NTNU – Trondheim
Norwegian University of
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Pumped Storage Development in Øvre Otra, Norway

Lars Marius Rognlien

Hydropower Development
Submission date: June 2012
Supervisor: Ånund Killingtveit, IVM
Co-supervisor: Leif Lia, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

Department of Hydraulic and Environmental Engineering

MSc Thesis
in
Hydropower Development

Candidate: **Lars Marius Rognlien**
Topic: **Pumped storage hydropower development in Øvre Otra, Norway**

1. Background

The future development of more renewable energy in Norway will probably mainly consist of small hydropower and wind power plants. This development is now mainly driven by the introduction of Green Certificates, which will secure funding also of projects that today are not economically feasible. Till 2020 it is planned that about 13 TWh of new capacity will be developed in Norway, and similar amounts in Sweden.

Also in the rest of Europe one can see a rapid development of new renewable energy, mainly as wind and also some solar power. Much of the wind power development will be located close to Norway, in the North Sea. The driver for this development, as in Norway, is the EU 20/20/20 plan where 20% of energy consumption in Europe should be supplied from renewable sources before 2020.

The rapid development of wind power, solar power and small hydro will put increasing pressure on the grid, since all of these lack storage capacity, the electrical energy production will be determined by the climatic conditions, not by the demand. It will therefore lead to the need for more balancing power sources, which can fill in when demand exceeds the production, for example during calm periods, and preferably also utilize some of the excess production during periods of strong wind.

One of the most promising technologies for such power balancing is pumped storage hydropower (PSH). There is now a rapidly growing development of pumped storage hydropower in Europe, and a growing interest also in Norway. The term “Green Battery” has been introduced, where Norwegian hydropower reservoirs can be “charged” by surplus wind power and emptied again in order to fill in load during calm periods.

In Centre for Environmental Design of Renewable Energy (CEDREN), several possible sites for PSH have been investigated in Southern Norway, some of these also in Otra river. This study has been on a very simplified level. We now want to investigate some of the more promising sites more in-depth, up to the level of a feasibility analysis. Two possible sites have been identified in Upper Otra, one between Botsvatn and Urarvatn (this thesis) and another between Vatnedalsvatn and Urarvatn. The two studies will later be used to compare and recommend the best alternative.

Only sites with existing hydropower reservoirs and existing power plant(s) are included in the analysis, and it is assumed that the new power plant and tunnel systems may be built in parallel with the existing power plant. An important part of the feasibility analysis is to study how the new plant may be integrated with the existing plant, and how this could affect the operation and possibly also the possibility for uprating and refurbishment of the existing plant.

The project will consist of the following topics to be included in the report
(though not necessarily be limited to these)

- A review and summary of international PSH technology discussing the state- of art
- An overview of the existing hydropower system in Upper Otra
- Important technical, topographical, geological and hydrological data for the area
- A model for the operation of the two reservoirs and for analysis of the impacts on water level fluctuations in the reservoirs (using an existing model)
- Identification of main project layout for one or a few alternatives of a PSH
- A special study of the tunnel system and optimization of tunnel parameters and construction method
- A feasibility analysis for the selected case(s) – including technical, economic and environmental conditions
- Investigate how the new PSH can be integrated with the existing hydropower plant, and what effect the new plant could have on operation and efficiency in the existing plant
- Summary and recommendations
- Reporting and presentation

3. Supervision

Supervisor:	Professor Ånund Killingtveit
Co-supervisor:	Professor Leif Lia, Director Atle Harby, CEDREN

This specification for the thesis should be reviewed after about 6 weeks, and not later than 1/3. If needed, the text could then be modified, based on proposal from the candidate and discussions with the supervisor.

4. Report format

Professional structuring of the report is important. Assume professional senior engineers as the main target group. The report shall include a summary, offering the reader the background, the objective of the study and the main results. The thesis report shall be in format A4, using NTNU's standard front and cover page for Thesis work. Figures, tables, etc shall be of good report quality. Table of contents, list of figures, list of tables, list of references and other relevant references shall be included. The complete manuscript should be compiled into a PDF file and submitted electronically to DAIM for registration, printing and archiving. Three hard copies, in addition to the students own copies, should be printed out and submitted. The entire thesis may be published on the Internet as full text publishing. All documents and data shall be written on a CD thereby producing a complete electronic documentation of the results from the project. This must be so complete that all computations can be reconstructed from the CD.

Finally, the candidate is requested to include a signed statement that the work presented is his own and that all significant outside input has been identified.

The thesis shall be submitted no later than **Tuesday 11 June, 2012**

Department of Hydraulic and Environmental Engineering, NTNU

Ånund Killingtveit
Professor

Preface

The goal with this master thesis was to address all the challenges related to pump storage hydropower in the project area.

I would like to thank everybody working with pumped storage hydropower, both in CEDREN and my fellow students. Also I would thank Ole Morten Egeland at Agder Energi, Professor Bjørn Nilsen, Pål-Tore Storli and my supervisor Ånund Killingtveit and co-supervisor Leif Lia.

Abstract

The objective with this thesis was to describe the challenges related to PSH, both for this particular study and in more general terms.

The method used was to make assumptions that would apply to traditional hydropower and do calculations based on these. The assumptions and the results of the assumptions were both commented and discussed. Challenges encountered that are unique to the project area and challenges with PSH in general were also discussed.

The project area lies in the Upper Otra area, north in Aust-Agder County, and includes the two reservoirs Urevatn and Botsvatn.

Three alternatives with the same layout scheme were chosen with a capacity of 500, 1000 and 1500 MW, referred to as alternative 1, 2 and 3, respectively.

The choice of turbines was Francis reversible pump-turbines, which are installed with 10% extra capacity for frequency balancing. The excavation method is drill-and-blast, based on the flexibility and cost. The total cost was found to be 6900, 12900 and 18500 MNOK for alternative 1-3, where the cable cost was 4300, 8600 and 12900 MNOK.

The price of pumping was chosen to be 0,1 kr/kWh, and the necessary price for production that gave zero NPV, was found to be 0,4 kr/kWh.

Some environmental conditions would be affected in the area, but most likely this would not include the wild reindeers in the area.

The total operation time was decreasing with a larger installation, and the number of days in a row with either pumping or production was stable regardless of the installation. With a larger installation there would be bigger fluctuations in the reservoirs, and more occurring larger fluctuations. It would be meaningless to have two different LRWL for summer and winter. The result would only be loss of production, but still large fluctuations. The biggest change in the water level during summer from one day to the next was 11 meter for Urevatn and 9 meter for Botsvatn.

If the existing power plant were taken out of production the fluctuations in Urevatn and Botsvatn would have the same maximum and average, approximately 1,5 and 3 meter/day.

The efficiency for Holen III would decrease, if maintaining the current production level.

The existing limitations in the operation regime should be ignored if developing PSH in Norway. The PSH-plant should be operated without limitations and have priority over any existing power plant in the same reservoir, to make full use of the PSH-plant and to make sure the investment would be profitable.

Sammendrag

Målet med denne oppgaven var å beskrive utfordringene i forbindelse med PSH, både for dette spesifikke prosjektområdet og mer generelt.

Metoden brukt i denne masteroppgaven var å gjøre antagelser som var overførbare til tradisjonell vannkraft og gjøre beregninger basert på disse. Diskutering av antagelsene og beregninger uten antagelsene ble også gjort. Utfordringer som var unike for prosjektområdet og utfordringer med PSH generelt, ble også diskutert.

Prosjektområdet ligger i øvre Otra, nord i Aust-Agder fylke, og inkluderer magasinene Urevatn og Botsvatn.

Tre alternativer med den samme utformingen ble valgt med en installert effekt på 500, 1000 og 1500 MW, kalt henholdsvis alternativ 1, 2 og 3.

Den valgte turbintypen var Francis reversibel pumpe-turbin, som er har en ekstra installert effekt på 10 % for frekvens balansering. Konvensjonell tunneldriving ble valgt på bakgrunn av fleksibilitet og kostnad. Den totale kostnaden ble beregnet til 6900, 12900 og 18500 for alternativ 1, 2 og 3, der kabelkostnaden utgjorde 4300, 8600 og 12900 MNOK.

Prisen for pumping ble satt til 0,1 kr/kWh, og prisen for produksjon som ga null NNV, ble beregnet til 0,4 kr/kWh.

Det vil bli noen miljøpåvirkninger, men dette gjelder høyst sannsynlig ikke reinsdyrene i området.

Den totale brukstiden gikk ned med større installert effekt, og antall dager på rad med produksjon eller pumping var relativt stabilt uavhengig av den installerte effekten. Med en større installert effekt vil det bli større svingninger i magasinene, og svingningene vil også forekomme oftere. Det vil være meningsløst å ha forskjellig LRV for sommer og vinter. Resultatet ville bare bli tapt produksjon, men fremdeles ha store svingninger. Den største endringen, i løpet av sommeren, i vannstanden fra en dag til den neste var 11 meter i Urevatn og 9 meter i Botsvatn.

Hvis det eksisterende kraftverket ble tatt ut av produksjon ville svingningene i Urevatn og Botsvatn ha samme maksimalverdi som gjennomsnittsverdi, henholdsvis 1,5 og 3 meter per dag.

Virkningsgraden til det eksisterende kraftverket vil minke hvis samme produksjonsnivå skal bli opprettholdt.

De eksisterende begrensningene burde bli ignorert for PSH-kraftverket. PSH-kraftverket burde kjøres som ønsket og ha prioritet over eventuelle eksisterende kraftverk i samme magasin, for full utnyttelse og gjøre investeringen mest mulig lønnsom.

Figures

Equations

Tables

Symbol explanation

A, a	Area	[m^2]
E	Energy	[kWh]
C	Degrees	[°]
c	Absolute velocity	[m/s]
DF	Discount factor	
D	Diameter	[m]
g	Gravitational acceleration	[m/s^2]
H	Head	[m]
h_f	Head loss	[m]
h	Net head	[m]
h	Pressure head	[mVs]
P	Effect	[MW]
L	Length	[m]
l	Length	[m]
M	Manning's number	[m$^{1/3}$/s]
n	Years	
n	Speed number	[RPM]
p	Electricity price	[kr/kWh]
Q	Discharge	[m^3/s]
R	Hydraulic radius	[m]
T_{total}	Operation time	[h/year]
T	Time	[s]
u	Peripheral velocity	[m/s]
V	Volume	[m^3]
VA	Apparent Power	[MVA]
v	Velocity	[m/s]
η	Efficiency	[%]
ω	Angular velocity	[rad/s]

Abbreviations

AC	Alternating Current
CEDREN	Centre of Environmental Design of Renewable Energy
DC	Direct Current
HRWL	Highest Regulated Water Level
HVDC	High-Voltage Direct Current
LRWL	Lowest Regulated Water Level
masl	Meter Above Sea Level
NPV	Net Present value
NVE	Norwegian Water Resources and Energy Directorate
VSC	Voltage Sourced converters
MNOK	Million Norwegian kroner
EEKV	Energy Equivalent

1 Introduction

The main goal of this thesis was to take everything related to building PSH into consideration, especially challenges unique to the project area. A feasibility study was done based on assumptions, rules of thumb and acceptable general values. Usually an optimization is done, but then it's necessary with a more accurate income estimate than done in this thesis.

The method was to do calculations based on the assumptions and analyse the results. The assumptions and the results of the assumptions were both commented and discussed. In some cases, scenarios with different outcomes were described based on the assumptions. Also general challenges regarding PSH were also commented.

Three alternatives with the same layout scheme were chosen, referred to as alternative 1, 2 and 3, with an installation of 500, 1000 and 1500 MW, respectively. Challenges and differences between the alternatives were commented.

Connection to the Norwegian grid was not a part of this thesis, but an overseas cable was taken into consideration.

1.1 Background

Today the focus on the environment and environmental issues has increased due to the ever-increasing amount of CO_2 released into the atmosphere. Much of this CO_2 is released from power plants using coal. To reduce the CO_2 emissions the EU has made a plan where 20% of all the energy consumed in Europe should be supplied from renewable sources before 2020, which are called the 20/20/20 plan.

With the earthquake in 2011 in Japan, and the following problems with the Fukushima nuclear power plant, the process of phasing out nuclear power plants in Germany, was speeded up.

So with the phasing out of nuclear power plants in Europe, and the EU's 20/20/20 plan, the construction rate of new renewable energy is high, especially solar power and wind power. The wind power is developed both on land and at sea, especially in the North Sea. In the North Sea there are huge areas with a lot of potential and in 2011 150 GW (EWEA) of wind power was under planning.

As the unregulated renewable energy sources becomes a larger part of the total energy production in Europe, the demand for something to compensate for lost production due no wind and sun, increases. This something could be PSH built in Norway.

The construction of a PSH-plant is done between two reservoirs, an upper and lower reservoir. The bigger the reservoirs, the bigger the balancing potential and in Norway there are several areas with large reservoirs with the potential for PSH.

One of these areas is in south of Norway, Aust-Agder County, and Bykle municipally. In this area there are several reservoirs, but this study was based on PSH between the two reservoirs Urevatn and Botsvatn.

1.2 Method and objectives

The model used for the simulations was developed by Ånund Killingtveit and Julian Sauterleute, both working at SINTEF. The model was used to simulate fluctuations in the two reservoirs Urevatn and Botsvatn.

The method used was to make assumptions that would apply to traditional hydropower and do calculations based on these. The results were commented and new calculations were done not including the assumptions.

The objective with this thesis was to describe the challenges related to PSH, both for this particular area and in more general terms.

2 Project area

2.1 General

Urevatn and Botsvatn are located next to two of Norway's largest reservoirs called Vatnedalsvatn and Blåsjø. Blåsjø is a part of another catchment, but Urevatn, Botsvatn and Vatnedalsvatn is a part of the same catchment and ends up in a river called Otra. Otra runs for 245 km before entering the town of Kristiansand and into the North Sea. The project area is called Upper Otra.

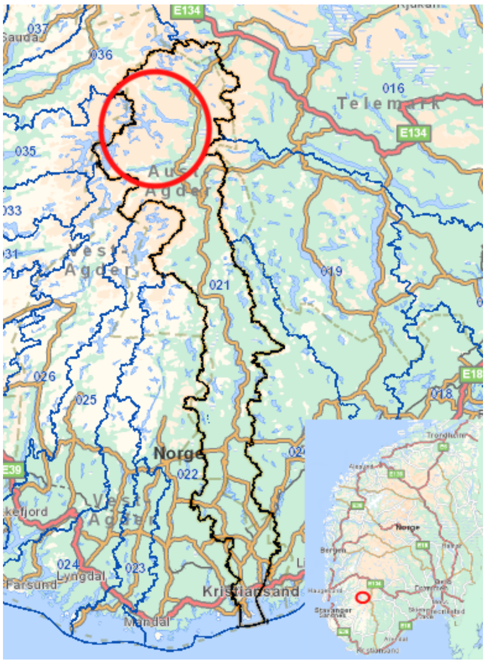

Figure 2.1 Project area (Picture from NVE atlas)

Connected to Urevatn, Botsvatn and Vatnedalsvatn, directly or indirectly, are several large and small power plants, owned by Agder Energy Production, were the most relevant is Brokke, Holen I-II and Holen III. The purpose of the smaller power plants is to supply Urevatn and Vatnedalsvatn with water that is not necessarily naturally available.

Holen I-II has the inlet in Vatnedalsvatn and outlet Botsvatn, Brokke has the inlet in Botsvatn and the outlet in Otra and the most relevant for this thesis is Holen III that has the inlet in Urevatn and outlet in Botsvatn.

Urevatn is dammed and consists originally of several smaller lakes. In maps Urevatn is often called Store Urevatn (Big Urevatn).

Around Botsvatn there are several cabins, which are mostly used during the summer.

In the figure below is an overview of the project area, where the lines represents the waterways. The smaller lines without names are the smaller power plants or brook inlets.

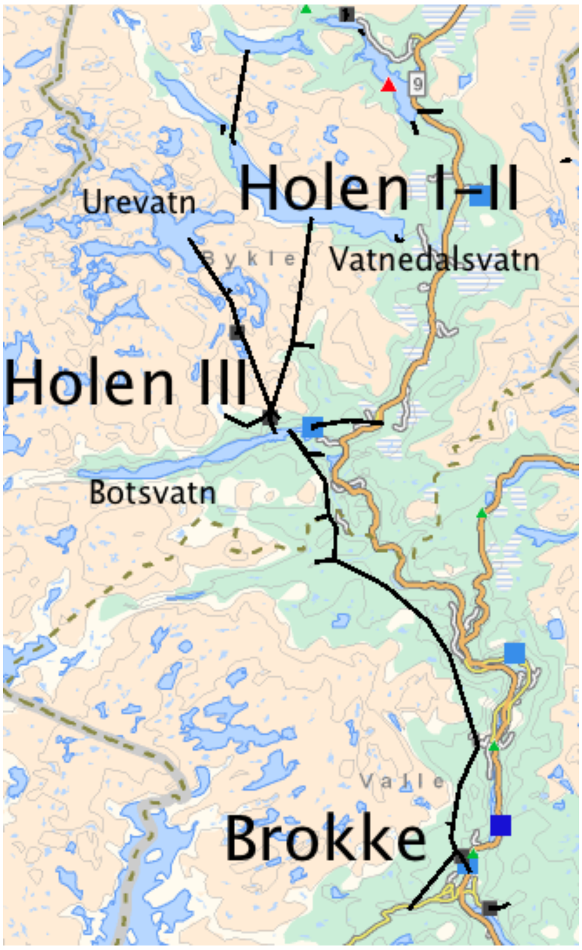

Figure 2.2 Existing power plants (Picture from NVE atlas)

Urevatn and Botsvatn lies in a protected area that also has a population of wild reindeers. The red-hatched area, from the figure below, is protected.

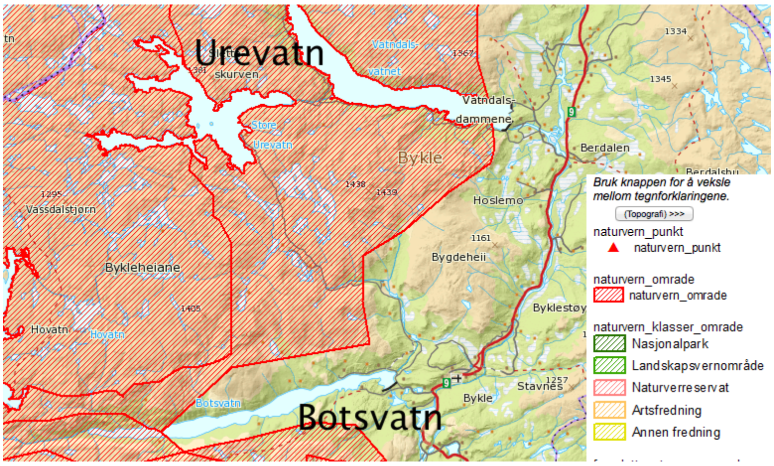

Figure 2.3 Protected area (Picture from ngu.no)

2.2 Operation regime

Brokke is under-dimensioned and must produce at maximum capacity to minimize the spill water. Holen I-II and III are operated in a traditional Norwegian way, with filling of the reservoirs in the summer and autumn, and producing in the winter and fall. Reservoir power plants are usually producing at best efficiency.

2.3 Technical data

	Holen I-II	Holen III	Brokke
Head (min/max) [m]	149/345 (310 summer)	590/680 (645 summer)	244/303
Installed effect [MW]	174	154	334
Tunnel length [km]	12	13	32
Average annual production [GWh]	613	275	1462

Table 2.1 Data of existing power plants

Reservoir	LWRL [masl]	HRWL [masl]	Volume [Mm3]
Vatnedalsvatn	840	700	1150
Urevatn	1141	1175	253
Botsvatn	495 (530 in the summer)	551	296

Table 2.2 Reservoir data

2.4 Geology and topography

The entrance of Holen power plant is located approximately 563 meter above sea level. From here the mountaintops looming over Botsvatn raises to a plateau, which is varying between 1100 and 1300 meter above sea level. This plateau is a typical Norwegian mountain area with little vegetation.

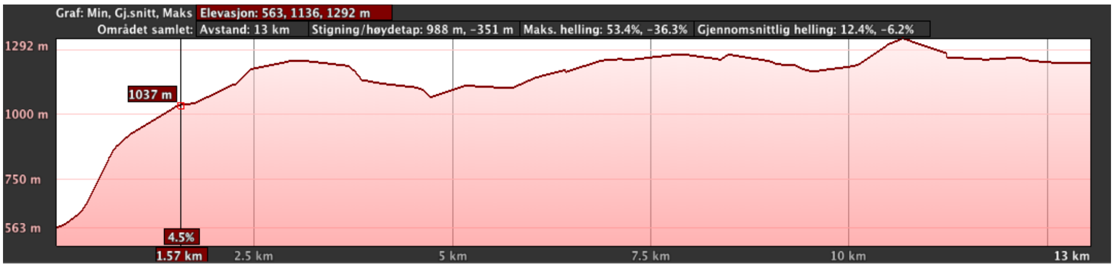

Figure 2.4 Elevation profile (Picture from Google earth)

The rock type of the area consists mainly of granite and amphibolite (red and orange in figure below) with elements of greenstone, volcanic rock (unspecified), basalt, dunite and quartzite. In the area there are fault zones related to some of the smaller lakes with a horizontal alignment.

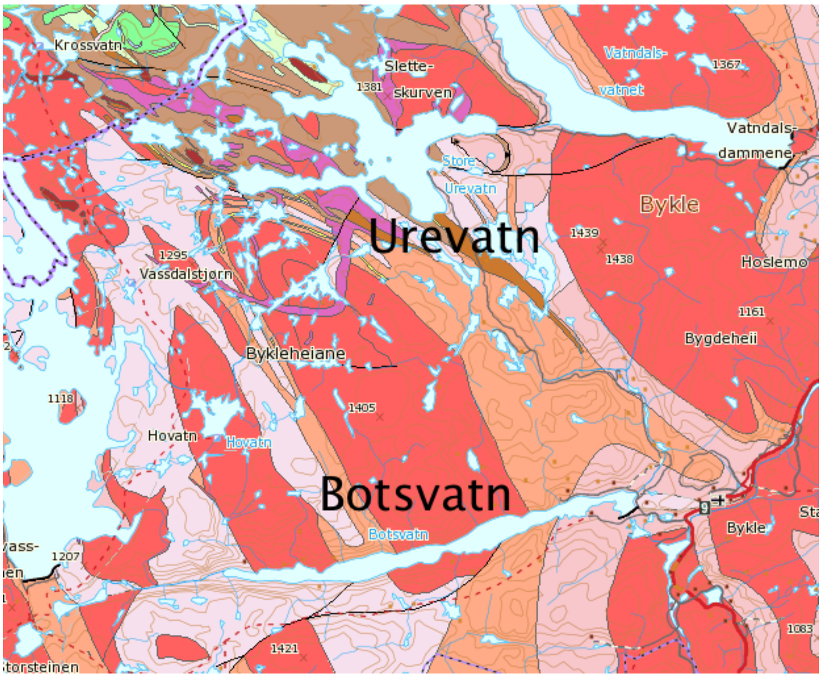

Figure 2.5 Geology of the area (Picture from ngu.no)

In the surrounding area of Botsvatn there are soils, which consist of thin moraine.

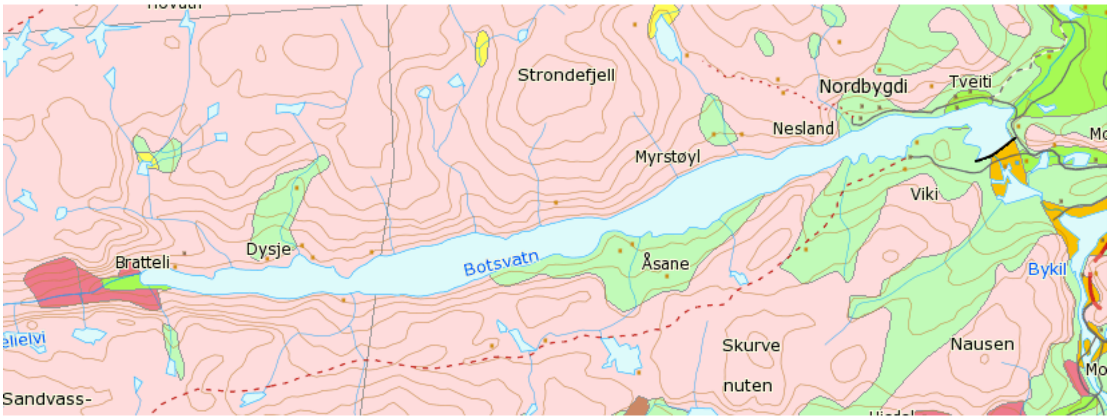

Figure 2.6 Soil around Botsvatn (Picture from ngu.no)

2.5 Hydrology

The data set used for simulations, includes the volume and water level for Urevatn and Botsvatn, so the hydrology is indirectly taken into consideration.

3 PSH technology

3.1 General about PSH

PSH is a well-known technology used in countries all over the world. In the last decade the interest for PSH has increased significantly as the building or planning of unregulated renewable energy sources has increased.

The PSH-plants are balancing the unregulated renewable energy by pumping water from the lower reservoir to the upper reservoir, and producing with water from the upper reservoir down to the lower reservoir.

When there are produced a lot of unregulated renewable energy the electricity price drops, making it less costly to pump water. When there are produced too little unregulated renewable energy there is a demand for energy, making the electricity price increase and making it profitable to produce electricity.

The price difference between the pumping and the production make up the basis of income. Taxes, investment and operation cost also must also be considered.

In Europe, unlike in Norway, the power plant owners can also own a part of the grid. To secure the delivery of electricity to the customers, if there are unregulated renewable energy sources connected to the grid, the owners built PSH-plants for balancing.

The scale of a PSH-plant can vary from a few megawatts to several hundreds of megawatts. The balancing capacity is dependent on the volume of the upper and lower reservoir, and the smallest reservoir is dimensioning.

3.1.1 Turbines and generator

There are two types of turbines used for PSH, a reversible Francis pump-turbine and a separate pump and turbine.

A reversible Francis pump-turbine is both a pump and a turbine. It looks and operates like a standard Francis, but by changing the rotation direction it can be used as a pump. When designing a reversible pump-turbine it is the pump characteristics that are dimensioning, as these are the strictest, including the speed number.

A reversible pump-turbine with a fixed speed number can only operate at one given effect in pump mode, and in production mode the speed number is too high as the reversible pump-turbine is dimensioned as a pump. By installing turbines with variable speed number, it is possible to vary the effect in pump mode, and thereby the flexibility. Also the speed number in production mode can vary, increasing the efficiency up to 8% (NVE, 2011).

If the speed number varies with ±10% then the effect varies with ±30%. So by installing several smaller turbines, rather than a few large, a bigger effect spectre can be reached in pump mode.

The other type of turbine used in PSH is a separate turbine and pump connected to the same shaft. By running the turbine and pump at the same time, creating a hydraulic short-circuit, it is possible to pump at any given effect.

By installing asynchronous motor-generator, it is possible to have turbines larger than 100 MW (NVE, 2011).

3.2 State of the art

One of the most modern and largest PSH projects in Europe is Goldisthal (1060 MW), which has been operating since 2004. Two of four turbines have variable speed number, and was installed with asynchronous motor-generator. This was the first PSH project of this size with that kind of equipment, in Europe.

The reason for several smaller turbines rather than a few big is to increase the flexibility and to secure as much production as possible in case of downtime on one of the turbines.

ALSTOM has developed reversible Francis pump-turbines with an installed capacity of 500 MW and the possibility to utilize heads up to 1200 meter.

4 Getting started

4.1 General assumptions

For planning the PSH-plant in the Upper Otra area, some general assumptions were made.

- The existing operation regime shall not be changed, meaning that the Holen III has priority over the PSH-plant
- The Norwegian electricity prices shall not increase
- The LWRL at 530 masl for Botsvatn during summer shall be kept
- There shall be no new environmental impacts, short term or long term
- Production and pumping shall only be at maximum capacity

The first PSH-plants built in Norway balancing wind power from the North Sea can choose freely the balancing capacity and operation regime. The last PSH-plants would have to balance the rest.

The PSH-plant described in this thesis was assumed to be one of the first and thereby free to choose capacity and, most important, operation regime.

4.2 Dimensioning head and discharge

The head and discharge are varying with the operation regime of a PSH-plant more or less on a daily basis. For calculations purposes one dimensioning head and discharge was necessary. The dimensioning discharge was based on the median discharge calculated, and the dimensioning head is the difference between the HRWL at Urevatn and Botsvatn.

The discharges were found by using the effect formula. The effect was given from the three alternatives and the head difference was found by the daily changes in the reservoir level from the simulated data. As all the data was on a daily basis, the energy produced or pumped is over a 24 hours period. The efficiency was varying for pump mode and turbine mode.

To calculate the total efficiency for pump and turbine mode, it was necessary to decide the efficiency for the generator, transformer, turbine and pump mode. Generator and transformer efficiency was set to 99 %. In turbine mode the efficiency was set to 94 %, and 90 % in pump mode.

The efficiency in pump mode and turbine mode was calculated using the formulas below.

$$\eta_{total,turbine} = \eta_{turbine} \cdot \eta_{generator} \cdot \eta_{transformer}$$

$$\eta_{total,pump} = \eta_{pump} \cdot \eta_{generator} \cdot \eta_{transformer}$$

Equation 4.1 Turbine and pump mode efficiency

$$Q = \frac{E}{H \cdot \eta \cdot g \cdot \gamma \cdot \Delta t}$$

Equation 4.2 Energy formula

	Alternative 1	Alternative 2	Alternative 3
Discharge			
Max	96,9	194,3	291,0
Min	0,0	0,0	0,0
Average	79,8	148,7	210,5
Median	90,4	179,0	266,7

Dimensioning discharge	90,0	179,0	267,0

Dimensioning head	624	624	624

Figure 4.1 Dimensioning head and discharge

4.3 Model

The model was based on daily wind data from the North Sea and the operation regime of Holen III. The simulations were done with data from a six-year period, 2000-2005.

By a weight factor in the model, it was possible to choose how much of the North Sea the PSH-plant should balance. For this thesis the weight factor was set to 100%, which means the model was trying to balance the whole North Sea. This is off course not possible, but the result would be an operation regime with maximum pumping or production most of the time.

For calculating the water level and reservoir volume in the model, reservoir curves were used. The reservoir curve for Urevatn was based on a twelve-year series and for Botsvatn a twenty-eight year series.

The data series for the existing operation regime in Urevatn and Botsvatn were taken from the first model Ånund Killingtveit made.

4.3.1 Energy equivalent

In the model the, the daily pumped energy or produced energy was calculated by an energy equivalent, based on the available volume. When calculating the energy equivalent there are two variables, the efficiency and the head loss. Calculating the efficiency is described above, but to calculate the head loss the discharge was necessary, which was dependent on the energy equivalent. This leads to an error loop, so the head loss was chosen to be 10 meter for all the alternatives.

When the turbine is in pump mode the head loss is added to the gross head, whilst in turbine mode the head loss is subtracted from the gross head. The efficiency also varies with turbine mode and pump mode.

$$e = \frac{\rho \cdot \eta \cdot g \cdot \left(H_g \pm h_f\right)}{3600}$$

Equation 4.3 Energy equivalent

Turbine mode [%]	0,94
Pump mode [%]	0,90
Generator [%]	0,99
Transformer [%]	0,99
Turbine mode efficiency [%]	0,92
Pump mode efficiency [%]	0,88
Gross head [m]	680
Head loss [m]	10
$EEKV_{turbine}$ [kWh/m^3]	1,68
$EEKV_{pump}$ [kWh/m^3]	1,66

Table 4.1 Energy equivalent data

4.3.2 Maximum pumped and produced energy

From the original model there were no limitations in the pumped and produced energy, which resulted in a wide range of variable energy produced or pumped. For this thesis one of the assumptions is that there shall only be maximum pumped or produced energy. To make sure there was only maximum pumped and produced energy, a lower limit in the pumped and produced energy was included in the model. Due to the design of the model, the lower limit was included the available volume used for pumping or production. The maximum volume for production or pumping is the maximum energy divided by the energy equivalent, and the lower limit was 90% of this. Volumes lower than this was considered as zero.

Another challenge with the original model was that the energy equivalent was varying with the head difference between Urevatn and Botsvatn, from the simulated data, on a daily basis. This resulted in pumped energy larger than maximum energy, and produced energy smaller than maximum energy.

Since there would only be maximum pumping and production in this thesis, the energy equivalent was changed secure this. This was done by dividing the maximum energy, for each alternative, with the available daily pumping or production volume.

The result was only exactly maximum produced and pumped energy for all days with operation, but due to the lower limit of 90% there were some days with lower production or pumping than maximum energy. This resulted in maximum production and pumping with too little water, due to an increase in the energy equivalent.

The choice of a lower limit of 90% is describe later in this thesis.

$$V_{lower\ limit} = \frac{E}{EEKV} \cdot 90\%$$

Equation 4.4 Calculation of the lower limit

	Alternative 1	Alternative 2	Alternative 3
Pumping [m3]	6,5	13,0	19,5
Production [m3]	6,4	12,8	19,3

Table 4.2 Lower limit in the volume

The energy equivalent used to calculate the lower limit differs from pumping and production.

$$EEKV = \frac{E}{volume}$$

Equation 4.5 Daily varying EEKV

	Alternative 1	Alternative 2	Alternative 3
Days with too high EEKV during production	17	26	24
Days with too high EEKV during pumping	6	8	20
Of the total [%]	1,1	1,6	2,0

Table 4.3 Days with too high energy equivalent

As can be seen in the table above, the days with too high EEKV is a small part of the total and was considered acceptable.

The maximum energy is 12, 24 and 36 GWh for alternative 1-3.

5 Project components

The general layout would be the same for all alternatives, with some variations in sizes and lengths.

5.1 Tunnel system

5.1.1 Tunnel cross-section

As the tunnel cost is a very large part of the total cost, it was important to find the tunnel cross-section that gives the lowest cost.

5.1.1.1 Method

The method used was based on the cost of head loss, and with a certain cross-section there is a certain head loss. This head loss represents loss of production and can thereby be considered a cost. With a bigger cross-section the head loss is lower, but the excavation cost is higher.

To use this method it was necessary to find the yearly operation time, choose a discount factor and a price for the electricity, and find the head loss for any given cross section.

5.1.1.2 Operation time

Since the energy produced and pumped was only at maximum, the yearly operation time was found by counting the hours when the PSH-plant was producing and pumping.

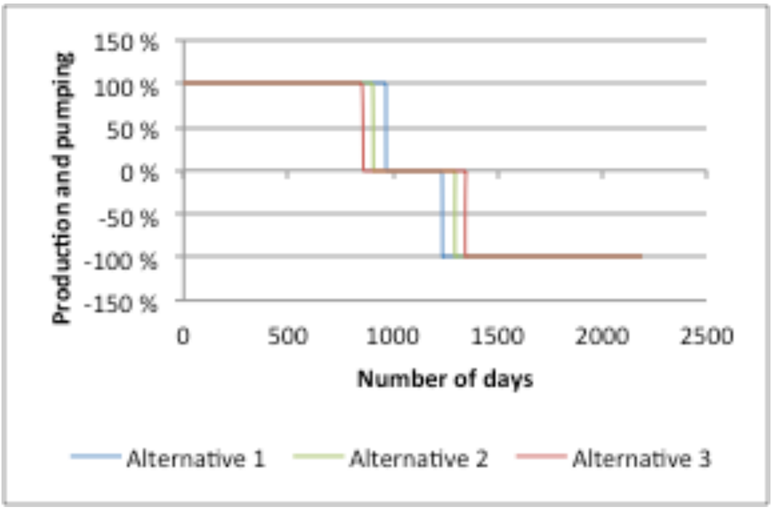

Figure 5.1 Relative production distribution

5.1.1.3 Electricity price and discount factor

Electricity price

When selecting the electricity price, it's the expected future electricity price that is chosen. This is of course difficult to predict, but a comparison with the value calculated in the income estimate was done to evaluate how realistic the chosen value was.

The chosen value was 0,45 kr/kWh. Compared with Norwegian prices this is a bit high, but compared with the future European marked depended on balancing power it seems reasonable.

Discount factor

To calculate the discount factor the interest was set to 4,5% over a 40 year period.

$$DF = \frac{(1+r)^n - 1}{r(1+r)^n}$$

Equation 5.1 Discount factor

If increasing the number of years over 40, the impact on the discount factor is minimal. The operation time for a hydropower plant could be as much as 100 years, so using NPV doesn't necessary gives the right answer, but it's the standard method.

5.1.1.4 Head loss

Manning's formula was used to find the friction loss. For standard horseshoe profile, R = 0,265√A (Guttormsen, 06).

$$h_f = \frac{Q^2\ L}{M^2\ A^2\ R^{4/3}}$$

Equation 5.2 Head loss

Singular loses was neglected in this thesis, as the head loss from the tunnel would dominate.

5.1.1.5 Results

The discount factor was found to be 18,4 for all alternatives.

	Alternative 1	Alternative 2	Alternative 3
Operation time [hours]	7700	7200	6800
Cross section [m2]	90	150	210
Diameter [m]	11	14	16
Velocity [m/s]	1,0	1,2	1,3

Table 5.1 Results cross-section

The velocities in the table above are relatively low, but are within a reasonable range.

Following the method describe above there was one cross-section with the lowest cost for each alternative. In the graph below the total cost of the tunnel and head loss were summarized. For each alternative there was a segment at the bottom of each curve where the total cost was more or less the same for several different cross-sections. This gives some flexibility in choosing a certain cross-section within the same price range.

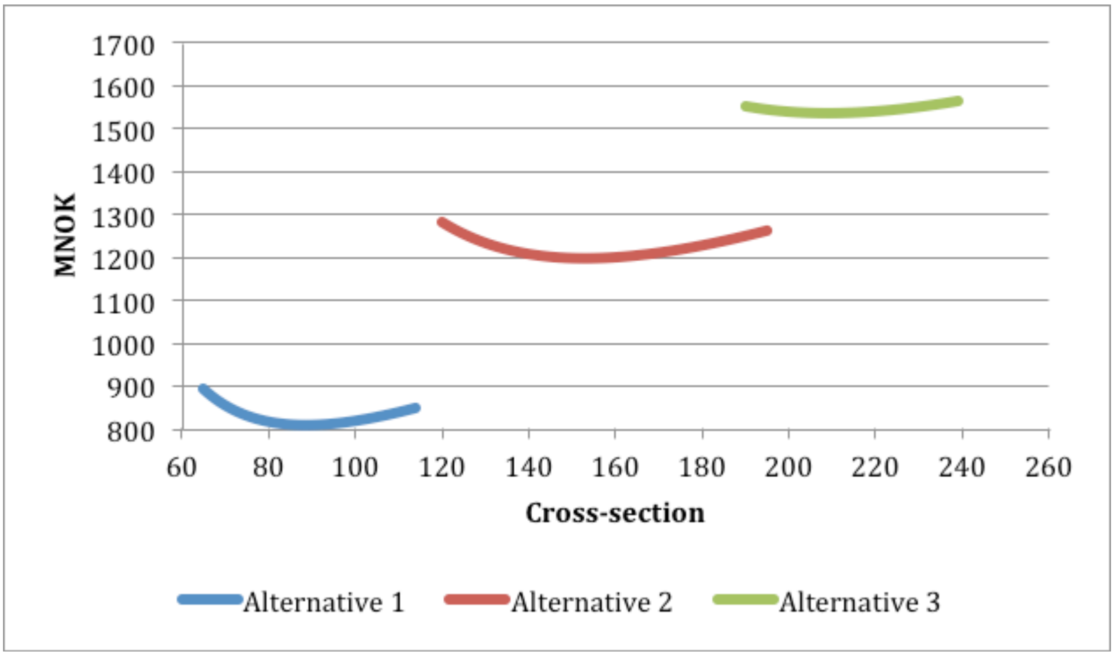

Figure 5.2 Total cost of cross-sections

For total cost and lowest costly cross-section for all alternatives, see appendix P1.

5.1.2 Construction method

There are two ways to excavate a tunnel, either by drill-and-blast or by Tunnel Boring Machine (TBM). A TBM hasn't been used in Norway, for hydropower purposes, since 1994, but since then there has only a few projects where a TBM were an alternative. In the newest edition of NVE's Cost Estimate, the cost estimate for using a TBM was left out, due to lack of data.

To find the cost and advance rate for drill-and-blast and TBM, an estimate was done (Bruland, 1998 and Zare, 2007). This estimate, even with several uncertainties and assumptions, was assumed to be more accurate than using the former edition of NVE's Cost Estimate where the cost of TBM was included.

In table the table below the smallest diameters are over ten meter, and in the estimate the maximum diameter for a TBM was 9 meter and the maximum length for a tunnel was 7 km, so these values was used for both TBM and drill-and-blast.

To do calculations with diameters larger than 9 meter, extrapolation could be done, but this would give very inaccurate answers. Therefore it was assumed that the result from this estimate applies for all the alternatives.

	Drill-and-blast	TBM
Cost [kr/m]	12200	13900
Advance rate [m]	65	140

Table 5.2 Cost and advance rate for TBM and drill-and-blast

The cost estimate shows that drill-and-blast is less expensive than TBM, per excavated meter. In the estimate the price for TBM is at year 1999-level and drill-and-blast is at year 2005-level. What the actual cost for each excavation method is to day was not found, but was assumed that the price level is more or less the same as in the calculations (see appendix P8 for details).

Based on the cost drill-and-blast is the preferred excavation method. If the advance rate is more important than the cost, then TBM is the preferred alternative.

5.1.2.1 Other reasons for choosing drill-and-blast

The dominating rock in the area is amphibolite, so a hard rock TBM would be used. The largest hard rock TBM ever manufactured was 14,4 meter in diameter (Robbins TBM). The results from the table above shows that alternative 1 and 2 are smaller than 14,4 meter, but alternative 3 are larger.

A TBM cannot be operated downhill, so drill-and-blast must be used to excavate the access tunnel and the tailrace tunnel. Drill-and-blast must also be used on the last part of the tunnel to be able to use a lake tap.

There is long experience and tradition with the use of drill-and-blast in Norway, and the flexibility is much better compared to a TBM. As a TBM has not been used in Norway for the last 18 years is a good indicator that drill-and-blast is the less costly and most preferred excavation method for Norwegian conditions.

5.1.3 Alignment

The tunnel alignment was planned to have an even elevation from the powerhouse cavern to Urevatn. This gives an elevation gradient of approximately 3,5 % (see appendix P2). Before entering Urevatn the tunnel should be excavated under land and not under the lake to avoid the possibility of leakage. Also a gate would be built and an entrance tunnel close to the intake, which would be easier to excavate if there was only land above the last part of the tunnel.

By placing the new tunnel to the west of the existing tunnel, the new tunnel would not be excavated under the existing tunnel, avoiding potential problems. The distance between the existing tunnel and the new tunnel is about 80 meter, which must to be taken into consideration during excavation to avoid interference.

With this kind of tunnel alignment, placing the powerhouse cavern, access tunnel and main tunnel would be much more flexible. The tunnel would also be shorter compared a horizontal tunnel and pressure shaft, and thereby less costly. The combination with drill-and-blast and an even elevating tunnel makes the excavation very flexible if problems should appear.

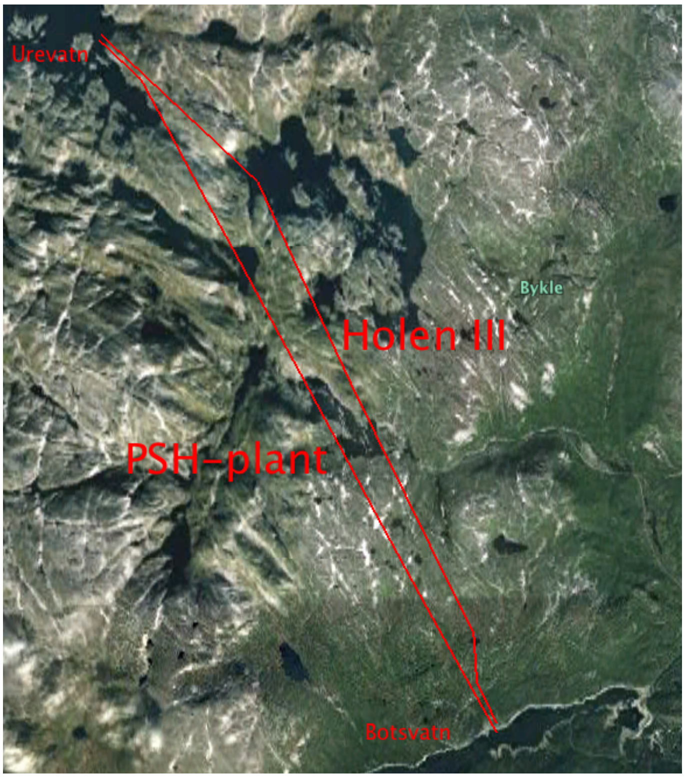

Figure 5.3 Tunnel alignment Holen III and PSH-plant (Google earth)

5.1.4 Inlet and outlet

The inlet and outlet would be placed approximately 80 meter west of the existing inlet and outlet, which should be sufficient to avoid interference.

To avoid interference with the existing operation regime, draining the lakes down to LWRL or lower must be avoided. This means that the inlet and outlet cannot be excavated from the outside, but instead excavated using a lake tap. A gate is necessary to prevent the water from coming into the tunnel, if using a lake tap, but also for later inspection of the tunnel. For inspections in as much of the tunnel as possible, the gates should be installed as close to the inlet and outlet as possible. Ideally, the gates would be placed just behind the inlet and outlet, but due to the topography of the area it would be placed 100 meters behind the inlet and 100 behind the outlet.

If the lake taps are too big to excavate using a lake tap, it is possible to apply to NVE for lowering the lakes beneath LRWL, preferably when the lakes are already at a natural LRWL, to excavate with drill-and-blast. A rock trap just beneath the lake tap is also necessary for the blasted rock to deposit.

The inlet and outlet would be placed just beneath the LRWL. Due to low velocity and retardation in the waterway, air would not be dragged into the tunnel if the water level were close to LRWL.

5.1.5 Sand trap

A sand trap must be installed before the transition between the tunnel and the cone going into the powerhouse cavern. To be able to accumulate rocks mass, the cross-section must to be widened reducing the water velocity in the tunnel. The standard procedure is to reduce the water velocity in the tunnel by 30-50 % (Guttormsen, 06).

5.1.6 Air cushion

The air cushion has two purposes. One is to dampen the fluctuations in the tunnel system when there is a change in the amount of discharge through the turbine. The other is to supply the turbine with enough water, due to retardation in the water. The longer the tunnel, the longer time to accelerate the water and the bigger air cushion needed.

To find out if an air cushion was actually necessary the equation below was used (Guttormsen, 06).

$$T_a = \frac{Q_o}{gH_o} \sum \left(\frac{l}{a}\right)$$

$$T_a \leq 1\ sec$$

Equation 5.3 Time constant

As the wind data used in the simulation operates on a daily basis, there were no rapid daily starts or stops, which mean that the main purpose of the air cushion is to supply enough water for the turbine due to retardation.

To find the necessary volume the equation below was used (Guttormsen, 06).

$$A_{min} \approx 0{,}0125 \frac{M^2 a^{\frac{5}{3}}}{H_o}$$

$$V \approx 1{,}4 h_{po} A_{min}$$

Equation 5.4 Necessary air cushion volume

	Alternative 1	Alternative 2	Alternative 3
Ta [sec]	2,0	2,3	2,5
Air cushion [m^3]	42000	102000	172000

Table 5.3 Air cushion data

5.1.7 Access tunnel and powerhouse cavern

The entrance of the access tunnel would be located next to the entrance of the existing access tunnel, 563 meter above sea level. The cross-section of the access tunnel was chosen to be 60 m^2.

The placement of the powerhouse cavern is dependent on enough overburden, the submerged turbine and that the access tunnel is not steeper than 1:7.

The asynchronous motor-generator is physically larger than a standard generator, but the exact size was unknown so it was not taken into consideration.

5.1.7.1 *Overburden*

The water pressure is at the highest where the tunnel enters the powerhouse cavern. For the rock mass to withstand the water pressure it is necessary with sufficient overburden, H. (Guttormsen, 06).

$$H > \frac{\gamma_w \, h}{y_r \cos \alpha}$$

Equation 5.5 Overburden

An elevation profile of the mountain was made with data from the elevation profile (see appendix P2) made in Google Earth. An elevation gradient was made between the access tunnel entrance and a chosen point on the elevation profile to the find sufficient overburden.

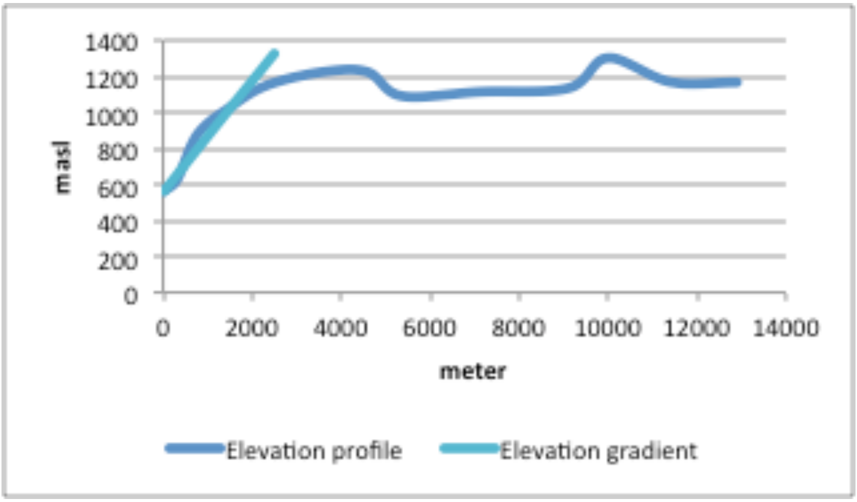

Figure 5.4 Elevation gradient for sufficient overburden

	Alternative 1	Alternative 2	Alternative 3
Access tunnel length [m]	1100	1000	1000
Powerhouse cavern [masl]	410	420	420
Powerhouse cavern [m^3]	51000	86000	117000
Necessary overburden [m]	230	230	230
Actual overburden [m]	480	460	460

Table 5.4 Access tunnel, powerhouse cavern and overburden

5.2 Turbine

5.2.1 Choice of turbine

The two most used turbines for PSH are reversible Francis pump-turbine and a separate turbine and pump attached to the same axis. If using a separate turbine and pump the goal is to have full flexibility in pump mode, to pump at any given capacity.

In this thesis there was only production or pumping at maximum capacity, meaning that full flexibility is unnecessary. For all the alternatives reversible Francis pump-turbines was used.

5.2.2 Energy or effect optimization

If the turbine is producing at full capacity, there is a higher effect production, but more water is used due to a lower efficiency, compared to a turbine producing with the highest efficiency. So if there is production at maximum capacity over several days, much water is lost.

If the turbine is producing at the highest efficiency, there is unused production potential, which gives an extra cost for a bigger turbine, and equipment.

So the essence of this optimization is; for how many days in row with maximum production before the cost of a bigger turbine and equipment pays off.

Such an optimization would be considered if frequency balancing were out of the question.

5.2.2.1 *Frequency balancing*

A PSH-plant is not only used for balancing purposes, but can also be used for frequency balancing. A Francis turbine can easily adjust the discharge, and thereby the frequency, and to do so the turbine cannot be producing at maximum effect.

Having the possibility to offer frequency balancing is common for most PSH-plants around the world. So if a PSH-plant is to be constructed in Norway, it is reasonable to assume that it would be capable of providing frequency balancing.

So based on the assumption of providing frequency balancing, the PSH-plant would be producing at the highest efficiency. This extra capacity could also be used for production and pumping purposes as backup or if the electricity price is beneficial.

The additional cost for a bigger turbine and equipment would be small compared to the total cost, and it was assumed that it pays off in the long run.

The additional installed effect was not used in the simulations, only in the cost estimate.

5.2.2.2 *Challenge with frequency balancing*

If the PSH-plant were to offer frequency balancing to the Norwegian marked, there would be no problems if the PSH-plant were a part of the Norwegian grid. If the PSH-plant were to offer frequency balancing to the European marked, there would be two problems.

First, the frequency in Norway can vary ±0,1 Hz, but in Germany the frequency can only vary ±0,01 Hz. Second, the electricity going through the cable bound for Europe, would be changed from AC to DC before entering the cable, and then back to AC again before entering the European grid.

5.2.3 Submerging

When submerging a reversible turbine, it's the pump characteristics that is dimensioning. The submerging is to avoid cavitation on the runner blades, and the result is how low beneath LRWL the turbine must to be placed. Standard submerging is 70-100 meter (Storli).

The variables a and b were chosen from the table below (Brekke, 2003).

Parameter	Turbines	Pumps
a	$1{,}05 < a < 1{,}15$	$1{,}6 < a < 2{,}0$
b	$0{,}05 < b < 0{,}15$	$0{,}2 < b < 0{,}25$

Table 5.5 Experience data for parameters a and b when calculating NPSH

The barometric pressure, h_b, is normally 10,3 meter at sea level and is decreasing with 0,12 meter for every 100 meter above sea level. The vapour pressure, h_{vp}, is 0,125 meter with a water temperature of 10°C. (Brekke, 2003). The peripheral velocity, u_1, is chosen to be at maximum, 55 m/s.

The necessary submerging is found from the Net Positive Suction Head$_{req}$, NPSH$_{req}$ (Brekke, 2003).

The number of pole pairs was changed to find the necessary submerging level, which was set to be approximate in the middle of the standard submerging level.

$$n = \frac{50 \cdot 60}{polepairs}$$

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

$$u = \omega \frac{D}{2}$$

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

$$NPSH = a\frac{c_{1m}^2}{2g} + b\frac{u^2}{2g}$$

$$H_s = h_{vp} - h_b - NPSH$$

Equation 5.6 Necessary submerging

The results can be seen in the table below.

	Alternative 1	Alternative 2	Alternative 3
Pole pairs [number]	7	10	12
Speed number [RPM]	429	300	250
Hs [m]	-80	-85	-80

Table 5.6 Results from necessary submerging

5.2.4 Number and capacity of the turbines

The maximum capacity of a turbine is 500 MW, and there was minimum two turbines installed for each alternative. This is to secure some production if one turbine is out of service.

The additional installed effect for frequency balancing was set to 10% of the chosen effect used in the model.

	Alternative 1	Alternative 2	Alternative 3
Capacity [MW]	500	1000	1500
Cost-dimensioning capacity [MW]	550	1100	1650
Number of turbines	2	3	4
Capacity of turbines [MW]	275	367	413

Table 5.7 Number and size of turbines

6 Cost and income estimates

6.1 Cost estimate

The cost estimates were based on NVE Cost Estimate, and if there were uncertainties, assumptions were made. Operation cost was not taken into consideration in the calculations.

6.1.1 Cost of reversible Francis pump-turbine

In NVE's Cost Estimate the price for a reversible Francis pump-turbine is 25% more expensive than a traditional Francis turbine.

Usually the producer gives a discount if more than one turbine is bought. This discount varies with size, number of turbines and the given marked. Due to the uncertainties of the discount, it is set to zero.

6.1.2 Generator cost

The cost of an asynchronous motor-generator was not found for this thesis, but was set to 25% more expensive than the price given in NVE's Cost Estimate

6.1.3 Cable

Today Norway is connected to Europe through several cables, but these cables are already operating at maximum capacity. So new cables must be built if PSH was to be realized in Norway.

Statnett, which is controlled by the government, is the owner and operator of the Norwegian grid, included the overseas cables. In Norway private companies cannot own and operate a part of the grid, meaning that Statnett must be a part of the overall planning of PSH, and would also pay for the overseas cable.

6.1.3.1 Cost of cable

The NORD.LINK-cable (Statnett, 2010) was a feasibility study finished in 2008, where the cable was planned to go between Norway and Germany. As Germany is the initiative taker and a major investor in wind power in the North Sea, a cable from Norway would probably to go to Germany.

To be able to estimate the cost of a cable, the calculations are based on the NORD.LINK-cable.

For comparison other cables was included in the table below (Wikipedia, NorNed, BritNed, Cross-Skagerrak 4).

Cable name	Length [km]	Effect [MW]	Type of current	Operation year	Cost [MNOK]
NORD.LINK	600	1400	HVDC	2017	12000
NorNed	580	700	HVDC	2008	5065
BritNed	260	1000	HVDC	2011	4635
Cross-Skagerrak 4	240	700	VSC	2014	3000

Table 6.1 Cost of cable

6.1.4 Results

	Alternative 1	Alternative 2	Alternative 3
Civil works [MNOK]	850	1200	1550
Electrical [MNOK]	750	1400	1950
Mechanical [MNOK]	350	550	750
Total [MNOK]	1950	3150	4250
Cable [MNOK]	4300	8600	12900

Table 6.2 Cost estimate

In table above uncertainties, planning and administration and cost during construction is not included.

6.2 Income estimates

There were too many uncertainties related with an income estimate, so the goal was simple to put the values in perspective.

The variables for the income estimate were the same variables as for the cross-sections, and the tax rate was a chosen value.

Tax	30%
Years	40
Interest	4,5%
Discount factor	18,4

Table 6.3 Variables used for the income estimate

In traditional hydropower, when calculating the income, it's the expected future electricity price level that decides if or how feasible the project is. The further into the future the power plant would be operating, the more difficult it is to predict the electricity price.

When planning PSH, predicting the future electricity price is very difficult as the marked is unfamiliar. One way to avoid this prediction, but still get reasonable answers is to find the price of production that gives zero NPV. This approach includes the prediction of the electricity price during pumping, and the cable cost. The price of pumping varies with how much excess wind power produced, but the price was assumed to be 0,1 kr/kWh.

Results from income estimate can be seen in the table below.

	Alternative 1	Alternative 2	Alternative 3
Minimum price [kr/kWh]	0,4	0,4	0,4
Price difference [kr/kWh]	0,3	0,3	0,3

Table 6.4 Results from income estimate

The cable price was approximate two times the price of the PSH-plant, making the price difference much higher than without the cable. As Statnett would pay for the cable they must naturally make money of it. By including the cable price in the income estimate, the price difference indicates what kind of price range the project would be in when all the participants were included.

There would be one cable for each PSH-plant, meaning that the cable can only be used for PSH purposes, except the few days without operation. So for Statnett to get their invested money back, the owner of the PSH-plant would have to pay some kind of rental fee, resulting in a necessarily higher price difference.

7 Environmental impacts

7.1 Fish

Acidification in Urevatn has led to the extinction of trout, and since the 1980s farmed trout and brook trout has been released. The trout has not been able to reproduce itself, but so has the brook trout (LFI, 03).

In all the lakes in the project area minnows are present, except for Urevatn. The minnow is competing with the trout and brook trout over the same livelihood, so an introduction of minnows in Urevatn would decrease the population of trout and brook trout. Building PSH between Urevatn and Botsvatn, it was reasonable to assume that minnows would be introduced in Urevatn.

7.2 Ice

In traditional Norwegian operated reservoirs, the lakes are frozen when close to HRWL, and through the winter the water level drops and so do the ice. This can lead to unsafe ice near land and the presence of surface water.

What would happen to the ice if PSH were introduced to Norwegian reservoirs is dependent on the height above sea level, size and shape of the reservoir, existing hydropower plants operation regime and many other factors. What is reasonable to assume is that the ice would form later and disappear earlier, there would be open water close to intake and outlet, and in general the ice would be weaker. Also, the water would be colder at the top and warmer at the bottom of the lakes during summer, and vice versa during winter, due to constant mixing of the water.

As Urevatn is located approximate 600 meter above Botsvatn, the ice would be in general better quality in Urevatn than Botsvatn.

7.3 Reindeer

In the area surrounding Urevatn and Botsvatn, called Setesdal and Ryfylke, there are a population of wild reindeers, which are protected by law (Wikipedia, Reindeer).

Except for the fluctuations in the reservoirs, no other physical impacts on the nature would be done that could affect the reindeers, with the introduction of PSH. The only challenge regarding reindeers, if PSH was introduced, is whether or not weaker ice on Urevatn would be a problem.

Mapping the movement of reindeers in the area was done by NINA, but whether the reindeers use the ice actively or not was not clearly stated.

So, if the reindeers uses the ice cover actively then mitigation measures has to be done to keep the ice on the lakes intact, and these mitigation measures would be restrictions in the operation regime. To secure the ice to form, long periods of total stop in the PSH-plant would be necessary, and to avoid the ice of break up, there must also be restrictions in the fluctuations during the whole winter.

As long as these restrictions were taken into consideration when dimensioning the PSH-plant, it would be possible to have a profitable project, but the capacity would most likely be much smaller than studied in this thesis.

Assuming that the reindeers were not using the frozen lakes actively, which seems more reasonable, as the quality of the ice in traditionally operated reservoirs is often poor, then there would be no problems regarding ice and reindeer.

7.4 Soils around Botsvatn

As the reservoir is emptied there are still a pore pressure inside the soils around Botsvatn, which take some time to drain. If the emptying of the reservoir was done slow enough so the pore pressure is drained simultaneously, then there would be no problems. If the emptying of the reservoir is done much faster than the pore pressure can be drained, then settlements can occur in the soils, leading to landslides.

For all the alternatives there would be rapid changes on more or less a daily basis. To ensure that there would be no problems regarding the soils, a geological survey should be carried out.

7.5 Excavated rock mass

The excavated rock mass can be used e.g. in road construction, fill mass for construction purposes or be dumped at a designated location.

The excavated rock mass from Holen I-II and II was either placed at different dumps in the area or placed in the reservoirs. Some of the dumps are still available, but most likely new ones would be established if no other solutions were found.

The amount of excavated rock mass can be seen in table below, where all the figures are in million cubic.

	Alternative 1	Alternative 2	Alternative 3
Tunnel	1,1	1,9	2,6
Other	0,2	0,2	0,3
Total	1,3	2,1	2,9

Table 7.1 Excavated rock mass

8 Fluctuations in the reservoirs and efficiency

During summer the LRWL is increased to 530 masl in Botsvatn due to the cabin owners in the area, but if a PSH-plant were built, daily fluctuations would be regularly, also during summer. So to what degree daily fluctuations are acceptable is not known. So there were no limitations in the fluctuation level in this thesis.

8.1 Fluctuations in general

As the wind data was on a daily basis, so were the fluctuations. Included in the model was a limitation keeping the water level from going below 530 masl during the summer months. The summer period is from first of May to thirty-first of August.

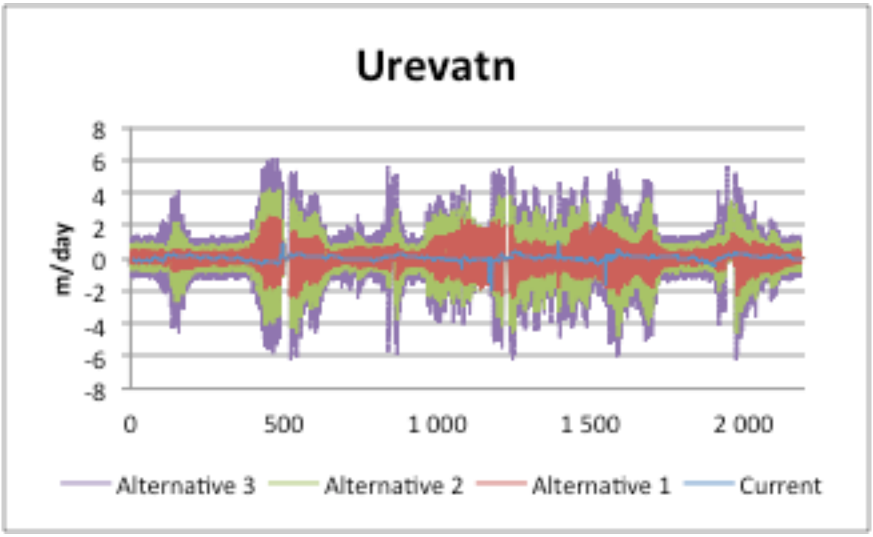

Figure 8.1 Fluctuations in Urevatn for the alternatives and Holen III

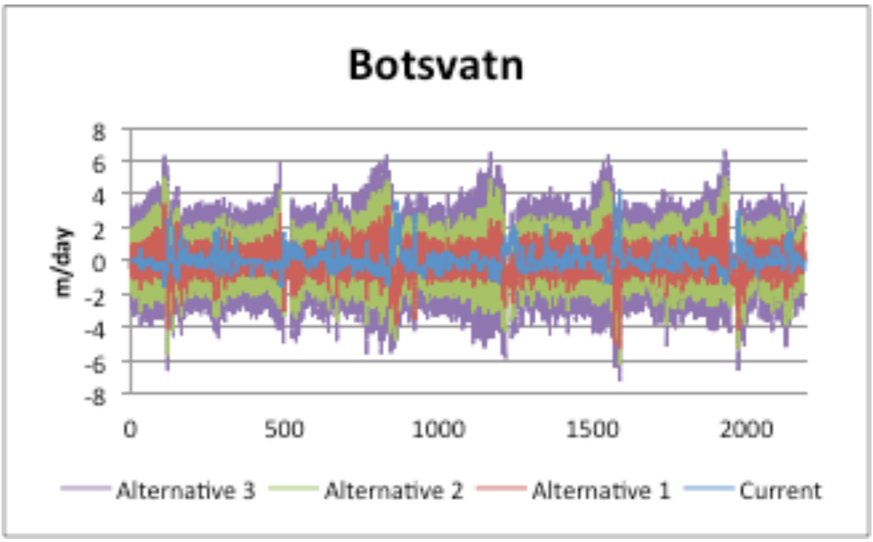

Figure 8.2 Fluctuations in Botsvatn for the alternatives and Holen III

From figure 8.1 and 8.2 the trend shows that a bigger capacity leads to bigger daily fluctuations. The “holes” in data set is during summer when the water level in Botsvatn was too low for pumping, resulting in low fluctuations in Urevatn as well.

In more general terms, if there were limitations in the operation regime, the result would be less flexibility to pump or produce. For the PSH-plant to start operating again, when too little water in Botsvatn, Holen III must produce or precipitation or inflow must fill up Botsvatn.

By sorting the fluctuations into intervals and by alternatives, it is possible to see how often each interval occurs. Zero production or pumping was not included.

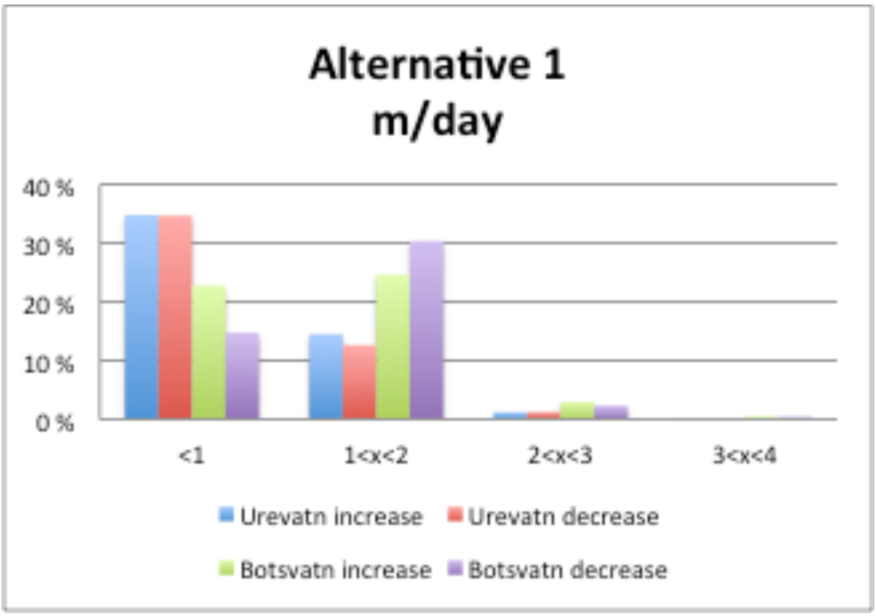

Figure 8.3 Fluctuations for alternative 1

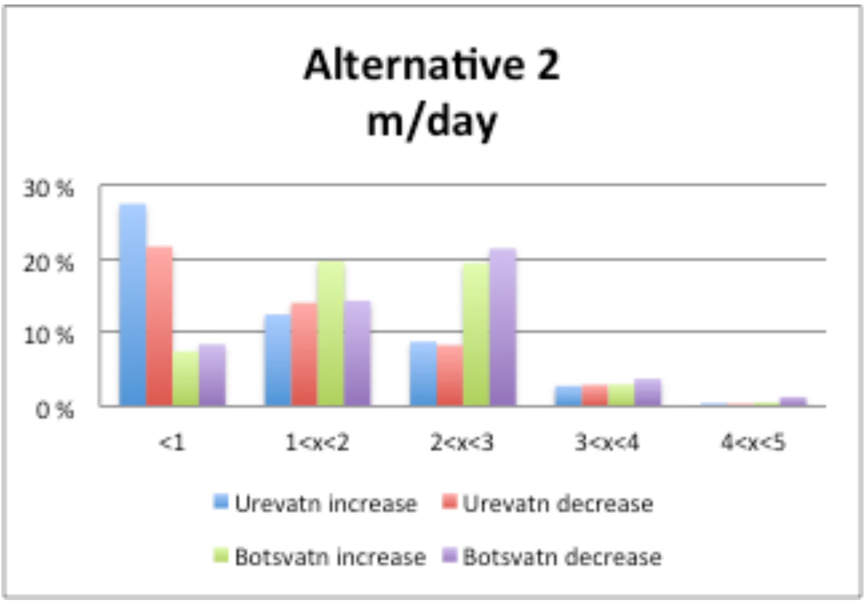

Figure 8.4 Fluctuations for alternative 2

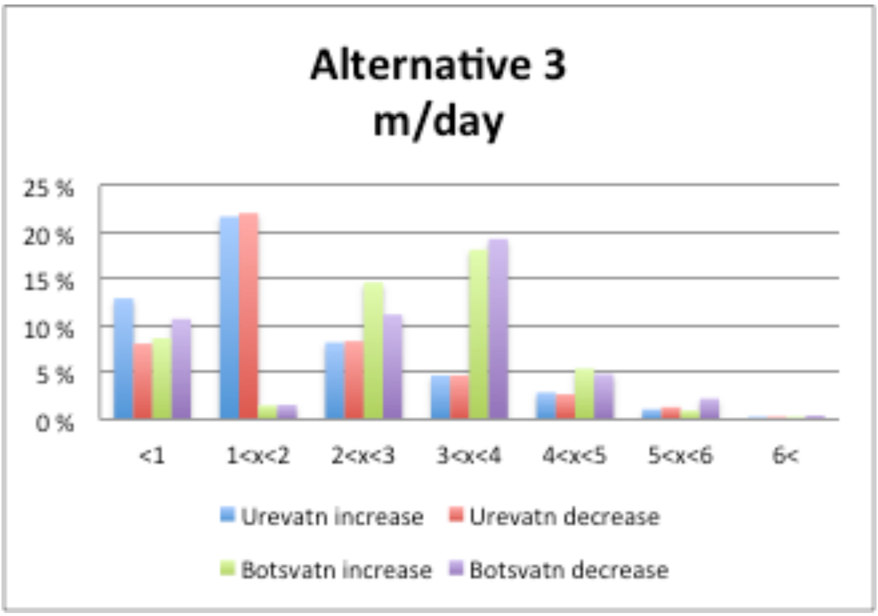

Figure 8.5 Fluctuations for alternative 3

Figure 8.3 to 8.5 shows that a larger installation leads to more occurring larger fluctuations, but also larger fluctuation occurring more often in Botsvatn than in Urevatn.

	Alternative 1	Alternative 2	Alternative 3
Production [days]	966	905	857
Pumping [days]	955	895	846
No activity [days]	271	392	489

Table 8.1 Number of days with pumping or production

In the table above shows the total number of days of either production, pumping or no activity. With a bigger installation the number of days with zero activity increases. The reason for this is fewer days with enough water available for production or pumping. This results in large drops in the reservoirs when there was enough water.

8.1.1 Number of days in a row

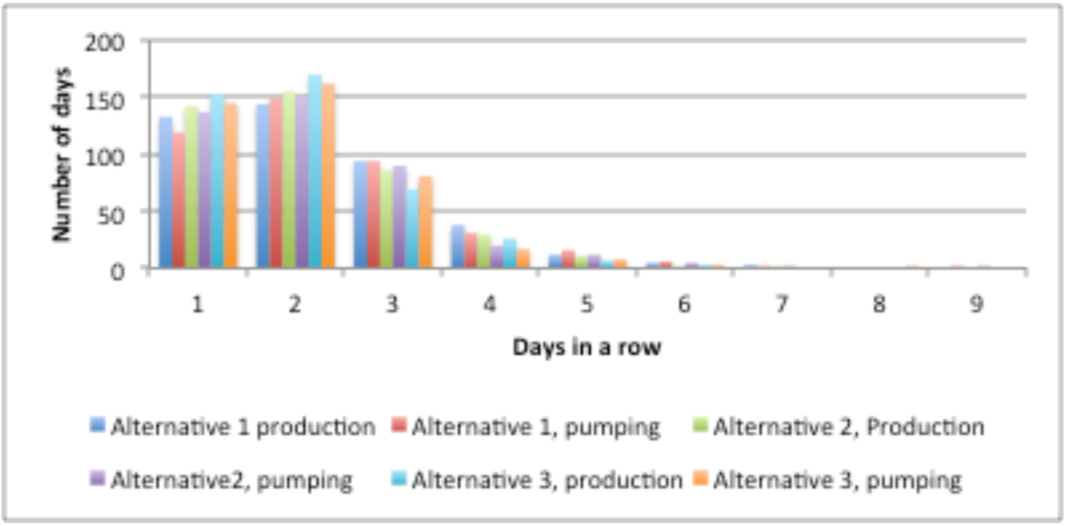

Figure 8.6 Days in a row with pumping or production

The figure above shows the number of days in a row of either production or pumping. Regardless of the alternatives, the number of days in a row is fairly stable.

8.2 Fluctuations during summer

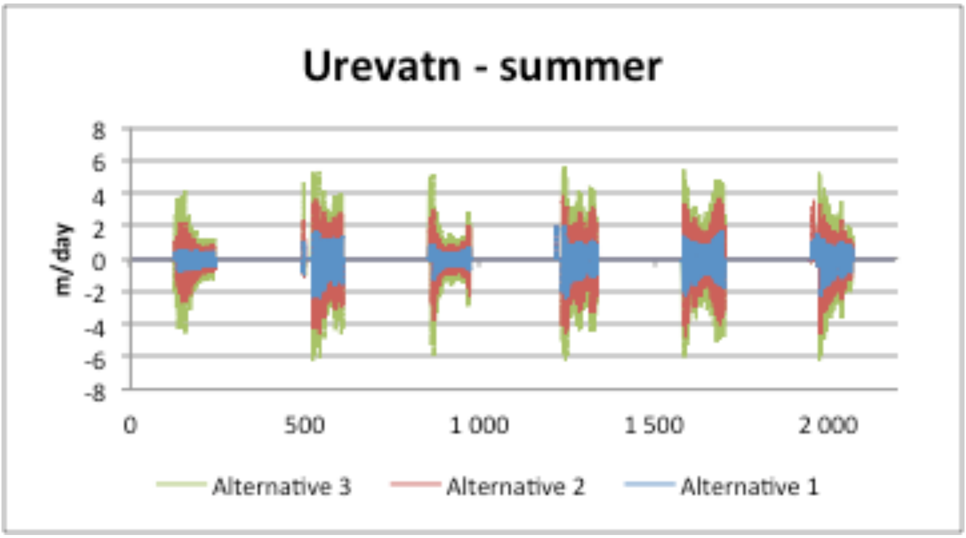

Figure 8.7 Fluctuations in Urevatn during summer

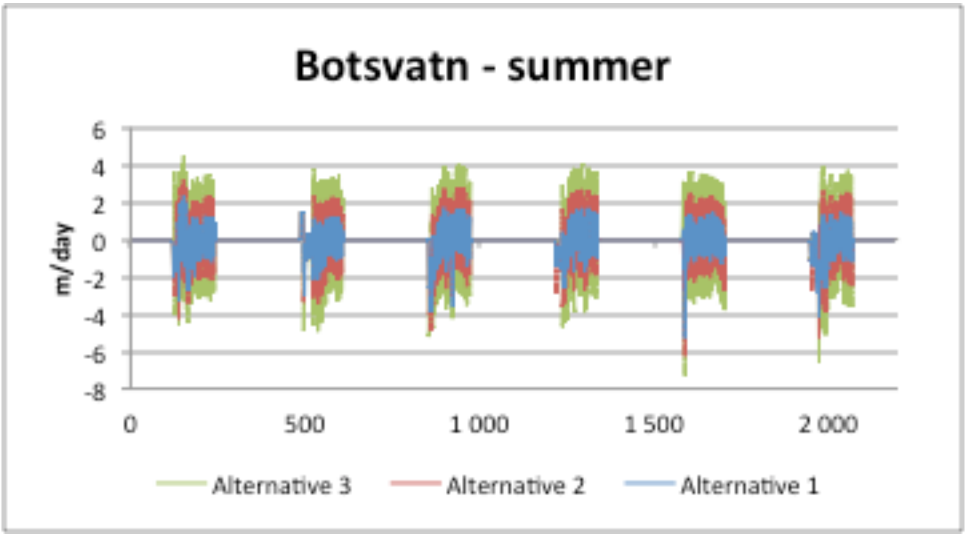

Figure 8.8 Fluctuations in Botsvatn during summer

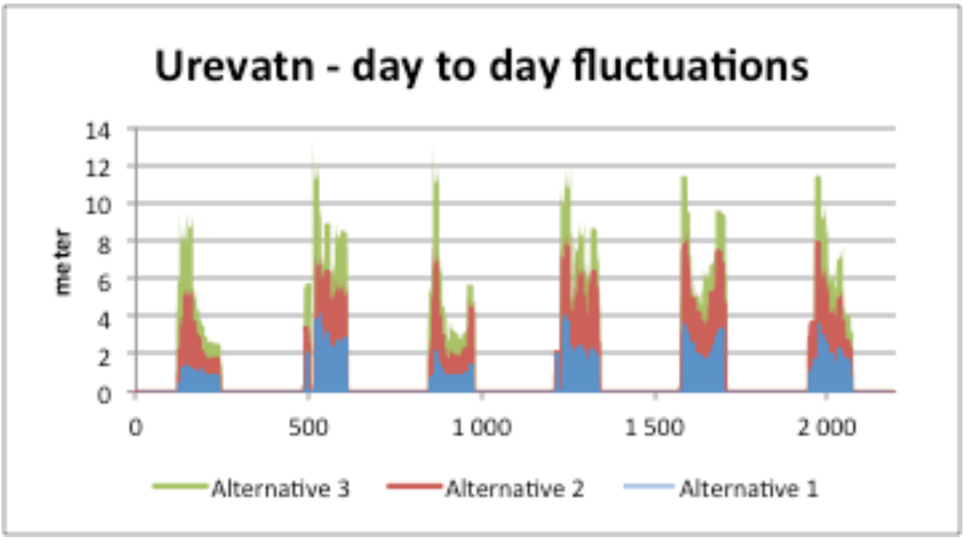

Figure 8.9 Urevatn day-to-day fluctuations

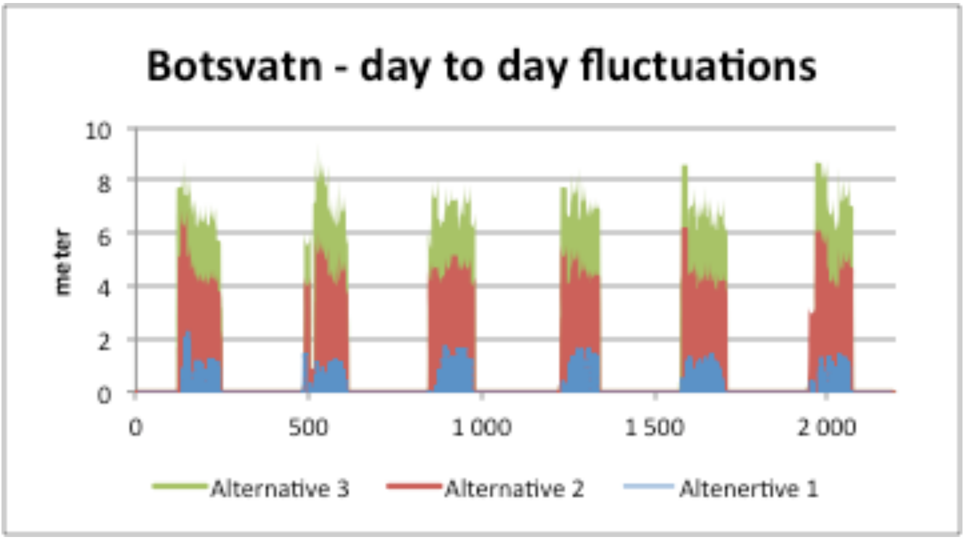

Figure 8.10 Botsvatn day-to-day fluctuations

Day-to-day fluctuations mean the height difference from one day of production to the day after with pumping, or vice versa. From figure 8.9 and 8.10 the trend is a bigger day-to-day fluctuation with a larger installation.

Urevatn	Alternative 1	Alternative 2	Alternative 3
Maximum [m/day]	2	4	6
Minimum [m/day]	-2	-5	-6
-1< and <1 [m/day]	65 %	36 %	29 %
-2< and <2 [m/day]	97 %	66 %	52 %
Maximum day to day fluctuation [m/day]	4	8	11

Table 8.2 Fluctuations data during summer in Urevatn

Botsvatn	Alternative 1	Alternative 2	Alternative 3
Maximum [m/day]	2	3	4
Minimum [m/day]	-5	-6	-7
-1< and <1 [m/day]	60 %	20 %	25 %
-2< and <2 [m/day]	95 %	65 %	30 %
Maximum day to day fluctuation [m/day]	4	6	9

Table 8.3 Fluctuations data during summer in Botsvatn

The percentages in table 8.2 and 8.3 includes days during summer when there were no production. With a bigger installation larger fluctuations occurs, and occurring more often as well.

8.3 Efficiency

If the PSH-plant is pumping Brokke is losing head, but Holen I-II and III would be gaining head. If the PSH-plant is producing it was vice versa.

To find out whether there was loss of head or gaining of head, the head difference between Urevatn and Botsvatn for the three alternatives and Holen III was found.

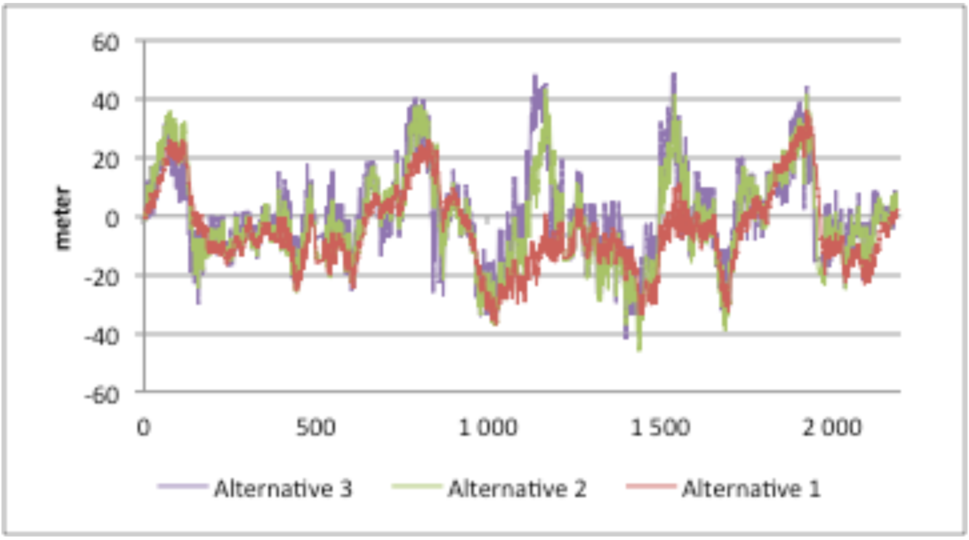

Figure 8.11 Head difference between the alternatives and Holen III

In the figure below is the head difference in percentage for the three alternatives and Holen III.

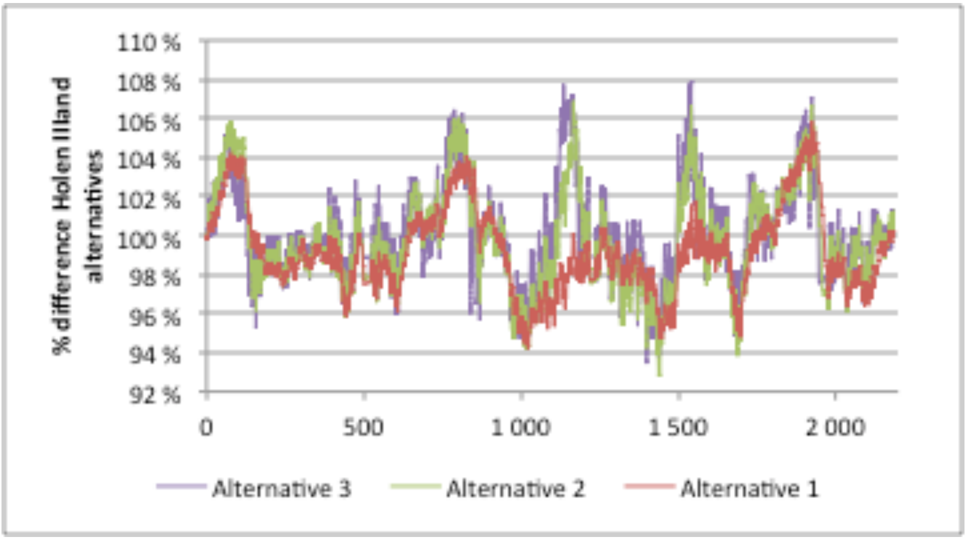

Figure 8.12 Percentage head difference

	Alternative 1	Alternative 2	Alternative 3
Maximum head difference [m]	36	43	49
Minimum head difference [m]	-37	-46	-42
Average head difference [m]	-5	-2	0
Maximum head difference [%]	105,8 %	106,9 %	107,9 %
Minimum head difference [%]	94,2 %	92,8 %	93,4 %
Average head difference [%]	99,2 %	99,8 %	100,1 %

Table 8.4 Data from head difference

For alternative 1 and 2 there is a decrease in the total head for Holen III, but for alternative 3 there is an increase in the total head.

For Holen I-II it was assumed a similar situation, but the decreased head for Holen III is increased head for Brokke.

Since the average head difference is lower for alternative 1 and 2, an increased discharge would be the result if the production for Holen III were to be the same. For alternative 3, a decreased discharge would be necessary to have the same production.

In both cases the efficiency would be lower, if maintaining the current production level.

9 Operation regime

These assumptions are relevant for the operation regime

- The Norwegian electricity prices shall not increase
- The existing operation regime shall not be changed
- The LWRL at 530 masl for Botsvatn during summer shall be kept

9.1 Electricity price

To avoid an increased electricity price in Norway due to development of PSH, then the power company operating the PSH-plant should not use water bound for Holen III to supply the European marked. To what extent the impact on the Norwegian electricity price with lost production from Holen III is not known, but it was assumed that it would have some impact.

In general this also depends on the number of PSH-plants built, but more important it depends on the timing of usage of the water. During a cold winter in Norway with very little water in the reservoirs, the impact on the electricity price would be much greater than during a warm summer.

If water bound for the Norwegian marked were used by the PSH-plant, then it would be possible to pump up water to replace it.

Another possibility is to import the low-price excess wind power. If the import of low-price excess wind power were the same as the export of electricity produced with water bound for the Norwegian marked, evenly distributed over the year, then the Norwegian electricity price would be unchanged, or lower. If the import were greater than the export then the electricity price in Norway would decrease, but this would lead to saved water in Norwegian reservoirs, which again could be used to supply the European marked, which again could lead to unchanged electricity price in Norway, as the saved water is used.

If the result from import was saved water in Norway, then not only PSH-plants could balance the European marked, but also regular hydropower plants.

To what extent this low-price excess wind power could be imported to Norway is not known, but it is a theoretical possibility, which is limited by the capacity of the cable, assumed that the other overseas cables are operating at maximum capacity.

In general terms, as long as the electricity prices in Norway doesn't increase, then the owner could operate both power plants as wanted.

9.2 Changing the existing operation regime

If the PSH-plant adopts the existing operation regime were unchanged, the result would be large fluctuations, occurring more often with a larger installation, as described in chapter 8. What would be the result if the existing operation regime were changed?

9.2.1 The same LRWL in Botsvatn the whole year

Changing the LRWL during summer doesn't change the operation regime of Holen III directly, but it's a part of the total picture.

The intention of increasing the LRWL during the summer is to make the area around Botsvatn more attractive to the cabin owners. When introducing a PSH-plant there would be fluctuations the whole year through, included summer. This means that the intention of increasing the LRWL during summer would be meaningless, as there would be large daily fluctuations that would not make the area more attractive.

In the simulated data set there were "holes" due to not enough water in Botsvatn to pump. The result was less flexibility, and thereby less income, but still large fluctuations when there was enough water.

So if lowering the LRWL during summer is out of the question, then the PSH-plant should not operate at all. This depends on what would be defined as acceptable fluctuations during summer.

By reducing the LRWL to 490 masl for the whole year through, the regulation flexibility would be much greater during the summer months, resulting in more income.

Below is a figure showing alternative 1 with a LRWL at 530 masl during summer and 490 masl the rest of the year, and 490 masl throughout the whole year. The two other alternatives have the same characteristics.

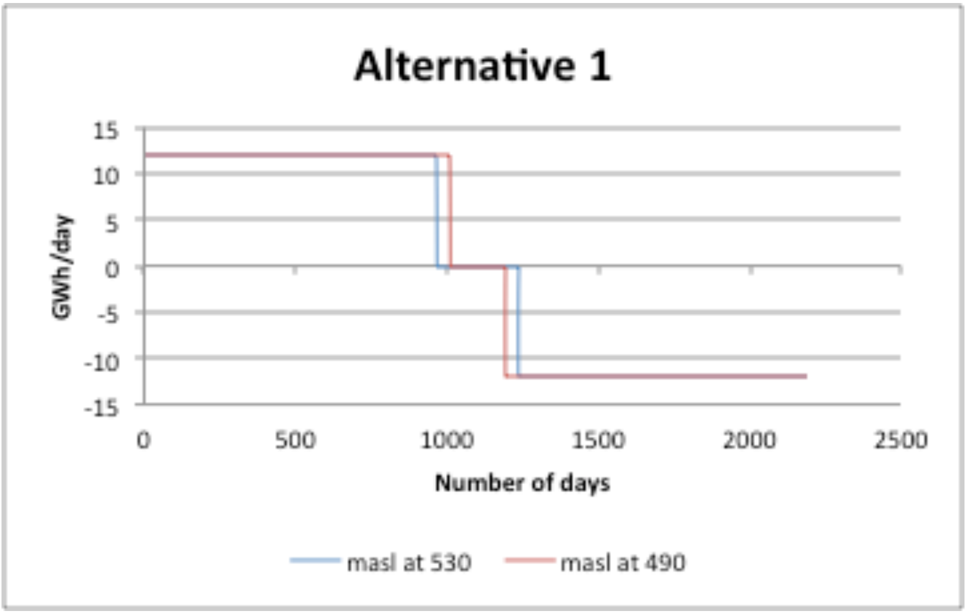

Figure 9.1 Different LRWL for alternative 1

	Alternative 1	Alternative 2	Alternative 3
530 masl	12 %	18 %	22 %
490 masl	8 %	13 %	18 %

Table 9.1 Percentage days with zero activity

In table above is the number of days with no production or pumping of the total number of days of operation, depended on a LRWL at 530 masl or 490 masl.

With a LRWL at 490 the whole year through, there would be approximate 4% more days with production or pumping.

9.2.2 Taking Holen III out of production

The result when leaving Holen III out of the simulation can be seen in the figure below. For comparison, the operation regime including summer limitations and not including summer limitations, when Holen III was a part of the simulations, was included. The figure 9.1 is showing alternative 3. Alternative 1 and 2 has the same characteristics.

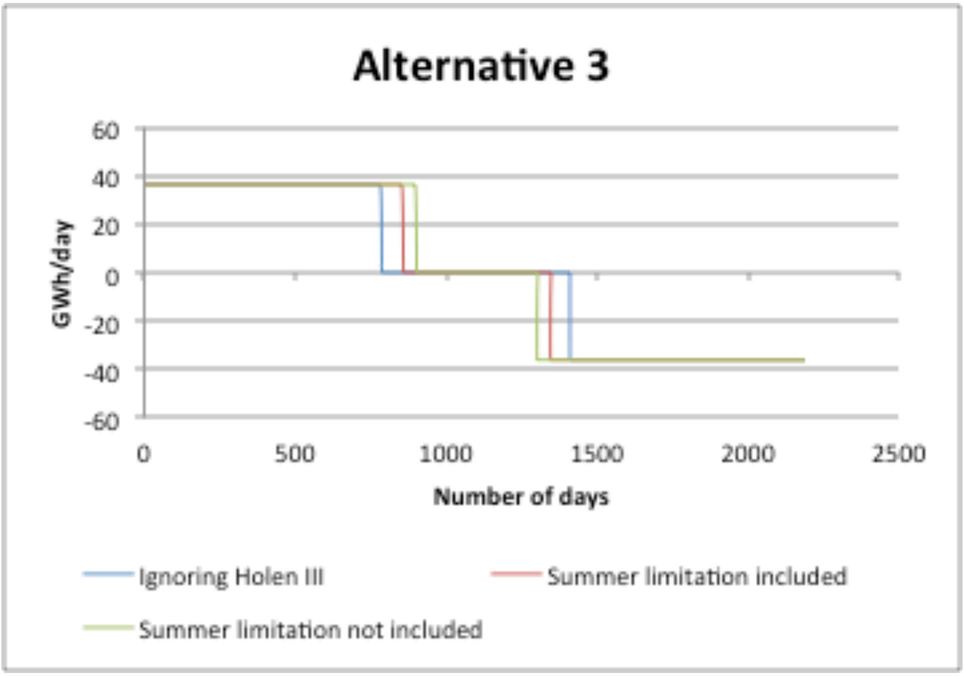

Figure 9.2 Ignoring Holen III, summer included and summer not included

	Alternative 1	Alternative 2	Alternative 3
Summer included	269	390	487
Summer not included	182	287	399
Ignoring Holen III	251	411	623

Table 9.2 Days with zero pumping or production

When Holen III was not included in the simulation, there were not necessary more days with pumping or production. For alternative 1 there were some few days extra with pumping or production, but for alternative 2 and 3 there were more days with pumping or production if Holen III was included.

The reason is more days where pumping is needed than production in the wind data, leading to a full Urevatn more often. When Holen III is operating it takes water from Urevatn, lowering the volume. So when Holen III was not included in the simulations, only the PSH-plant would lower the volume in Urevatn, meaning that the PSH-plant must wait for days with too little wind.

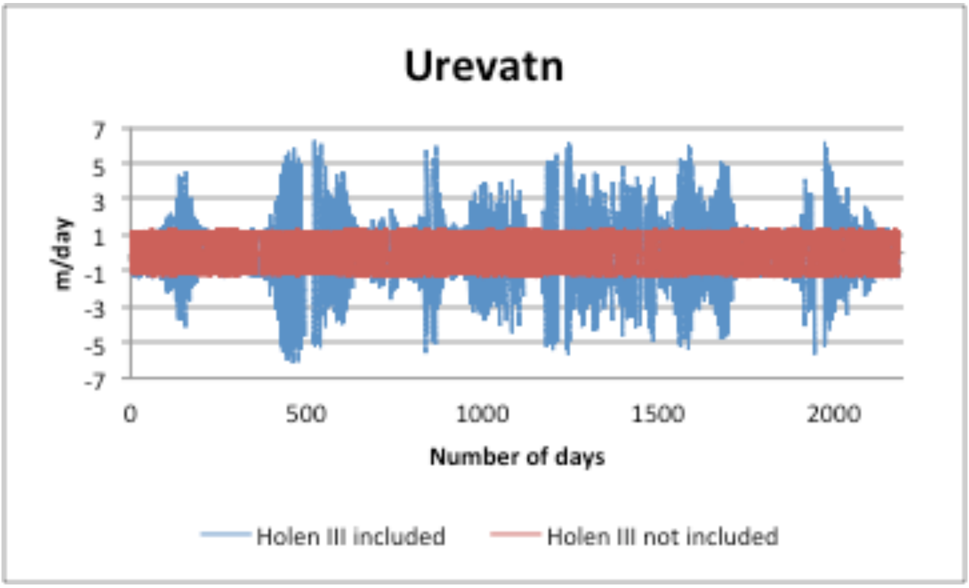

Figure 9.3 Rate of change Urevatn

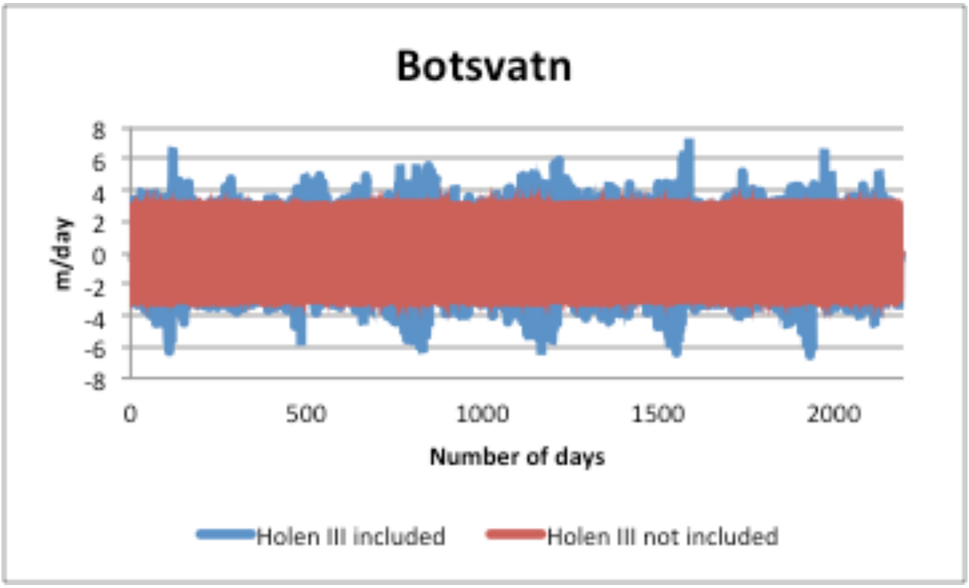

Figure 9.4 Rate of change Botsvatn

When Holen III was not included in the simulations the rate of change was very stable, where the average was the same as the maximum rate of change. In Urevatn the fluctuations were varying maximum ±1,5 meter and Botsvatn maximum ±3 meter.

10 Discussion

10.1 Operation regime

In Norway all the reservoirs where there is a potential for a PSH-plant, are there existing power plants. Presumably the owner of the existing power plant would be the owner and operator of the PSH-plant.

How would these two power plants be operated? If operated simultaneously, what would be gained and what would be lost for each power plant?

If the existing power plant was operated with priority over the PSH-plant, limitations could be included in the existing operation regime, resulting in lost income for the PSH-plant. If vice versa, the result would be lost production for the existing power plant.

How would the lost production from the existing power plant be compensated, and would it lead to an increase in the electricity price in Norway?

As the reservoirs with the best potential for PSH also includes large power plants with a high production rate, the lost production could have an impact on the Norwegian marked.

10.2 Cost and prices

10.2.1 Price of pumping

The price of pumping was set to 0,1 kr/kWh, which was just a chosen value. Whether this value is realistic is not known. For comparison, two other prices of pumping were set to 0,05 and 0,2 kr/kWh.

In the table below, all the values are in kr/kWh. Where the NPV are zero are called the minimum price.

	Alternative 1	Alternative 2	Alternative 3
Price of pumping	0,2	0,2	0,2
Minimum price	0,5	0,6	0,6
Price of pumping	0,1	0,1	0,1
Minimum price	0,4	0,4	0,4
Price of pumping	0,05	0,05	0,05
Minimum price	0,34	0,34	0,35

Table 10.1 Different prices of pumping

The price difference between pumping and production was approximately the same for all the chosen pumping prices.

10.2.2 Comparing electricity prices

For finding the least costly tunnel cross-section the price was chosen to be 0,45 kr/kWh and in the income estimate the minimum price was calculated to approximately 0,40 kr/kWh.

10.3 Model

10.3.1 Change the weight of balancing for the wind production

As mentioned before, it's possible to choose how much of the wind production the PSH-plant shall balance, and in this thesis it was set to 100%. For comparison the balance percentage was changed to 50%, 20%, 10% and 5%.

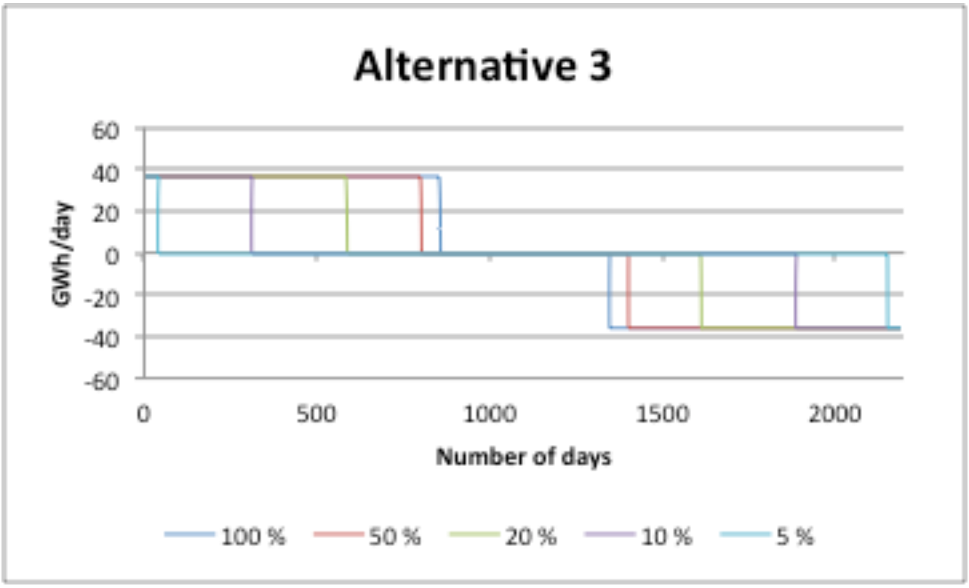

Figure 10.1 Different weight factors

By lowering the weight factor the number of days with production and pumping were decreasing. The reason for this was fewer days with enough wind to pump or produce at maximum.

10.3.2 Time interval

The wind data was on a daily basis, which seems realistic as the wind turbines are built over a very large area, meaning there are always some places where the wind is blowing.

With this said, it seems more likely that the PSH-plant would operate on an hourly basis. The result would be more occurring fluctuations, but with smaller changes in the water level. The impact on the efficiency of the existing power plants would also be much lower.

10.3.3 Increasing the minimum level of pumping and production

For this thesis it was assumed that the turbines should produce or pump at maximum effect. The limitation included in the simulation was set to 90% of the maximum energy divided by the energy equivalent. With this limitation there was still some days with production lower than maximum, so for comparison the limitation was increased to 95%.

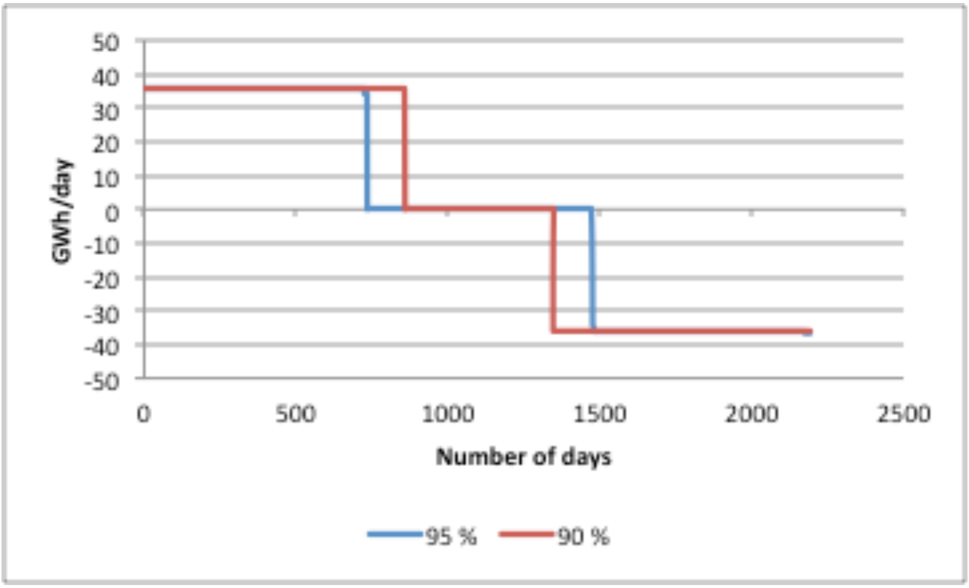

Figure 10.2 Limitations in maximum capacity

So when increasing the limitation to 95% the result was a reduction in the amount of hours with production or pumping lower than maximum, but also a reduction in the amount of hours with available volume for pumping and production. The total amount of hours of operation for both cases was 6816 for 90% and 5796 for 95%.

10.4 Choice of installed effect

When installing additional 10% for frequency balancing the total capacity for alternative 1, 2 and 3 were 550, 1100 and 1650 MW. As the maximum capacity for one turbine was 500 MW, the result would be one extra turbine and generator for alternative 2 and 3.

By choosing an installed capacity, included the additional 10%, which is less than 1000 MW or 1500 MW, is it possible to save the cost for the extra turbine and generator. But, with a larger installed capacity it is possible balance more and thereby makes more money.

If the extra turbine and generator is profitable, with the larger installed capacity, was not found for this thesis.

10.5 Number of cables and capacity

The overseas cables always have some downtime during operation, which means that the receiver of the balance service must replace the lost effect. The larger the cable, the more balance service can be offered, but the more effect must be replaced during downtime of the cable. How often and for how long a typical downtime lasts, is not known.

So there might be a limitation in the cable size due to downtime, which means that there would be a limitation in capacity of the PSH-plant, if there were one cable per PSH-plant. The alternative would be more than one cable per PSH-plant, but that would be very expensive.

10.6 Operation time

Usually for traditional hydropower when calculating the total yearly operation time, the equation below is used. The number of hours when the power plant is operated at certain Q/Q_{max} is counted.

$$T_{Total} = \sum_{year} \left(\frac{Q}{Q_{\max}} \right)^3 \Delta t$$

Equation 10.1 Yearly operation time

In this thesis it was assumed that there would only be maximum production or pumping when operating the PSH-plant. To find the total yearly operation time, it was just a matter of counting the hours at maximum pumping or production. This means it was not necessary to use the equation above, as the PSH-plant wouldn’t operate at partial loads.

10.7 Changing HRWL in Urevatn

The area between Urevatn and Blåsjø, to the west, is the only untouched place wild reindeers can cross from the area south of Urevatn to the area north of Urevatn. This area is also relatively flat and lies in a nature reserve. By raising the HRWL, this area would be reduced, resulting in physical barrier for wild reindeers. Besides, more impacts in a nature-protected area would be unlikely.

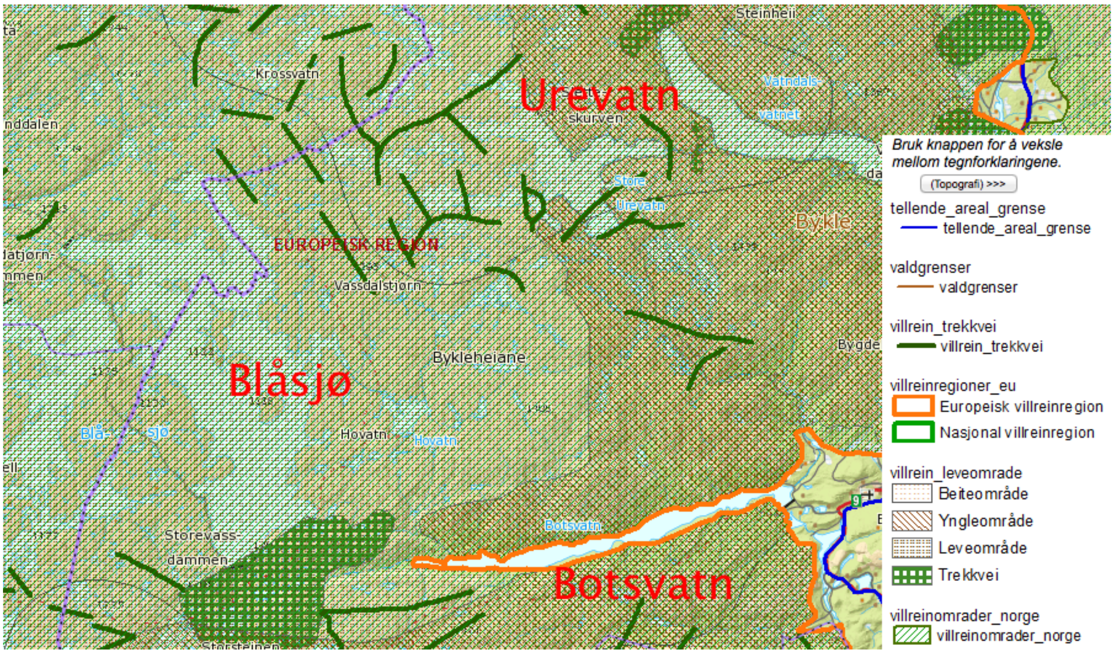

Figure 10.3 Reindeer trails (Picture from ngu.no)

The green lines show the trails of the reindeers. The green-hatched areas show where the reindeers breed, live and feeds.

10.8 How to make money from PSH

The technical part of realising PSH is possible, but how to make money is by far the biggest challenge, as so many different participants must to be involved.

10.8.1 Business model

In the report "Norge som leverandør av fornybar fleksibilitet" (2011) (Norway as a supplier of renewable flexibility), there are described sixteen different business models. In this theses deciding which one of these business models would be best for Norway were not done.

10.8.2 Gas as an alternative to PSH

Norway exports gas to the European marked, and the gas-plant operators are claiming that gas can be used for balancing purposes. If this were the case then Norwegian PSH would compete against Norwegian gas.

The gas industry in Norway is already developed and has a very favourable deal with the European marked. The question is; would the Norwegian government allow a competitor to establish when there are so many uncertainties related to PSH?

11 Conclusion

The existing limitations in the operation regime should be ignored if developing PSH in Norway. The PSH-plant should be operated without limitations and have priority over any existing power plant in the same reservoir, to make full use of the PSH-plant and to make sure the large investment is profitable.

12 Future work

12.1 Wind data and reservoir curves

To be able to plan and operate a PSH-plant, accurate wind data on an hourly basis is necessary along with accurate reservoir curves. Daily wind data gives a good indication on how the plant would be operated, but hourly wind data would give a more realistic and more accurate operation regime.

12.2 Electricity price

The greatest challenge when planning PSH in Norway is the expected electricity price. Costs of building PSH can be calculated accurate enough, but must be compared to the income.

To decide the electricity price a business model must be made between the developer and the buyer. This business model should include the electricity price the buyer would be willing to pay for, and long-term contracts. Another possible business model is that the buyer pays a yearly sum and operates the PSH-plant as wanted. In either case the income can be decided.

So the most important aspect for further PSH planning is to find the electricity price.

12.3 Deciding acceptable fluctuations

What would be acceptable fluctuations in Norwegian reservoirs if a PSH-plant were introduced?

This is the second most important question regarding PSH, as this would be dimensioning for the capacity of the PSH-plant and decide the operation regime.

The acceptable fluctuations would most likely vary from reservoir to reservoir, depending on the surrounding area, reservoir usage and environmental issues.

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Appendix

Paper appendix

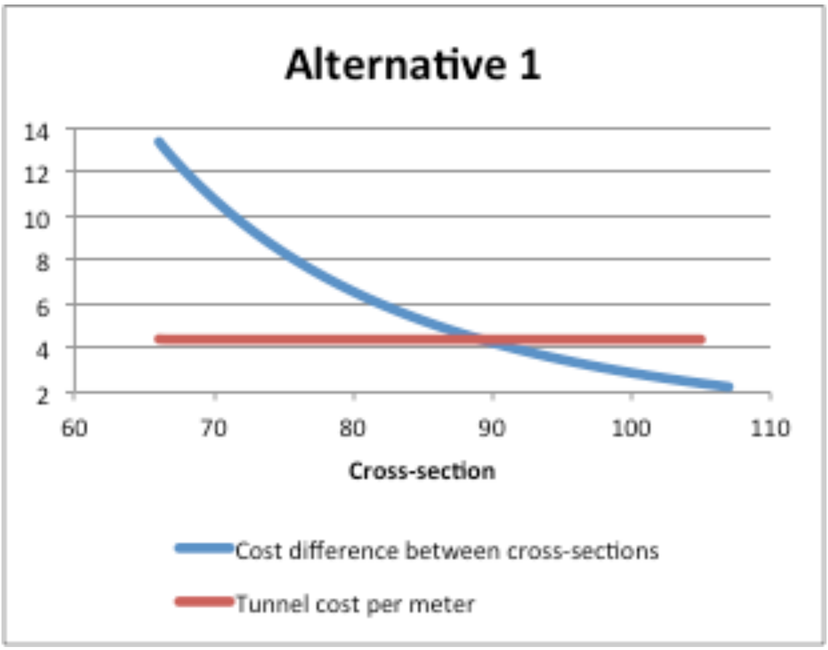
P1 Optimal cross-section
P2 Elevation profile
P3 Cost
P4 Submerging
P5 Access tunnel, overburden, tunnel length and angle
P6 Income estimate
P7 Reservoir curves
P8 Advance rate and cost for TBM and drill-and-blast

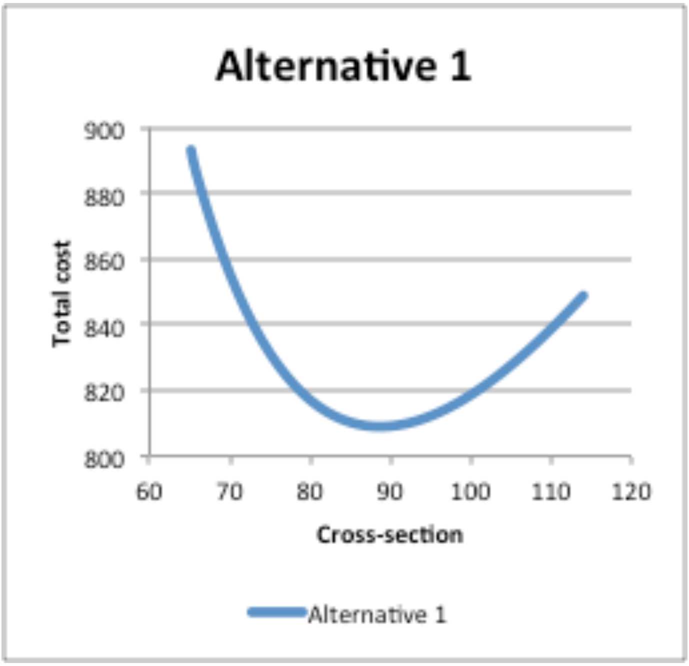
Electronic appendix

E1 Calculations.xlsx
E2 Alternative 1 limit.xlsx
E3 Alternative 2 limit.xlsx
E4 Alternative 3 limit.xlsx
E5 Alternative 1.xlsx
E6 Alternative 2.xlsx
E7 Alternative 3.xlsx
E8 Not Holen III.xlsx

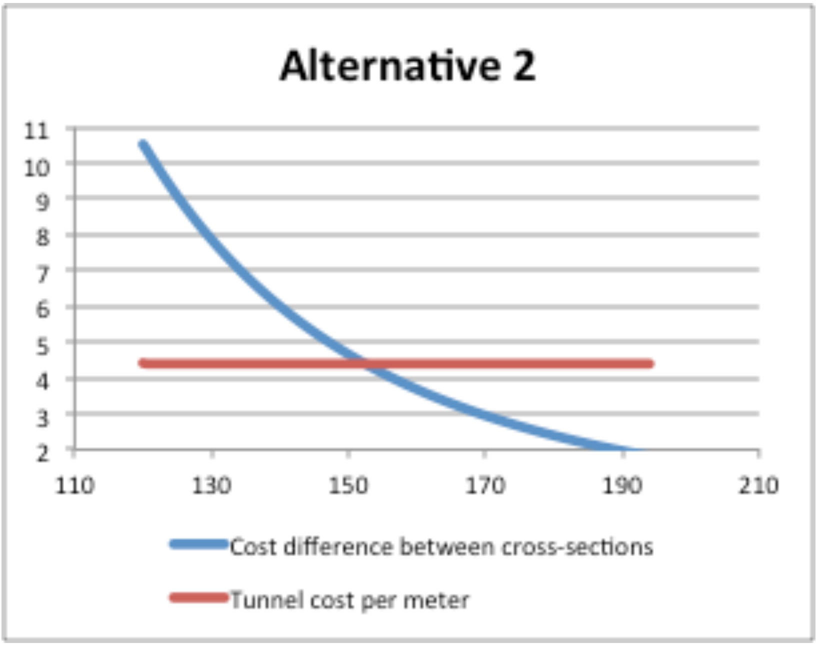
P1 Optimal cross-section

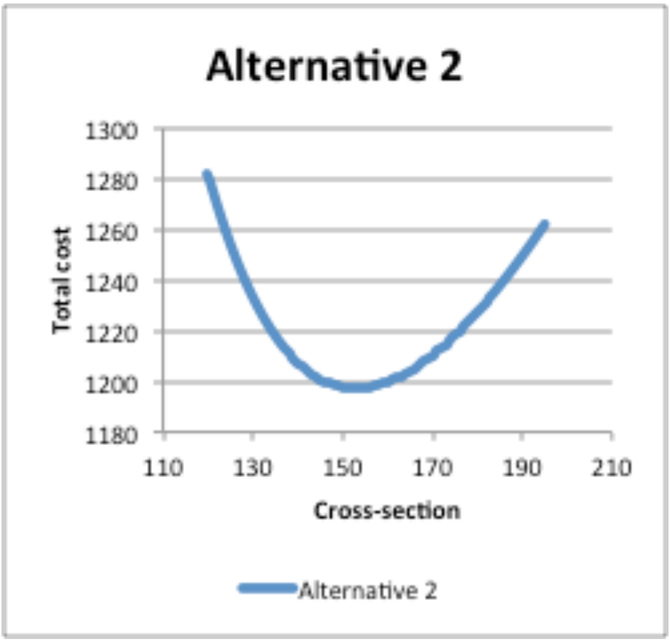
P1.1 Alternative 1



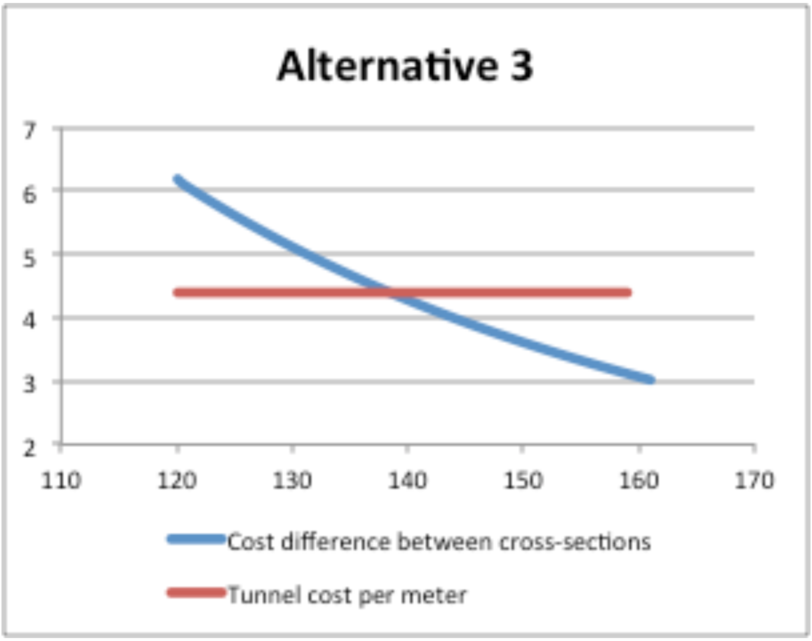


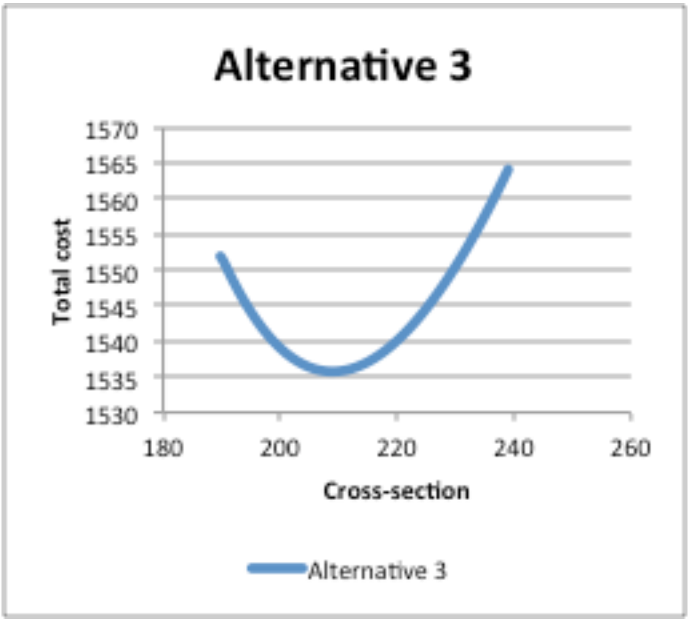
P1.2 Alternative 2



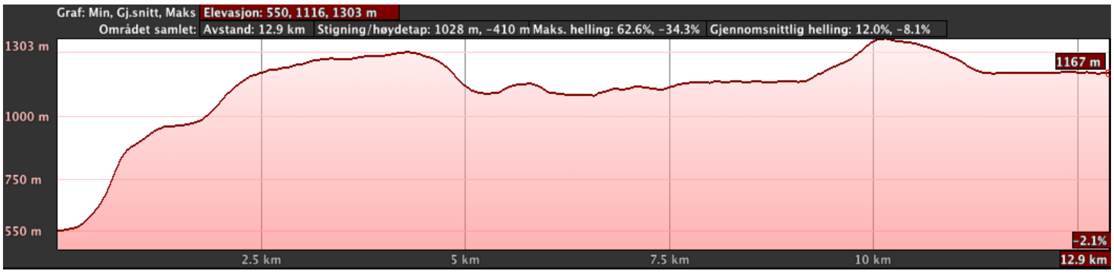


P1.3 Alternative 3





P2 Elevation profile



P3 Costs

MNOK	Alternative 1	Alternative 2	Alternative 3
Civil works			
Tunnel	664	945	1191
Lake tap	4	5	6
Air cushion	20	50	84
Entrance gate	1	1	2
Power station	101	171	233
Access tunnel	37	35	35
Sum	827	1208	1551
Electrical			
Generator	209	472	678
Transformer	68	121	173
Other	463	831	1081
Sum	739	1424	1932
Mechanical			
Francis turbine	315	511	678
Other	26	39	49
Sum	340	549	727

Sum	1907	3181	4210
Uncertainties 15%	286	477	632
Planning and admin 10%	191	318	421
Cost during construction 10%	191	318	421

Total cost	2574	4294	5684

P4 Submerging

	Alternative 1	Alternative 2	Alternative 3
Pole pairs	7	10	12
u	55	55	55
a	1,8	1,8	1,8
b	0,23	0,23	0,23
Vapour pressure	0,125	0,125	0,125
Barometric pressure	9,4	9,4	9,4
Discharge	90	200	267
Speed number	429	300	250
w	45	31	26
Diameter	2,5	3,5	4,2
c	19,1	21	19
NPSH	69	75	69
Hs [m]	-78	-84	-79

P5 Access tunnel, overburden, tunnel length and angle

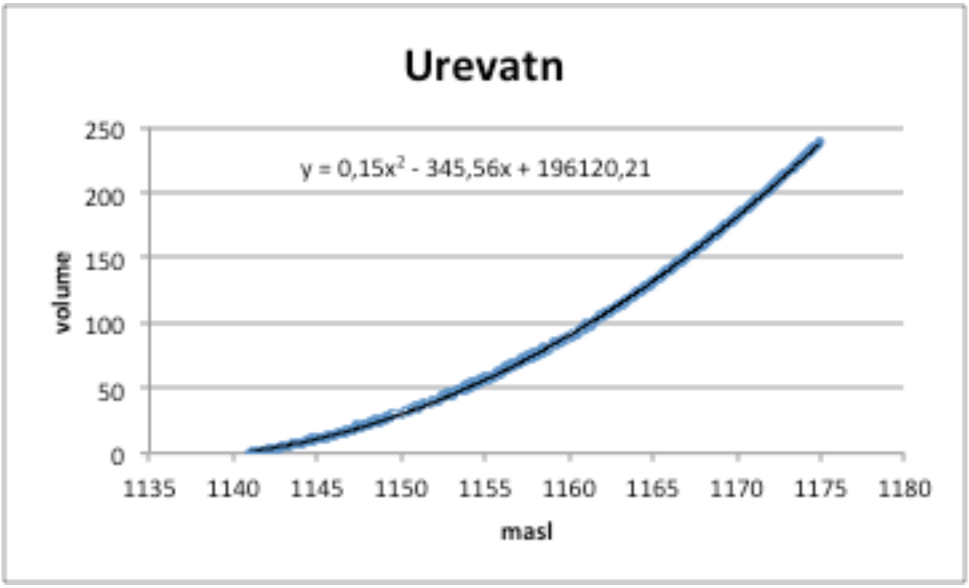
	Alternative 1	Alternative 2	Alternative 3	
Access tunnel length				
Elevation 1:	7	7	7	
Access tunnel entrance	563	563	563	masl
LRWL lower	495	495	495	masl
LRWL upper	1141	1141	1141	masl
Elevation gradient	0,305	0,305	0,305	
Submersion below LRWL	-84	-78	-79	m
Level	411	417	416	masl
Height difference access tunnel entrance and submerged turbine	152	146	147	m
Length	1066	1023	1027	m
Access tunnel length	1077	1033	1038	meters
How much mountain left?	246	227	229	m
Main tunnel				
LRWL	1141	1141	1141	masl
Intake under LRWL	1	1	1	m
Intake	1140	1140	1140	masl
Height difference LRWL upper and submerged turbine	729	723	724	m
Total length	12900	12900	12900	m
Length for tunnel	11856	11899	11895	m
Tunnel angle	3,53	3,48	3,49	
Necessary overburden	232	232	232	m

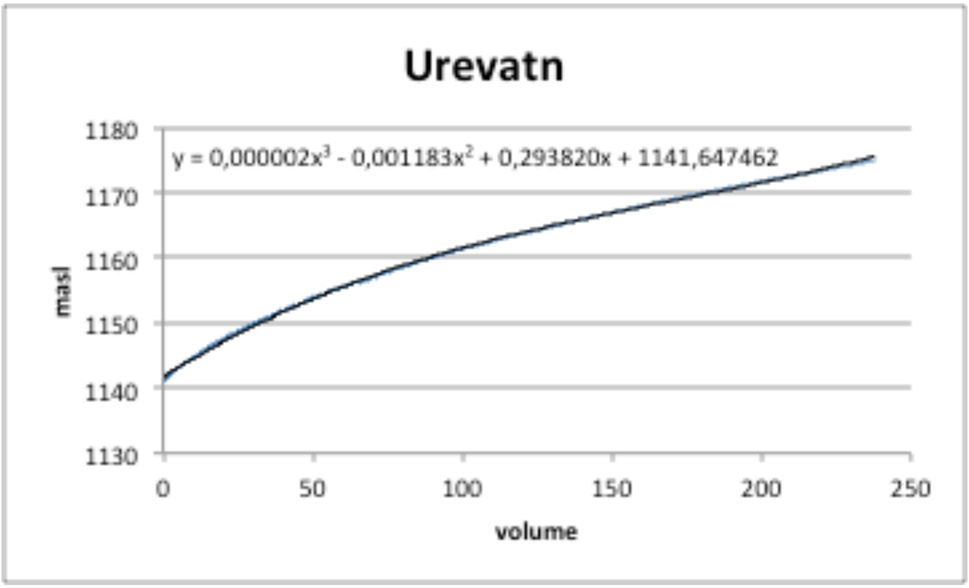
P6 Income estimate

	Alternative 1	Alternative 2	Alternative 3
Average production [MNOK]	564	1057	1515
Average pumping [MNOK]	-191	-358	-508
Average sum [MNOK]	373	699	1008
Cable cost [MNOK]	4286	8571	12857
Power plant cost [MNOK]	2574	4294	5684
Income [MNOK]	6860	12865	18541
Minimum price [kr/kWh]	0,406	0,411	0,420
Price difference [kr/kWh]	0,31	0,31	0,32

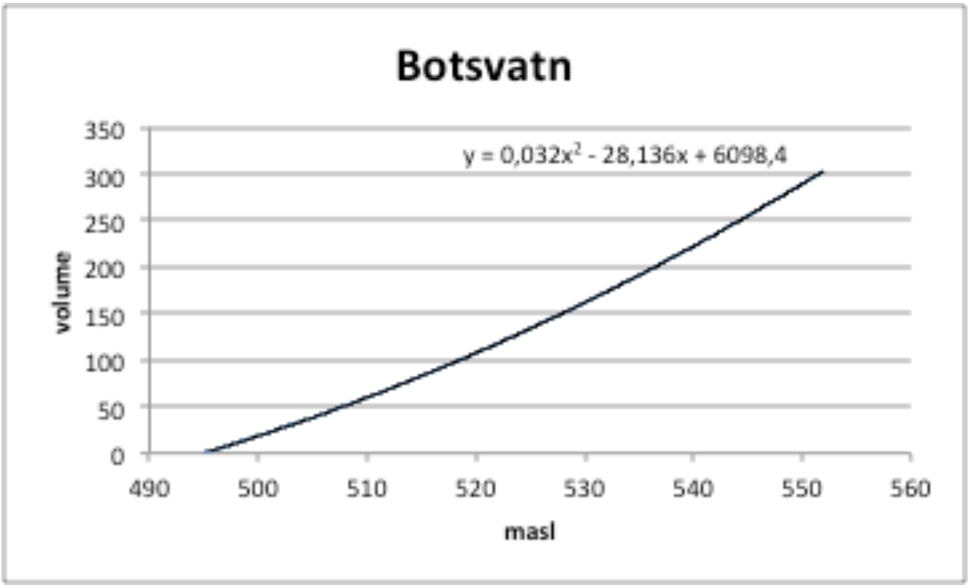
P7 Reservoir curves

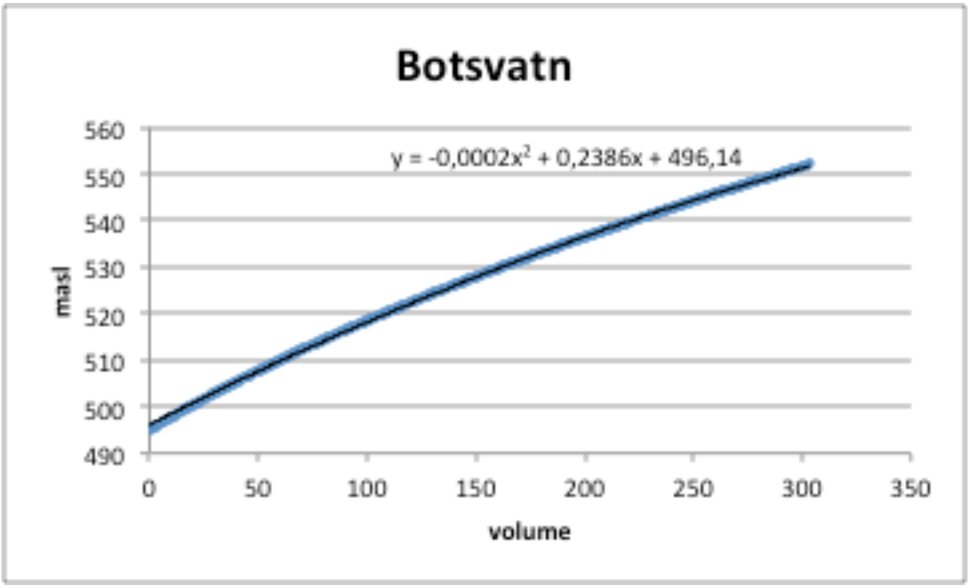
P7.1 Reservoir curve Urevatn





P7.2 Botsvatn





P8 Advance rate and cost for TBM and drill-and-blast

P8.1 Advance rate TBM

Weekly advance rate	
Net penetration rate	3,2
Boring time	308,6
Stroke length	2,0
Time per regrip	4,5
Regripping time	37,5
Time per changed cutter	60,0
Cutter ring life	2,5
Cutter time	124,1
Repair and service of TBM	60,0
Repair and service of backup	33,0
Other time consumption	145,0
Machine utilization	43,6
Nominal working hours	100,0
Effective working hours	100,0
Weekly advance rate	141,2

Net penetration rate	
Rock mass fracturing factor	1,1
Correction for DRI	0,9
Correction for porosity >2%	1,7
Equivalent fracturing	1,7
Gross thrust per cutter	280,0
Correction for cutter diameter	1,0
Correction for average cutter spacing	0,9
Equivalent thrust	257,6
Basic penetration	9,0
Cutter head RPM	6,0
Basic net penetration rate	3,2

Machine data	
TBM diameter	9,0
Cutter diameter	483,0
Cutter head rpm	6,0
Number of cutters on the cutter head	55,0
Average cutter spacing	81,8
Gross thrust per cutter	280,0
Installed power	3450,0
Relative position of the average cutter	0,6
Stroke length	2,0

Geological parameters	
Length	12900,0
DRI	40,0
CLI	20,0
Quartz content	20,0
Rock group	Granite
Porosity	5,0
Fracture class	1,0
Orientation	60,0
Fracturing factor	1,1
Total fracturing factor	1,1

Cutter ring life	
CLI	20,0
Quartz content	20,0
Rock group	Granite
Basic cutter ring life	85,0
Correction for TBM diameter	1,6
Correction for quartz content	1,1
TBM diameter	9,0
Cutter head	6,0
Correction for cutter head rpm	0,9
Number of cutters on the head	55,0
Standard number of cutters	55,0
Correction for number of cutters	1,0
Cutter ring life	2,5
Net penetration rate	3,2
Cutter ring life	8,1
Cutter ring life	512,6
	3,2
Average cutter ring life	2,5
Average cutter ring life	8,1
Average cutter ring life	512,6
Average cutter ring life	136,8

P8.2 Advance rate drill-and-blast

Advance rate

Tunnel cross section	64
Skill level	
Blastability	
Drill hole diameter	48
Number of drill holes for standard round length of 5 m	85
Drilled length	500
Correction for drilled length	1
Number of holes excluding large holes	85
Diameter of large drill holes	102
Number of large drill holes	3
Type of drilling hammers	AC COP 3038
Number of drilling hammers	4
DRI	65
Penetration rate 48 mm drill hole	345
Correction of penetration rate for dh	100
Penetration rate charged holes	345
Correction of penetration rate for dg	44
Penetration rate large holes	151,8
Drilling time charged holes	31
Drilling time large holes	3,1
Time for moving per hole	0,75
Time for moving	17,0625
Unit time for rod adding	0
Time for rod adding	0
Rock wear quality	High
Bit changing factor	0,04
Unit time for bit changing	3
Time for bit changing	13,65
Lack of simultaneousness factor	0,06
Extra time for lack of simultaneousness	3,1
Necessary drilling time	68
Type of explosives	ANFO
Number of charging lines	3

Time-determinant charging time for basic round length	47
Correction for drilled length	1
Time-determinant charging time	47
Rig time, charging, blasting	19
Incidental lost time drilling charging, blasting	14,83563828
Sum for drilling, charging, blasting	148
Ventilation break	18
Type of loader	Volvo L330E
Transport equipment	Dump
Normalised gross loading capacity	270
Factor of over break, excluding niches	1,15
Advance per round	90
Actual volume per round	331,2
Loading time per round	73,6
Rig time loading and hauling	22
Incidental lost time loading and hauling	10,6116
Sum loading and hauling	106,2116
Scaling time for basic round length	30
Correction for drilled length	1
Scaling time	30
Net round cycle time	303
Extra time for niches	0
Tunnel length	7000
Correction for tunnel length and job training effect	1,1
Standard round cycle time	332,9718009
Effective working time per week	101
Standard weekly advance rate	82
Time for rock support	90
Unforeseen time	23
Gross Round cycle time	438
Gross weekly advance rate	62

P8.3 Cost TBM

Normalised Excavation Costs

TBM diameter	9,0
Tunnel length	12900,0
Average net penetration rate	3,2
Average cutter life	136,8
Average cutter life	2,5
Numbers of cutters on the cutter head	55,0
Muck transport	
Adit	
Assembly cost	9000000,0
Assembly and disassembly	697,7
TBM costs	4000,0
Backup equipment costs	650,0
Basic cutter costs	50,0
Cutter costs	848,8
Basic costs for work behind the face	3300,0
Correction factor for length	1,2
Correction factor for net penetration rate	1,0
Costs for work behind the face	3999,6
Basic labour cost	1250,0
Correction factor for net penetration rate	1,0
Correction factor for cutter life	0,9
Labour costs	1147,5
Additional cost for declined adit	80,0
Sum	11423,5
Correction factor for unforeseen costs	0,1
Unforeseen costs	1142,4
Excavation costs	12565,9
Efficiency factor	1,1
Price increase	1,0
Excavation costs	13822,5

P8.4 Cost drill-and-blast

Cost

Cross section	64
Tunnel length	7000
Excavation method	4 boom wheel mounted jumbo
Drillability	Good
Blastability	Good
Adit	Horizontal
Drill hole diameter	48
Drill length	5
Total drilling cost	1250
Explosives type	ANFO
Explosives cost	1000
Correction for drilled length	1
Correction for dynamite proportion	1
Corrected explosives costs	1000
Scaling costs	150
Correction for drilled length	1
Correction scaling costs	150
Sum drilling, explosives and scaling cost	2400
Loading equipment	Excavator - 35t dump truck
Loading cost	880
Traceless/track transport	Trackless
Hauling cost	2500
Costs for roadway/rails	360
Tip costs	150
Total hauling cost	3010
Ventilation costs	1300
Electrical installation costs	100
Water supply cost	115
Miscellaneous cost	235
Additional cost	1750
Labour costs	2900
Correction for drilled length	1
Correction for tunnel length	1,03
Corrected labour cost	2987
Cost of niches	50
Sum elemental costs	11077
Correction for unforeseen costs	1,1
Correction for price level	1
Standard costs	12184,7