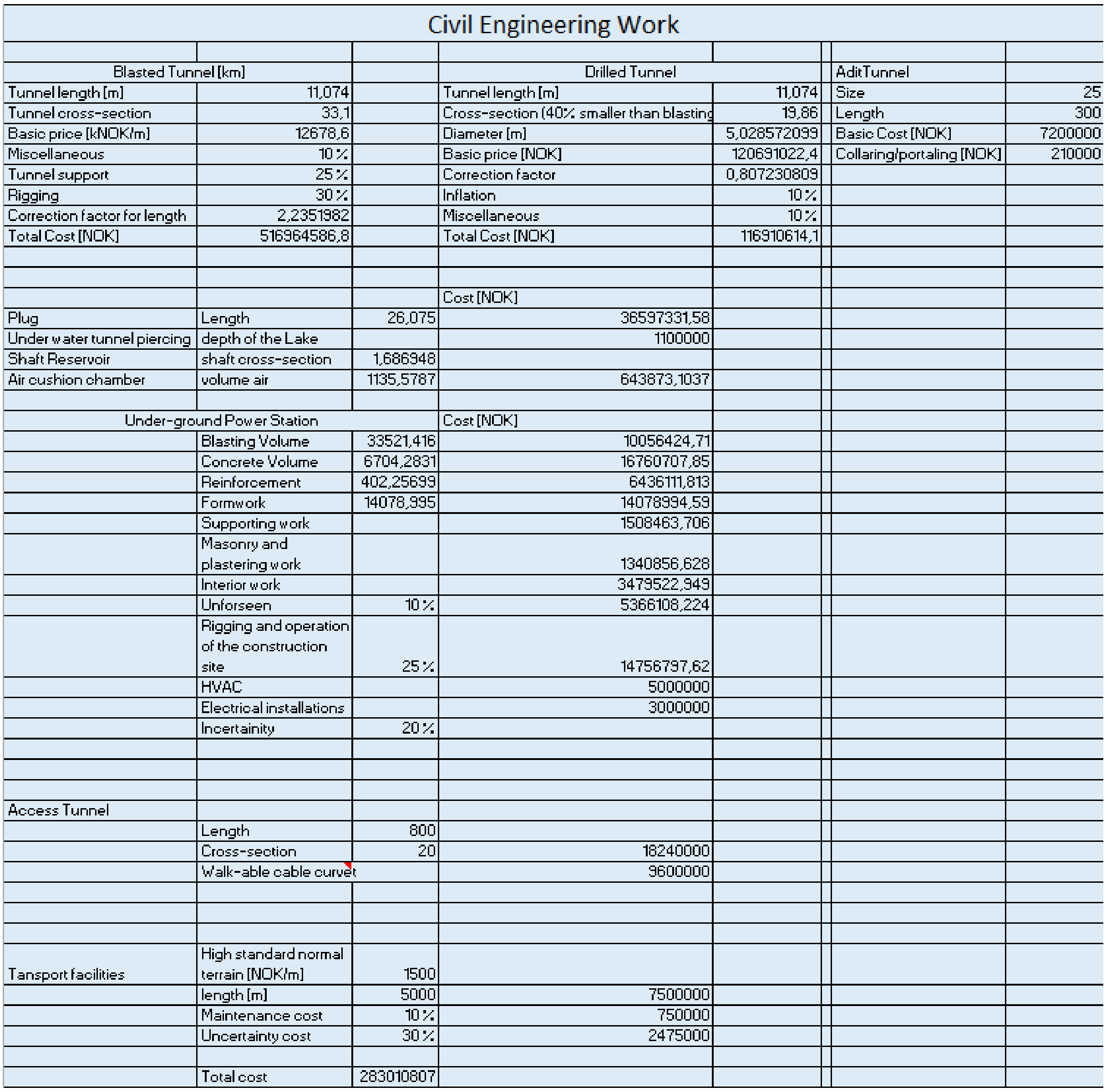
E.1 Isvatn-Langvatnet



Project	[10.1.8]	Upper	Lower				
Reservoirs		Isvatn	Langvatnet				
Volumes		44	54	million m^3	power generatio with max power	24	hous/day
HRWL		562,5	43,7	masl	pumping with max power	6	hous/day
LRWL		538,5	41	masl	gross pressure head	521,5	m
HRWL-LRWL		24	2,7	m	tunnel length	11	km
Area		2,08	22,67	km^2	number of unit	1	
Effective area		1,83	20	km^2	efficiency	80 %	
start level		100	0	%	access tunnel	800	m
other inflow		0	0	m^3	adit tunnel	300	m
other discharge		0	0	m^3	EEKV	1,13687	

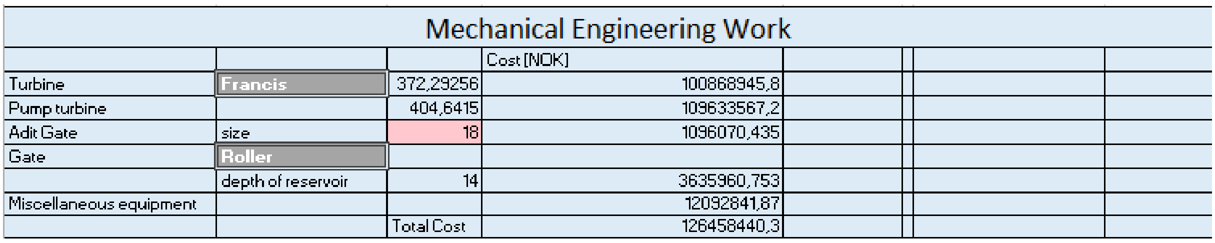
Variation of water level in upper reservoir [cm/hours]	Maximum absorption capacity [m^3/s]	Max power generated [MW]	Decrease in water level 1 day [m]	Decrease in water level 3 days [m]	Decrease in water level 7 days [m]	Emptying upper reservoirs [days]	Increase in water level in lower reservoir [cm/h]	Filling of lower reservoir [days]	Tunnel cross sectional area [m^2]	Tunnel volume [m^3]	Stational volume [m^3]	Total excavated [mill m^3]	Total cost [mill kr]	Unit cost [kr/kW]
-1	5,09	20,83	-0,24	-0,72	-1,68	100	0,09	125	1,527	0,01691	4993,759744	0,02	199,9979393	9601,44
-2	10,19	41,7	-0,48	-1,44	-3,36	50	0,18	62,5	3,057	0,033853	8117,964077	0,04	249,264161	5977,56
-3	15,28	62,54	-0,72	-2,16	-5,04	33,3	0,28	40,17857	4,584	0,050763	10779,82087	0,06	288,9481067	4620,21
-4	20,37	83,37	-0,96	-2,88	-6,72	25	0,37	30,40541	6,111	0,067673	13183,1416	0,08	325,0054581	3898,35
-5	25,46	104,2	-1,2	-3,6	-8,4	20	0,46	24,45652	7,638	0,084583	15410,83164	0,10	358,6345994	3441,79
-6	30,56	125,07	-1,44	-4,32	-10,08	16,7	0,55	20,45455	9,168	0,101526	17511,87068	0,12	404,9082493	3237,45
-7	35,65	145,91	-1,68	-5,04	-11,76	14,3	0,64	17,57813	10,695	0,118436	19505,93939	0,14	436,7928508	2993,58
-8	40,74	166,74	-1,92	-5,76	-13,44	12,5	0,73	15,41096	12,222	0,135346	21416,0767	0,16	467,4493923	2803,46
-9	45,83	187,57	-2,16	-6,48	-15,12	11,1	0,83	13,55422	13,749	0,152256	23255,73642	0,18	497,0896594	2650,16
-10	50,93	208,44	-2,4	-7,2	-16,8	10	0,92	12,22826	15,279	0,1692	25038,41133	0,19	525,9169805	2523,11
-11	56,02	229,27	-2,64	-7,92	-18,48	9,1	1,01	11,13861	16,806	0,18611	26764,88425	0,21	553,9346175	2416,08
-12	61,11	250,11	-2,88	-8,64	-20,16	8,3	1,1	10,22727	18,333	0,20302	28444,85963	0,23	581,2987331	2324,17
-13	66,2	270,94	-3,12	-9,36	-21,84	7,7	1,19	9,453782	19,86	0,21993	30083,32178	0,25	608,0627739	2244,27

Figure E.1: Isvatn-Langvatnet Unit Cost for variation of water level in upper reservoir



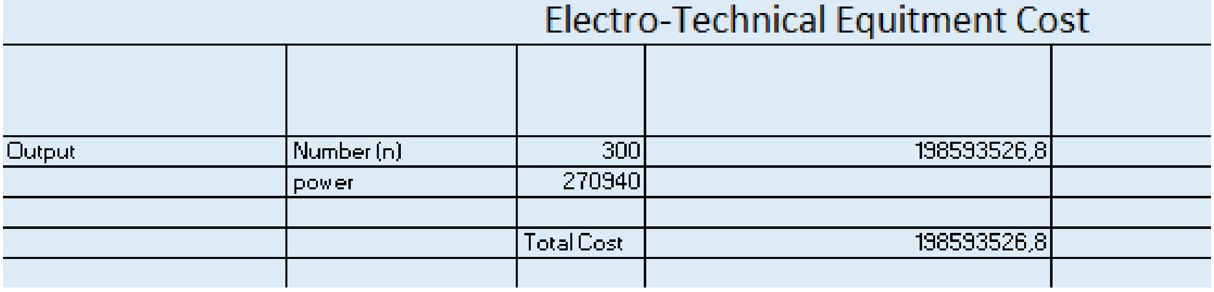
Civil Engineering Work

Blasted Tunnel [km]			Drilled Tunnel		Adit Tunnel	
Tunnel length [m]	11,074		Tunnel length [m]	11,074	Size	25
Tunnel cross-section	33,1		Cross-section (40% smaller than blasting	19,86	Length	300
Basic price [kNOK/m]	12678,6		Diameter [m]	5,028572099	Basic Cost [NOK]	7200000
Miscellaneous	10 %		Basic price [NOK]	120691022,4	Collaring/portaling [NOK]	210000
Tunnel support	25 %		Correction factor	0,807230809		
Rigging	30 %		Inflation	10 %		
Correction factor for length	2,2351982		Miscellaneous	10 %		
Total Cost [NOK]	516964586,8		Total Cost [NOK]	116910614,1		
			Cost [NOK]			
Plug	Length	26,075	36597331,58			
Under water tunnel piercing	depth of the Lake		1100000			
Shaft Reservoir	shaft cross-section	1,686948				
Air cushion chamber	volume air	1135,5787	643873,1037			
Under-ground Power Station			Cost [NOK]			
	Blasting Volume	33521,416	10056424,71			
	Concrete Volume	6704,2831	16760707,85			
	Reinforcement	402,25699	6436111,813			
	Formwork	14078,995	14078994,59			
	Supporting work		1508463,706			
	Masonry and plastering work		1340856,628			
	Interior work		3479522,949			
	Unforseen	10 %	5366108,224			
	Rigging and operation of the construction site	25 %	14756797,62			
	HVAC		5000000			
	Electrical installations		3000000			
	Incertainity	20 %				
Access Tunnel						
	Length	800				
	Cross-section	20	18240000			
	Walk-able cable curvet		9600000			
Tansport facilities	High standard normal terrain [NOK/m]	1500				
	length [m]	5000	7500000			
	Maintenance cost	10 %	750000			
	Uncertainty cost	30 %	2475000			
	Total cost	283010807				



Mechanical Engineering Work

			Cost [NOK]			
Turbine	Francis	372,29256	100868945,8			
Pump turbine		404,6415	109633567,2			
Adit Gate	size	18	1096070,435			
Gate	Roller					
	depth of reservoir	14	3635960,753			
Miscellaneous equipment			12092841,87			
		Total Cost	126458440,3			



Electro-Technical Equitment Cost				
Output	Number (n)	300	198593526,8	
	power	270940		
		Total Cost	198593526,8	

Figure E.1: Isvatn-Langvatnet total cost review

Appendix F Balancing power VS Production

F.1 Balancing power vs Production

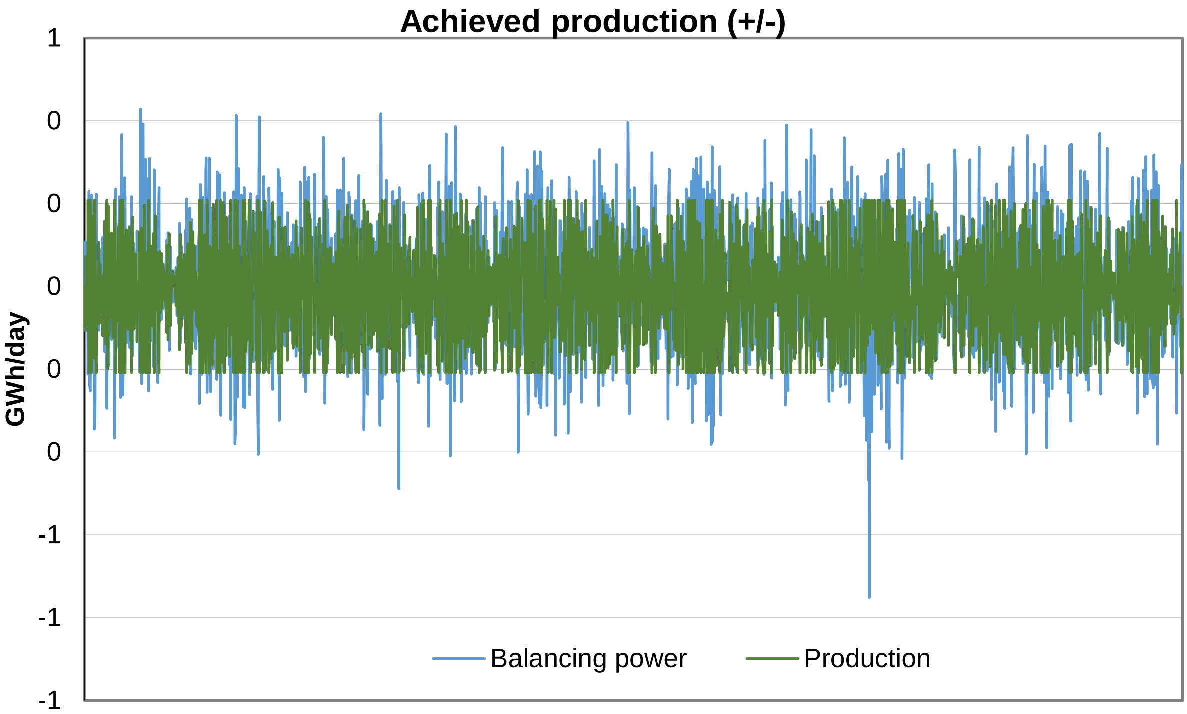


Figure F.1: Case Study on Isvatn-Langvatnet- Balancing power vs produciton