Nordic Council of Ministers

Nordic Energy Research

Wind power based pumped storage

Pre-Feasibility Study

Suðuroy, Faroe Islands

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Norconsult

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Contents

Summary

The background for the study is a potential future scenario with approximately 10 MW of wind power installed on Suðuroy, Faroe Islands, to cover the increasing demand for electric energy.

The study outlines a pumped storage scheme on the island including waterways and power station with pumps, turbines and related equipment. The idea is to utilise periods of surplus wind power (e.g. during night time) for pumping of water between reservoirs and to produce hydropower to enhance the power system during periods of higher power demand (e.g. during daytime).

The study has mainly focused on two issues:

- Pre-feasibility study for a pumped storage power plant (PSPP)

- Simulation of one power production and consumption scenario on Suðuroy in order to investigate how much power that may be produced and consumed on Suðuroy for a base case. Two variants, one with a slightly larger turbine in the PSPP and one with a slightly larger turbine plus an enlarged upper reservoir were also studied.

Pumped storage power plant (PSPP)

Connecting the reservoirs at Miðvatn (as an upper reservoir) and Vatnsnes (as the lower reservoir) was the basis for the investigations in the pre-feasibility study for the PSPP, pumping water in the case of wind power surplus and producing power in the case of reduced wind power production.

The powerhouse cavern for the PSPP is planned to be located along the existing tunnel between the Vatnsnes reservoir and existing Botní power plant. The access tunnel to the powerhouse cavern is planned located with a starting point by the road to Botní and Ryskivatn. The waterway between the Miðvatn reservoir and the powerhouse cavern are planned with a combination of tunnel and steel lined pressure shaft.

One turbine and four independent industrial pumps are proposed installed in the PSPP. This technology is well proven, also for small pumps. The solution is very flexible from an operational point of view.

For the turbine in the PSPP, a Pelton turbine is considered to be best suited, even if a Francis turbine also would be possible.

The investment cost for a PSPP is about 100 mill. NOK.

Simulation of power production and consumption

The simulation model included the following elements as a base case: reservoirs Miðvatn and Vatnsnes, PSPP with a 2,5 MW Pelton turbine and 4x1,25 MW pumps, the Vatnsnes-branch of the Botní power plant, 11 wind turbines (E 44) with 0,9 MW each (in total ≈ 10 MW).

For all the existing elements, actual dimensions and characteristics were used (power curve, waterway dimensions, reservoir size and geometry). For new elements (pumps, new turbine etc.) typical values were used.

As input for the simulation the following data was used: hourly measured wind data for a period of 6 years (2007-2012) and the water inflow for 11 different years (calculated from production data in Botní power plant).

Hourly consumption data was provided by the local authority Jarðfeingi who also established a series for the assumed future consumption including higher power consumption in the fish processing factory in Vágur and extensive use of heat pumps on the island.

The simulations showed that the production potential of wind power for the base case, as described above, is about 39 GWh whereas a substantial part (27 GWh) meets the power demand on Suðuroy directly. About 7 GWh can be used to pump water to the upper reservoir in the PSPP, while 5 GWh is surplus power with the consumption used as input to the simulations.

The PSPP will produce 5,3 GWh and the Vatnsnes-branch in Botní will produce 3,5 GWh in the PSPP-system, while the production in the Ryskivatn-branch of the Botní power plant will be reduced. I.e. the PSPP will allow an extra net production of 4,5 GWh hydro power.

Even with the new wind- and hydropower capacity, 9 GWh need to be imported from the main grid or produced by other means.

The simulations for the base case resulted in 65 % power from wind power, 18,5 %[1] from hydropower and 16,5 % from other sources.

The simulation variants (with a slightly larger turbine in the PSPP and with a slightly larger turbine plus an enlarged upper reservoir) resulted in minimal changes in the production of hydropower.

Economy

The overall cost for the introduction of 10 MW wind power and a pumped storage plant is estimated to be about 5.7 NOK/kWh.

It is recommended to initiate a more detailed economic analysis comparing the scenarios with the wind farm and the pumped storage plant to a scenario with power production based on fossil fuels.

[1] new and existing hydropower

Increased power production from renewable resources will make the Faroe Islands less dependent on fuel import.

Grid

A pre-requisite for pumped storage on Suðuroy is connecting the local grid to the main grid by a subsea power cable.

Integrating a new wind farm and pumped storage in the Suðuroy grid will require detailed power system studies to identify the need for grid investments (reinforcements) and to verify the power system operation and response and stability requirements to the new wind power and the pumped storage operation.

Environment issues

A pumped storage plant at Suðuroy has a minimum of impact on the environment, as the reservoirs already exist.

A positive consequence is that the pumped storage plant will replace hydrocarbon based power production with power from renewable resources, thus reducing the output of CO_2 to the atmosphere.

1 Background

The Nordic working group for sparsely populated areas (TBO), coordinated by Nordic Energy Research, the funding institution for energy research under the Nordic Council of Ministers, assigned Norconsult AS to evaluate the possibility to use wind power to operate a pumped storage plant on the southern island of Suðuroy in the Faroe Islands. TBO is funded by the Nordic Council of Ministers.

The Faroese Earth and Energy Directorate, Jarðfeingi, and the Faroese energy supplier, Elfelagið SEV, have been important partners in the project and have contributed with essential information in this project.

The following persons have been responsible for this study: Franziska Ludescher-Huber (project manager), Hans Olav Nyland (electro-mechanical engineering), Kjell Mathiesen (civil works) and Xin Xin Li (production simulations).

Contact persons were Ina Jakobsen, Nordic Energy Research and Kári Mortensen, chair of TBO.

2 Introduction

The background setting for the study is a possible future situation with about 10 MW of wind power installed on Suðuroy, Faroe Islands, to cover the increasing demand for electric energy.

The study outlines a pumped storage scheme on the island including waterways and power station with pumps, turbines and related equipment. The idea is to utilise periods of surplus wind power (e.g. during night time) for pumping of water between reservoirs and to produce hydropower to enhance system power during periods of higher power demand (e.g. during daytime).

The planning of the wind farm and grid studies is not part of this study. The study is based on the assumption that 10 MW wind power effect will be installed on Suðuroy and that the grid can be considered stable if linked to the main grid.

Based on an assumed optimum[2] distribution 4:2:1 between the installed wind power and pump & turbine effects, the following effect configuration has been selected; 10 MW wind power, 5 MW pumping capacity and 2.5 MW turbine output. This document contains a brief description of the required works in order to use two existing reservoirs in a pumped storage plant, shows the results of a production simulation, and draws conclusions from the results.

[2] In the study "Vind- og pumpekraft på det færøyske kraftnettet" that Norconsult made for Elfelagið SEV in 2010, many different ratios for wind power effect : pump effect : turbine effect were simulated. The ratio 4:2:1 gave the best results.

3 Pumped storage plant - Technical description

3.1 PROJECT OVERVIEW

The map below gives an overview over the project: the reservoirs Miðvatn and Vatnsnes, the waterways connecting them, and the pumping/power station with access tunnel. The coloured areas show the catchments of the existing reservoirs.

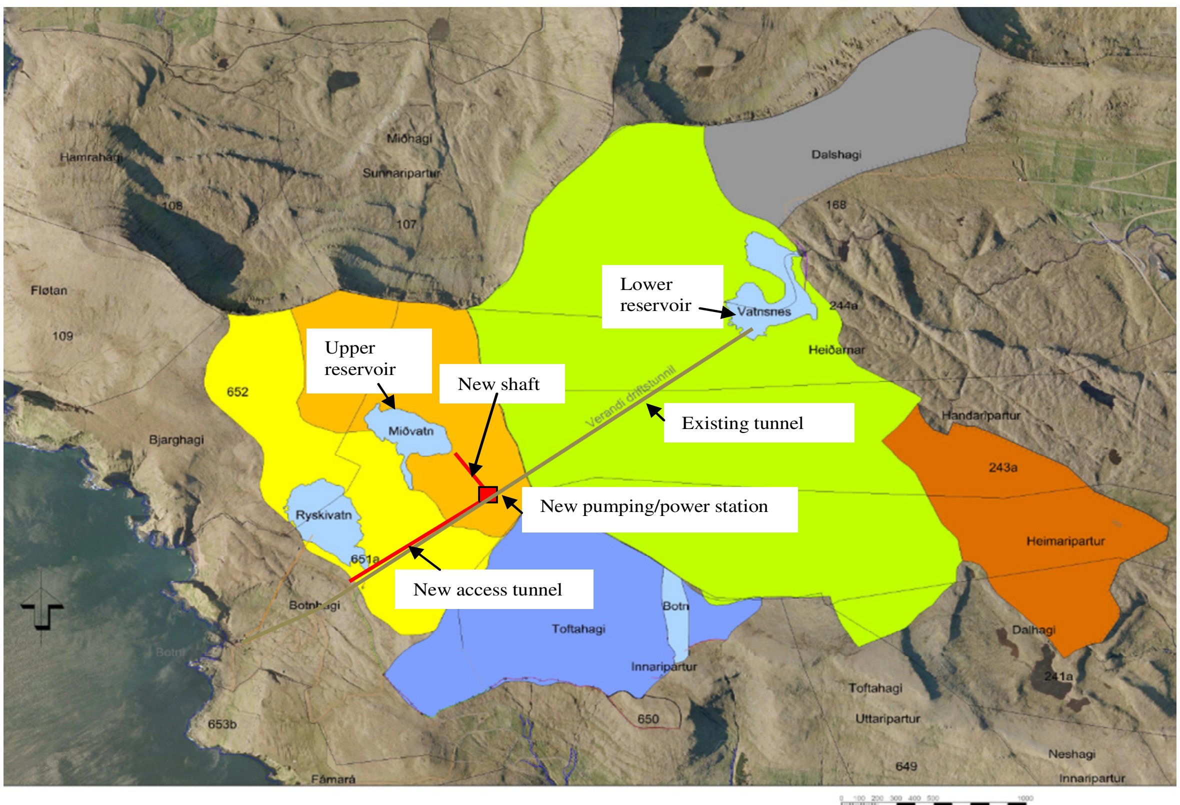


Figure 1 Overview over the project. The map with coloured catchment areas has been provided by Elfelagið SEV.

3.2 CIVIL WORKS

The power house cavern will be located along the 1x2 m Vatnsnes tunnel and will be reached through a 500 m long 18 m^2, access tunnel starting at 250 m asl on the road to Ryskivatn. The access tunnel is declining about 1:7 down to the underground cavern at 180 m asl.

The pump/power station connects to the Vatnsnes tunnel through a 50 m long, 12 m^2 tunnel. The powerhouse cavern end of the connecting tunnel will have a free surface pool level with Vatnsnes (178-180 m asl). with the pool will have sufficient area to avoid flooding the powerhouse during upsurge or sucking air into the Vatnsnes tunnel during downsurge.

The pump intake chambers (Figure 12) will connect to the Vatnsnes system 5-10 m below the free surface. The turbine outlet will be arranged with the turbine centre at approximately 182 m asl.

Operation of the lower reservoir; Vatnsnes, remains unchanged. Some instrumentation and possibly trash rack modifications may be necessary in order to make sure that the hydraulic steelwork at Vatnsnes meets the requirements of the pumped storage equipment (e.g. minimum water passage opening through pumps and turbine etc.)

From the powerhouse cavern in direction Miðvatn the waterway will start with a 25 m long 12 m^2 tunnel to the base of a steel lined pressure shaft. From this point on the waterway to Miðvatn consists of two parts; first a 225 m long, 45˚ inclined 4 m^2 shaft followed by a 350 m long tunnel underneath the lake to reach an appropriate location for lake piercing sufficiently below the LSL (Lowest Supply Level) of the Miðvatn reservoir.

The turbine intake / pump outlet structure at Miðvatn will comprise a trashrack of stainless steel, a self-closing roller gate (or a butterfly valve) with hydraulic pressure actuator, air vent piping and a maintenance gate all placed at the bottom of a gate shaft located on-shore near the south east end of Miðvatn. The hydraulic power unit (HPU), gate control and access to gate shaft will be placed inside a gate house on top of the shaft.

Earlier in the project it has been considered to enlarge the Miðvatn reservoir, but under the assumption of a long, subsequently costly dam not yielding any significant additional reservoir capacity, it is suggested to base the project on the existing reservoir size only.

3.3 TURBINE AND GENERATOR

The turbine-pump configuration[3] concept is sketched in Figure 2, Figure 3 and Figure 4.

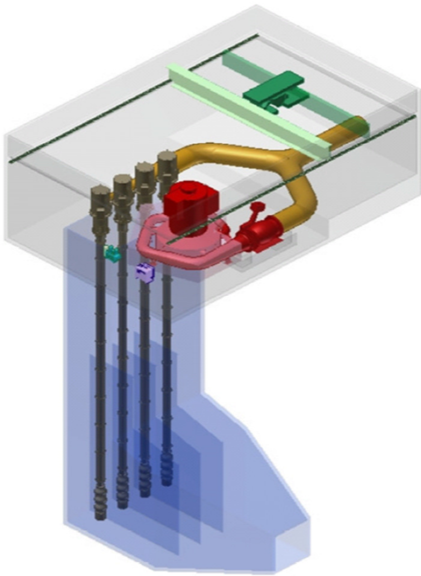
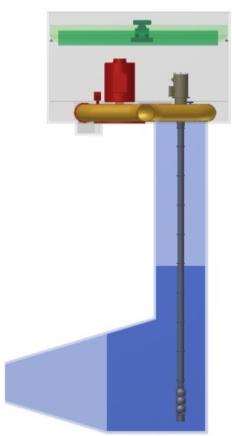


Figure 2 Power house overview. 3D-sketch of suggested concept with one Pelton turbine and 4 pumps



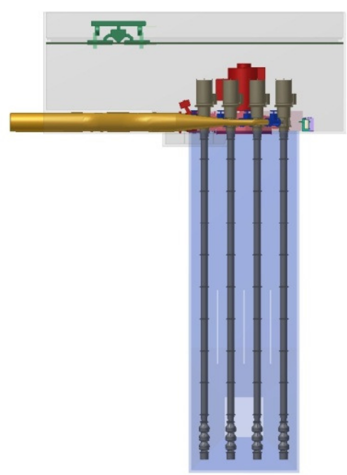


Figure 3 Powerhouse, seen from the side

[3] Figure 2, Figure 3 and Figure 4 were produced by Norconsult for a similar project for Elfelagið SEV in 2010. They are shown with permission of Elfelagið SEV.

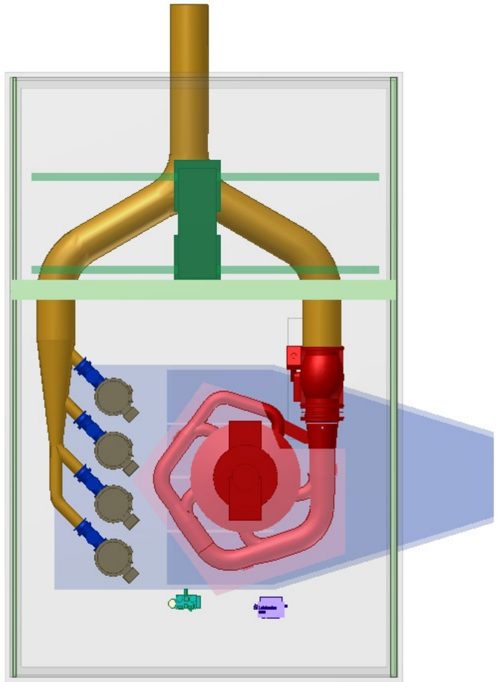


Figure 4 Powerhouse, seen from above

3.3.1 Turbine - discussion

3.3.1.1 Turbine selection

The speed number (combination of head, flow and speed), better stability plus the large flow range (if needed) make Pelton turbine the most applicable turbine type in this case. A Francis turbine is also possible, but would require relatively long and narrow runner vane canals, with tough requirements both to hydraulic design and manufacturing. However, if a large turbine flow range is not required, thus allowing the turbine to run around best point only (about 80% of full load), but with intermittent operation, a Francis turbine may still be a preferable option.

The Pelton turbine can operate at lower discharge through the turbine and has higher efficiency at low loads, causing smaller transients in the waterway, and is better adapted for spinning reserve operation. In opposite to a Francis turbine, a Pelton turbine in synchronous condenser mode does not require extra bearing cooling during spinning in air, and can be kept running with one jet to save water and power. The Pelton turbine's deflectors, directing the water away from the turbine runner, make governing simpler and more robust, and minimize the load on the machinery and the waterway. The Pelton turbine runner centreline must be placed 1-2 m above the highest tailwater level (at 181.5-182 masl), depending on the size, with embedded ring pipe/spiral case. The typical configuration in this case would be a vertical shaft unit with 5 or 6 nozzles, and 500 rpm. Besides, a small Pelton turbine of this size has higher probability of a hassle-free operation, than a similar sized Francis turbine.

A Francis turbine will have higher peak efficiency, and be less expensive. A Francis turbine will also harness the full head down to the highest tailwater, and will thus utilise 1-2 m more head and, subsequently, yield higher outputs than a Pelton turbine. A Francis unit of this size will typically be built with horizontal shaft and positive suction height, i.e. the turbine centre is above highest tailwater while the draft tube outlet will be submerged. The running speed would be 1000 rpm that would entail a cheaper generator compared to the 500 rpm one.

Based on the discussion above a Pelton turbine is considered to be the preferred turbine type.

We have assumed a spherical valve as turbine shut-off valve.

3.3.1.2 Relevant turbine suppliers

The most relevant suppliers of turbines for this project will be Andritz (formerly VA Tech Escher Wyss) of Austria/Switzerland and Rainpower (formerly known as GE Energy, Kvaerner) of Norway, as well as Voith of Germany. The unit will be well within the product portfolio all of these vendors, with respect to both Pelton and Francis units. In addition a few new suppliers especially from Norway, with high expertise in compact Pelton and Francis units, have emerged on the market. We consider the highest ranking of these to be Spetals Verk and to some extent Energi Teknikk (Brekke-Turbin). In projects of this size, turbines, generators, transformers and control system usually come in full package deals.

3.3.2 Generator

A synchronous generator is assumed. Asynchronous generators require a lot of reactive power from the network and are considered irrelevant for this output. A synchronous generator can control the reactive power fed to the grid by itself.

A generator voltage of 6.6kV is appropriate for this case. The turbines have all different speeds and it is up to the provider to offer a generator that is best suited for the plant. According to Norconsult's experience, generators up to 10 MW are often of the rebuilt motor type or ship generators. These generators have a low moment of inertia and will probably not be able to help maintain the stability of the grid. In general it can be said that low transient reactance, large moment of inertia and high voltage for excitation gear will enhance the stability conditions. A grid analysis study will clarify what special requirements must be set for the generator. It is recommended to choose a generator with cooling air/water in a closed circuit. In addition, there is a huge advantage that the generator is specified with sleeve bushings. All generator suppliers can deliver this.

3.3.3 Main data turbine and generator

Main data for turbine and generator, plus diagrams showing expected turbine efficiency and output for both the Pelton and Francis turbine alternative, is given below.

Turbine type:	Vertical Pelton turbine with 6 jets, or Horizontal Francis turbine	
Plant capacity flow	°Q (m^3/s):	1,8
Nominal turbine output	°N (MW):	2,5
Nominal head	He (mWc):	160 (162 if Francis)
Running speed	n (rpm)	500 (1000 if Francis)
Net positive suction head (if Francis)	NPSH (mWc)	Appr. 6.6 m (CL turbine - TW < 3.6 m)

Runner material		Cr13Ni4
Generator type:	Vertical synchronous generator (Horizontal if Francis)	
Generator rated output	P (MVA)	3.13
Nominal voltage	kV	6.6

Table 1 Suðuroy Pumped Storage Plant. Main data turbine and generator

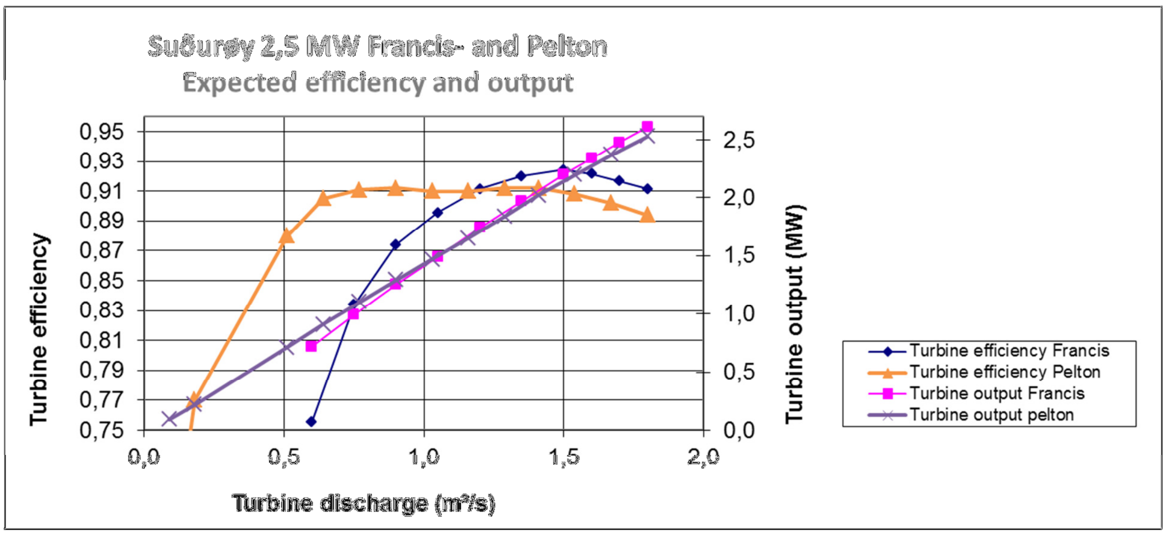


Figure 5 Typical turbine efficiency and –output diagram.

Normal operational range: Pelton 10 - 100%, Francis 40-100% .of design flow.

Peak efficiency for the turbines suggested for Suðuroy is typically around 91% for a Pelton and 93 % for a Francis turbine (see Figure 5), and about 90-97% for the generator, increasing with increasing load, resulting in a unit efficiency of 80-87 % depending on the load and turbine type.

3.3.4 Transformer

An oil filled 6.6/22 kV transformer will be located in a separate, explosion secured chamber in the powerhouse cavern. The power will be evacuated through oil filled cables the about 500 m to a substation out in the open where the existing 22 kV line from the power plant in Botnì is passing by.

3.4 PUMP SYSTEM

See 3D-sketch on Figure 2 to Figure 4 for station arrangement.

The pump system is described below:

3.4.1 Motor and pump selection - discussion

3.4.1.1 Motors

Asynchronous motors are recommended because they are simple, robust and relatively cost effective. They are easy to repair and parts are readily available.

Synchronous motors can also be used, but they are more complex and have a high start-up current. An advantage with synchronous motors is that they have the ability to adjust the reactive power. Mechanically they are more complicated and more expensive than asynchronous motors. We have assumed frequency converter (also known as variable speed drive or VSD) to avoid too high start-up current. These can be used both for synchronous and asynchronous motors. "Soft starters" may also be used, but then all operational conditions must be known and specified upon procurement. VSD has the big advantage that it is easily programmable, while the soft starter is much less flexible. A VSD may contribute to saving energy during times of reduced lifting head (low upper reservoir level and high lower reservoir level).

3.4.1.2 Variable speed drive (VSD)

During normal operation, it is not desirable to use the VSD, as the pump motors will then chase each other up and down in speed and contribute to instability in the grid. There is also a risk that the VSD will cause one or more pumps to run against closed valves and break down, due to low speed and lifting head in relation to the other pumps. A configuration that has been up for discussion in the project, and which in theory should provide ample flexibility, are 3 fixed speed pumps with VSD. However, in practice this may fail instantly without strict conditions in controlling the speed governing. Accordingly, the speed range and thus the usefulness of a VSD may be limited. By simultaneous operation of the pumps and turbine (in extreme situations for instance where a large consumer may contribute to stabilizing an unstable grid) a turbine generator flywheel will be stabilizing on the grid, while the VSD can contribute to instability. The lifting head of the pumps vary with the square of speed; $H1/H2 = (n1/n2)^2$. Thus, the speed adjustment during operation is practically only applicable at relatively low head in relation to the head variation. The head between Vatnsnes and Miðvatn may range between approximately 157 and 172 m, which means that the maximum speed can be varied by (172/162)^0,5 = 1.12, i.e. +/-6%. The recommended solution is therefore that each pump motor has fixed speed. The total pump load can then be varied with start/stop and the number of pumps in service. The motors can even withstand a frequency variation of a few percent, depending on pump characteristics and supplier.

The evaluations above; a simple and robust system with the use of VSD only to limit starting current have been used as basis for cost estimates and production simulations in this study. We will not, however, drop the idea of VSD for load regulation entirely. In a well-designed control system use of the VSD would still entail benefits such as greater efficiency, as well as improved load regulation.

3.4.1.3 Pump configuration

Two principal pump-turbine alternatives can be evaluated.

1. Turbine and pump are on the same shaft
2. The turbine is separated from the pump(s)

<u>Alternative 1</u>
The turbine will have its centreline elevation at about 182 masl, with a generator mounted above. The shaft will be extended down to the elevation of the pump, at approximate 174 masl. Between the turbine and the pump there must be a specially designed sealing device and a clutch. The entire shaft will be approximately 12 m long, requiring ample height in the powerhouse for disassembly. The pump load cannot vary over a wide range as the case would be with more pumps and must stick to one operation point. It must be installed dry with closing valves on the suction and pressure side. The pump room must be drained and secured against buoyancy. For this type of pump the turbine has to start first pulling the pump up to the right speed. Then the motor takes over and the turbine flow closes. This also assumes that there is enough water available in the upper reservoir for the entire start-up sequence.

Alternative 2

The number of pumps can be increased to for example 4, such that each of them draws up to 1.25 MW. The inlet is submerged the length of which can be adjusted with little impact on the price. The flexibility of the plant's pump capacity will be significantly increased varying from 0.6 m3/s for one pump in service to 2.4 m3/s for 4 pumps in service, each of which is equivalent to 1.25 MW power consumption. Pump start-ups are done with VSD for each pump (using a switch) to limit the start-up current to the nominal current. The flexibility is high and pumping can be done completely independent of power source. The pumps' asynchronous motors are robust and can withstand variation in grid frequency; they go only a few revolutions faster or slower. The pumps can be run on the local network or the main grid. Overall dimensions of the pump cells (intakes) become relatively large as isolation of each pump from the others by use of dividers between the cells are required.

Conclusion pump configuration

Alternative 1 would be more appropriate the larger the plant. For a plant of the size applicable to Suðuroy, it seems, however, that Alternative 1 will have overly complicated mechanical sets with low operational flexibility, as well as becoming costly. We therefore exclude Alternative 1 and suggest Alternative 2 (turbine is separated from the pumps), using well-proven-technology industrial pumps with relatively easy access to both service and spare parts. From an operational point of view this solution is very flexible.

The pumping station can also, if necessary, be physically separated from the turbine cavern. In this project, however, we have assumed that pumps and turbine be located in the same cavern, serviced by the same crane and station facilities.

The peak efficiency of Alternative 2 will be equal to that of Alternative 1 (turbine and pump on the same shaft), as the water will undergo exactly the same processes on the way from the Vatnsnes system to Miðvatn, and back again.

3.5 COST ESTIMATE

Pumped Storage Suduroy, Faroe Islands Preliminary cost estimate - 2013							
	Quantity	Unit	Type	NOK/unit	Unit	Total, NOK	Total, NOK
Civil Works*:							
Power station:							
Tunnel opening					LS	250 000	250 000
Access tunnel incl. of cable culvert	500	m	18 m² Decline 1:7	26 000	m	13 000 000	13 000 000
Power station cavern	3 200	m³	Underground	1 600	m³	5 120 000	5 120 000
Waterways:							-
Connection to Vatnes tunnel	50	m	12 m²	13 000	m³	650 000	650 000
Tunnel to shaft base	25	m	12 m²	13 000	m	325 000	325 000
Embedded penstock shaft 1:1 to Midvatn	225	m	D=1,200 mm	22 000	m	4 950 000	4 950 000
Tunnel, top shaft to lake piercing	350	m	12 m²	13 000	m	4 550 000	4 550 000
Gate shaft and gate house					LS	500 000	500 000
Miscellaneous components			10% of above	10 %		2 934 500	2 934 500
Temp. works, rig etc			30% of above	30 %		9 683 850	9 683 850
Total Civil Works price level 2010						41 963 350	41 963 350
Price escalation 2010 - 2013 Total Civil Works **			~	10 %		4 196 335	4 196 335
							-
Total Civil Works price level 2013						46 159 685	46 159 685
Electro-mechanical works:							+25% larger turbine, generator and transformer
Mechanical works						25 475 000	26 425 000
Trashrack, 3x2,5 m, 10 mVs	1	pcs		250 000		250 000	250 000
Maintenance gate at intake, or stop log system	1	pcs		200 000		200 000	200 000
Intake gate, self closing, 0.9x0.9 m, 10 mVs	1	pcs		600 000		550 000	550 000
Trashrack modifications Vatnsnes	1	pcs		100 000		100 000	100 000
Embedded penstock DN1200	225	m		25 000		5 625 000	5 625 000
Turbin inlet pipe from end embedded penstock to turbine, DN1200mm, with cast-in ribs, bifurcation etc	25	m		30 000		1 500 000	1 500 000
Pipe supports, turbine inlet pipe	25	m		5 000		250 000	250 000
Pump pipe Ø=400-1200mm, with bifurcation for each pump	1	pcs		1 200 000		1 200 000	1 200 000
Vertikal Peltonturbin, 2,5 MW, 500 o/min, 5 dyser with governtor and TSV	1	pcs		5 400 000		6 300 000	7 150 000
Vertical centrifugal pumps, 3-stage 1.25 MW, 1500 o/min	4	pcs		1 600 000		6 400 000	6 400 000
Valve and venting/bleeding system for pumps	4	pcs		150 000		600 000	600 000
Power house crane, 15 tons	1	pcs		1 000 000		1 000 000	1 000 000
Cooling water system	1	pcs		1 500 000		1 500 000	1 600 000
Electrical works						13 550 000	14 720 000
Generator, 3,1 MVA, 500 o/min	1	pcs		3 000 000		3 000 000	3 500 000
Motors, 1.25 MVA, 1500 o/min	4	pcs		450 000		1 800 000	1 800 000
Transformer, 3,1 MVA	1	pcs		750 000		750 000	920 000
Variable speed drive (VSD)	1	pcs		500 000		500 000	500 000
Control and protection system	1	pcs		5 000 000		7 500 000	8 000 000
Miscellaneous				10 %		3 902 500	4 114 500
Total Electro-mechanical works						42 927 500	45 259 500
Transmission lines:							
Windpark - power plant access tunnel	5	km	22 kV - FeAl 70	600 000		3 000 000	3 000 000
Switchyard at powerhouse access tunnel (not yet included)							
Connection from/to power grid, 22 kV cables	500	m	Oil filled	2 500		1 250 000	1 250 000
Miscellaneous				5 %		212 500	212 500
Total Transmission lines						4 462 500	4 462 500
Subtotal all works						93 549 685	95 881 685
Contingecies:							
Civil works				20 %		9 231 937	9 231 937
El. mech.				10 %		4 292 750	4 292 750
Transmission lines				5 %		223 125	223 125
Subtotal contingencies						13 524 687	13 524 687
							-
SUBTOTAL						107 074 372	109 406 372
							-
Adm, Eng, superv, etc.				10 %		10 707 437	10 940 637
							-
SUBTOTAL						117 781 809	120 347 009
GRAND TOTAL						117 800 000	120 300 000
							-
							-
Subtotal all works ex. contingencies						93 549 685	95 881 685
							-
Adm, Eng, superv, etc.				10 %		9 354 969	9 588 169
							-
SUBTOTAL ex. contingencies						102 904 654	105 469 854
GRAND TOTAL ex. contingencies						102 900 000	105 500 000
*Price Basis - Early stage cost estimation for planning of power plants in Norway, 2010							
**Based on World Bank MUV-Index for 2010 and the projection for 2013 published on 7 sep 2012							

4 Grid

The Suðuroy grid and power system is relatively small. The new wind farm will in periods be a dominant power producer and the pumped storage plant will be a significant consumer while in pumping mode.

Integration of the new wind farm and pumped storage will increase stress on system operations. With wind power, by nature a fluctuating power source, and pumped storage dominating the total load, the risk of system collapse will increase the latter considering system response to faults and loss of load etc.

An Elfelagið SEV pre-requisite for pumped storage on Suðuroy is connecting the local grid to the main grid by a subsea power cable.

Nordic Energy Research indicated that the study shall be based on up to 100 % wind power supply in the power system in periods with much wind, even if this is a challenge for grid operation.

Grid connection and power system operation have not been part of this study. In a previous study by Norconsult for SEV in 2009/2010 (study for integrating wind power and pumped storage in the main grid), the preliminary power system analysis indicated that such integration will be technically feasible, but will, however, require more detailed studies.

Integrating a new wind farm and pumped storage in the Suðuroy grid will require detailed power system studies at a later stage to identify the need for grid investments (reinforcements) and to verify the power system operation and response.

5 Production simulations

5.1 MODEL USED FOR SIMULATION

The model includes the existing reservoirs Miðvatn and Vatnsnes and the Vatnsnes-branch of the existing power plant in Botní.

The Ryskivatn-branch in the power plant in Botní was not included in the simulation, hence references to Botní further on the Vatnsnes-branch only are meant.

As new elements, the pumped storage power plant as well as the 10 MW wind farm were introduced to the system. Input data are described in the next chapter.

For the simulations wind data and power demand forecast are required[4]. On this basis and a series of reservoir inflows the program optimizes the operation of the pumped storage plant and the hydropower production in Botní.

In situations where demand exceeds the production from wind and hydropower the model assumes additional supply from another source of power.

Figure 6 below illustrates the model that was used for the simulations.

In addition to the base case, to other cases were simulated:

+ 25 % turbine capacity in the pumped storage plant with other variables unchanged

+ 25 % turbine capacity + the same usable volume in the Miðvatn reservoir as in Vatnsnes (i.e. volume in Miðvatn enlarged from 525 000 m^3 to 725 000 m^3, requiring about 1,2 m higher FSL in Miðvatn).

[4] Exception: wind turbine production can be regulated down if the power could not be used for general demand or pumping.

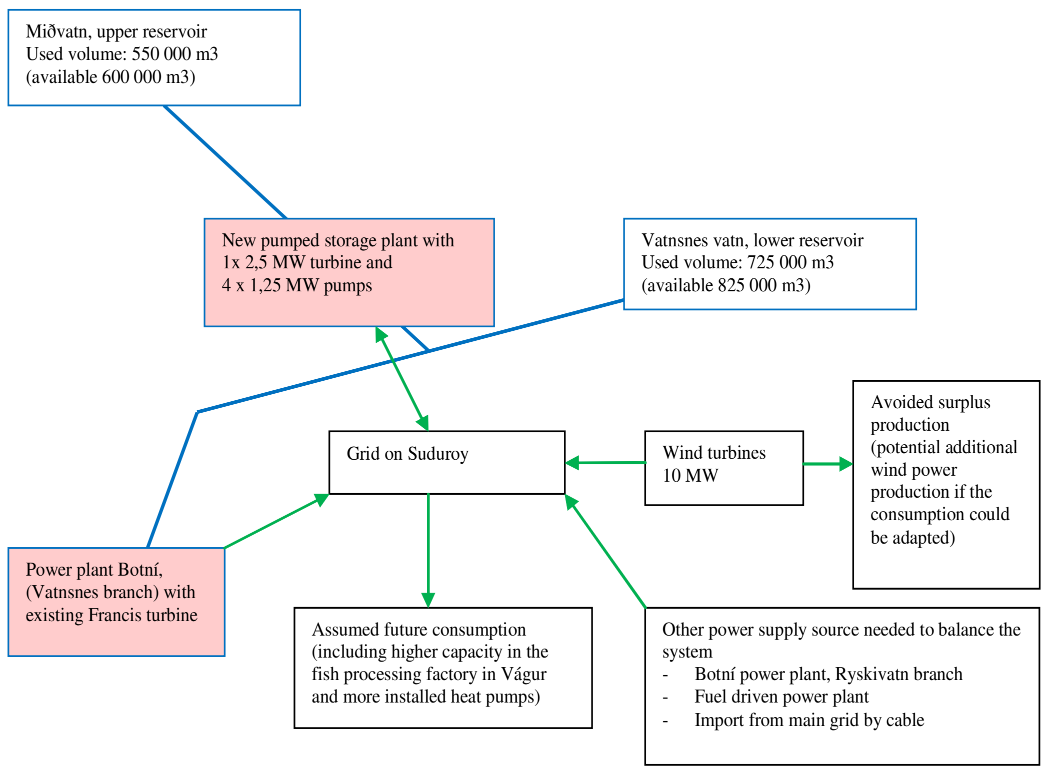


Figure 6 Elements of the model that was used for simulating power production and demand on Suðuroy (base case). The blue lines indicate the parts of the pumped storage plant and the Vatnsnes-branch of the power plant in Botní. The green lines symbolize the exchange of power.

5.2 INPUT DATA

5.2.1 *Demand*

The demand data were provided by Jarðfeingi. The data are partly based on the actual demand on Suðuroy for 2012 (provided by SEV). As the fish processing factory in Vágur only started operation in summer 2012, some research was made to include full production in this factory, including assumed higher capacity in the future.

In addition it was assumed that more heat pumps would be used in the future. The data were produced showing hourly demand for one year that was "endlessly" repeated in the simulation.

The consumption data are considered to be good for a "future model year".

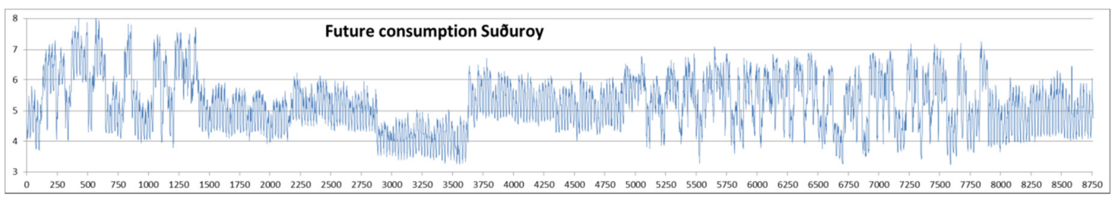


Figure 7 Assumed future demand on Suðuroy, data for one "model year" provided by Jarðfeingi

5.3 INFLOW TO RESERVOIRS

The inflow to the reservoirs is calculated based on the production data (power/water use) from the Botní power plant. According to SEV overflow hardly ever occurs, which means that the production can be considered a good bases for calculating the inflow.

The Ryskivatn-branch in Botní today gets water from both Miðvatn and Ryskivatn. It is assumed that the respective catchments contribute proportionally to their size. As Miðvatn is at a higher elevation than Ryskivatn the inflow to Miðvatn may have been estimated somewhat too low.

As production data for Botní were available on monthly bases only with no reservoir level variations available, the inflow was assumed constant for each month in the 11-year period for which data was available.

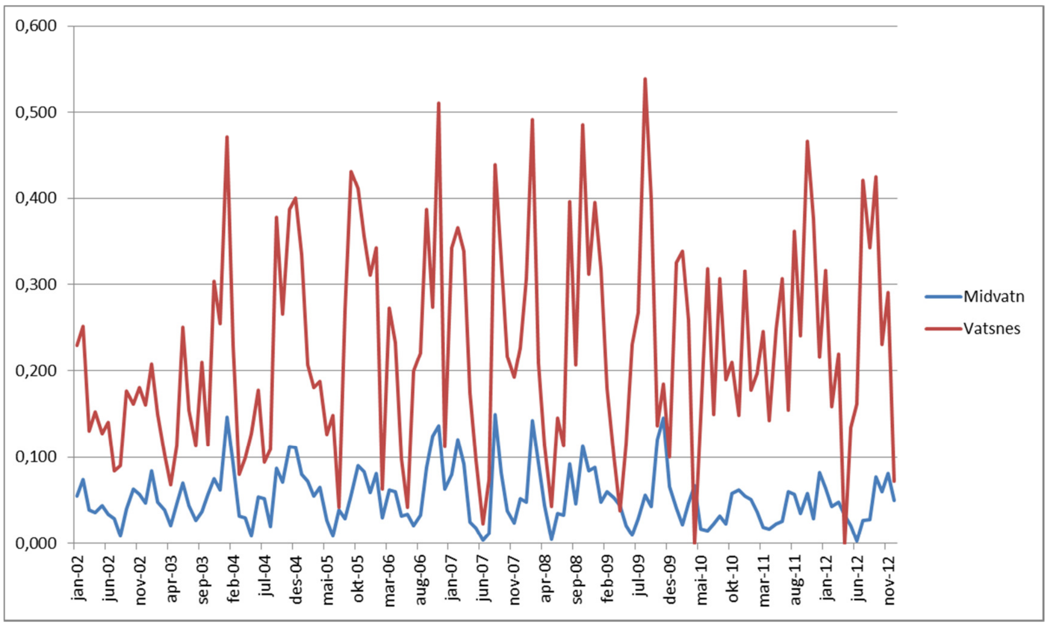


Figure 8 Hourly inflow data in m3/s to the reservoirs Miðvatn and Vatnsnes from January 2002 to December 2012.

The available inflow data are regarded as sufficient and good as input for the simulations. The capacity of the existing turbines at Botní is large (relative to inflow) and there is no spill, hence monthly values for the production provides a sufficient basis for the analysis. Data for 11 years is considered to provide a good basis.

5.4 WIND DATA

Wind data measured by the Danish Meteorological Institute, DMI were provided by Jarðfeingi. The wind measurements were effected at 10 m altitude and were adjusted to match an assumed wind speed at 45 m altitude. The wind power production was calculated based on the power curve for an Enercon E 44 (0.9 MW) turbine. In the simulation, 11 turbines were used (9.9 MW total effect).

Hourly wind data were available for the years 2007 – 2012. These data were also used for simulating the years 2002 – 2006, as no wind data were available for this period.

The available wind data are regarded as sufficient and good as input for the simulations.

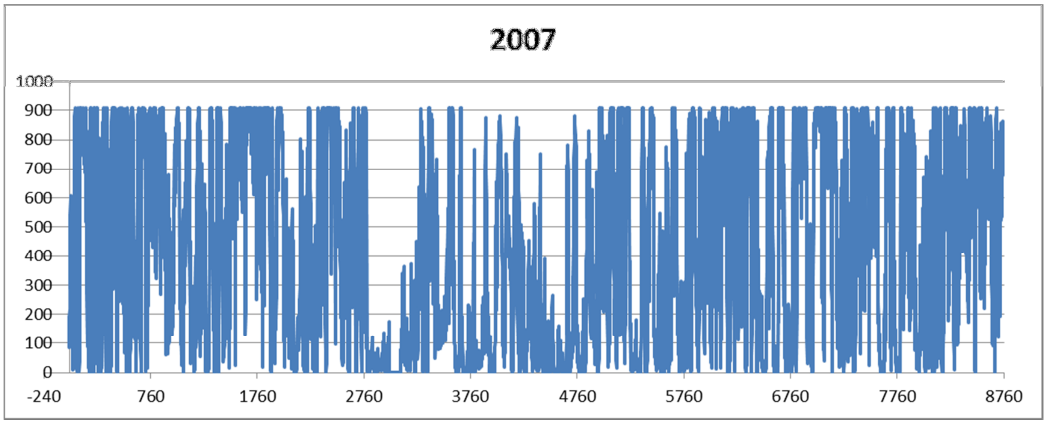


Figure 9 Wind power production per 0.9 MW Enercon turbine for the year 2007. X-axes: hours per year, y-axes: power production in kW

The figure shows highly fluctuating production, however, at maximum capacity for a significant number of hours annually. Only during few periods the wind power production is low for several consecutive days.

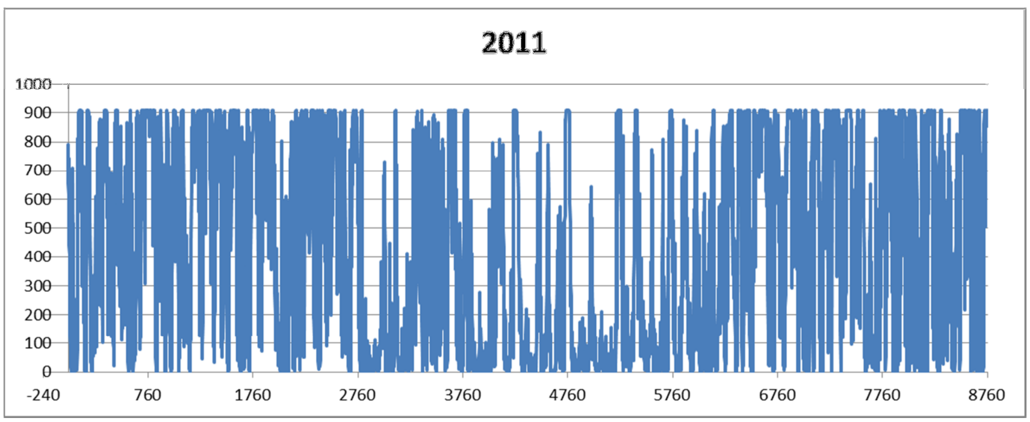


Figure 10 Wind power production per 0.9 MW Enercon turbine for the year 2011.X-axes: hours per year, y-axes: power production in kW

The figure shows highly fluctuating production, however, at maximum capacity for a significant number of hours annually. For both years shown, spring to autumn (hours 2760 -5760), the periods with low production are longer.

5.5 SIMULATION RESULTS

The simulations were made for each hour from 1.1.2002 - 31.12.2012. The simulations included an optimization for the operation of pumps and turbines, as well as reservoir levels/volumes in order to maximize total production of renewable energy. The tables (Table 2 and Table 3) and the figure below (Figure 11) show the simulation results.
With 10 MW of wind power installed on Suðuroy and with a new pumped storage plant, the island can be supplied with more than 80% renewable energy. Wind power will on average contribute with 65%, hydro power with 18 % whereas 17 % must be imported from the main grid or be produced by other means.

Table 2 Share of power source

	Base case	+ 25% turbine capacity	+ 25% turbine capacity and larger upper reservoir
Wind power	64,9 %	65,1 %	65,3 %
Hydro power	18,5 %	18,8 %	19,0 %
Fuel based power production or import from main grid	16,6 %	16,1 %	15,7 %
	100 %	100 %	100 %

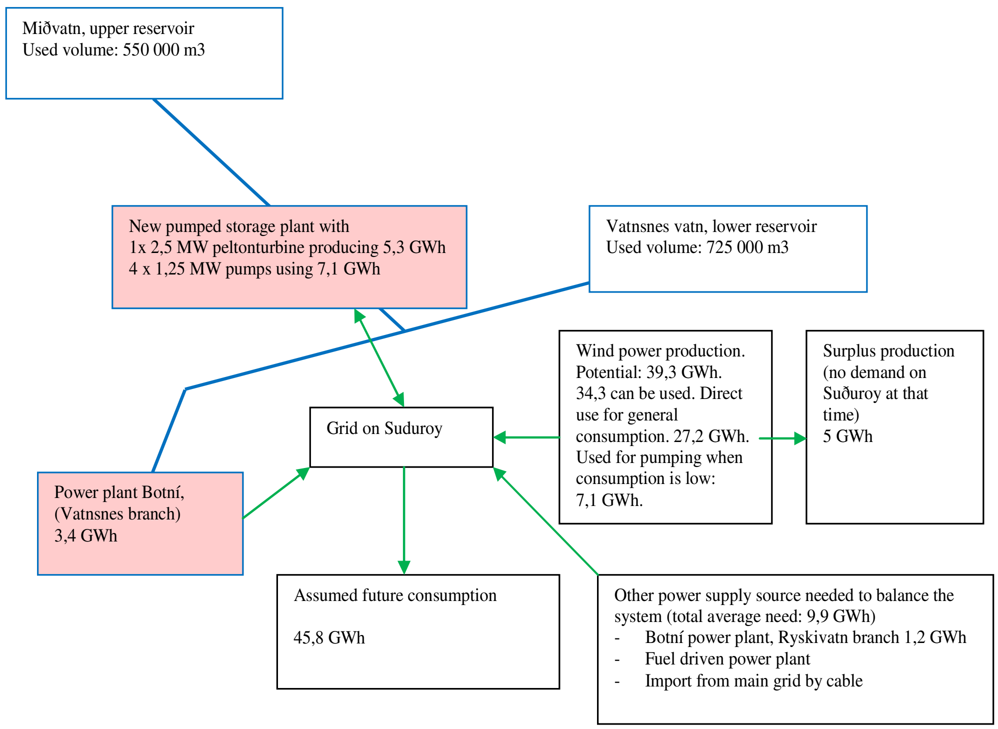


Figure 11 Power demand and production in the system, base case

Table 3 Main results from the simulation of power production/ demand. Average per year based on hourly simulations.

Production	Base case	+ 25% turbine capacity	+ 25% turbine capacity and larger upper reservoir
	GWh	GWh	GWh
Wind power production (used for general consumption and pumping)	**34,3**	**34,6**	**34,9**
Hydropower production (pumped storage and Vatnsnes branch in Botni)	8,6	8,8	9,0
Hydropower production (Ryskivatn branch in Botni)	1,2	1,2	1,2
Total hydropower	**9,8**	**10,0**	**10,2**
Wind-and hydropower available	44,1	44,6	45,1
Fuel based power production or import from main grid	**8,8**	**8,6**	**8,4**
Total power production	**52,9**	**53,2**	**53,5**
Consumption			
	GWh	GWh	GWh
General consumption	45,8	45,8	45,8
Pumping energy	7,1	7,4	7,7
General consumption and pumping	**52,9**	**53,2**	**53,5**
Surplus wind power production (no demand on Suðuroy)	*5,0*	*4,7*	*4,4*

As seen in the table above, the simulations indicate that 25% larger generating unit (turbine discharge increased from 1.8 to 2.25 m³/s) will yield 0.2 GWh higher hydropower production. A rough cost estimate suggests a cost increase of approximately 2.6 MNOK for this capacity increase.

A larger upper reservoir (725 000 m3 instead of 550 000 m3) would contribute with additional 0.2 GWh hydropower.

5.6 CHANGE OF PRODUCTION IN THE BOTNÍ POWER PLANT

The inflow from the Miðvatn reservoir is simulated being used in the pumped storage plant and has to be subtracted from the overall production of the Ryskivatn branch in the Botní power plant. On average the remaining power production will be 42 % of the production today, i.e. 0.86 GWh, which is about 10 % of the power needed from "alternative" sources.

Reservoir	Catchment area		Part
Ryskivatn	1,5	km2	58 %
Midvatn	1,1	km2	42 %
Total Ryskivatn branch	2,6	km2	100 %

Production in Botní for the years 2002-2012 was 4.95 GWh

- Power unit 1 (Ryskivatn branch) 2.04 GWh
- Power unit 2 (Vatnsnes branch) 2.91 GWh.

With a pumped storage plant, the production in Botní will be reduced to 4.6 GWh, because the water from Miðvatn will be used in the Vatnsnes branch with a lower head.

- Power unit 1 (Ryskivatn branch) 1.18 GWh
- Power unit 2 (Vatnsnes branch) 3.44 GWh

The head between Miðvatn and Vatnsnes is used in the pumped storage turbine, meaning that the overall hydropower production from the Miðvatn water will increase as of today it drops down to Ryskivatn unused.

6 Economical issues

With a cost of 2.9 NOK/kWh, wind power production on the Faroe islands is cheap. As only surplus power is used for pumping, the cost per kWh is even lower (2.3 NOK/kWh) when pumped storage plant is included in the considerations, because the pumps create a higher demand.

Investment cost wind turbines	8	mill. NOK/MW
For 9,9 MW (11 E 44 turbines)	79,2	mill. NOK
Wind power production (meeting demand for general consumption)	27,19	GWh
Wind power production (for general consumption and puming)	34,30	GWh
Costs wind power/ kWh (only for general consumption)	2,9	NOK/kWh
Costs wind power/ kWh for general consumption and pumping)	2,3	NOK/kWh

The costs for establishing a pumped storage plant are relatively high. With a larger capacity, the cost/kWh goes slightly down, when only considering hydro power.

	Base case	**+ 25% turbine capacity**	
Hydropower existing power plants	4,95	4,95	GWh
Hydropwer additional GWh	4,57	4,77	GWh
Costs pumped storage plant in millions	102,9	105,5	NOK
Costs pumped storage plant / kWh	22,5	22,1	NOK/kWh

	Base case	**+ 25% turbine capacity**	
Investment cost wind power + pumped storage	182,1	184,7	mill NOK
Wind for general consumption + new (net) hydropwer production	31,8	32,0	GWh
Production cost i kr/kWh	5,7	5,8	NOK/kWh

As the pumped storage plant will produce renewable power when the wind turbines cannot deliver and is driven with surplus power, the wind farm and the pumped storage power plant should be regarded as a total.

The overall cost for the introduction of 10 MW wind power and a pumped storage plant is about 5.7 NOK/kWh. When the investment cost for wind and hydropower plants are seen as a total and devised through total production, a larger turbine has a negative effect on the cost/kWh, i.e. the cost rises slightly to 5.8 NOK/kWh.

The wind turbines need to be replaced after about 25 years, while the lifespan for hydro power plants is assumed to be in the range of 40-70 years, i.e. the respective values for NOK/kWh cannot be compared directly. It is recommended to initiate a more detailed economic analysis for a project with wind turbines and a pumped storage plant and compare it with future power production based on fossil fuels.

Increased power production from renewable resources will make the Faroe Island more independent to fuel import.

7 Environment

A pumped storage plant at Suðuroy has a minimum of impact on the environment, as the reservoirs already exist. Anyhow, some negative impacts must be expected.

The main consequences that are expected are as follows:

- As operation of pumped storage plant involves that the reservoirs will be drawn down and refilled much more frequently than today, the surrounding banks will to a larger extent be exposed to erosion/degradation. This may have strong impact on plants and animals living in the reservoirs today.
- During times of low reservoir levels, the eroded shoreline will be exposed. This may trigger negative reactions by visitors.
- The new aquatic connection between the reservoirs may have an impact on the biodiversity of the reservoirs.

As a positive consequence, it must be mentioned that the pumped storage plant will replace hydrocarbon based power production with power from renewable resources, thus reducing the output of CO_2 to the atmosphere.

8 Conclusions[5] to be generalized?

In sparsely populated areas with a high share of non-renewable energy, alternative ways to produce power should be considered. Fuel based power production is relatively costly and renewable energy may provide a cheaper alternative on the long run.

Whether renewable power production based on wind, water or other sources is feasible is highly dependent on local conditions. At locations with a certain reservoir capacity, pumped storage may help to match production and demand better. Detailed production simulations are important in order to assess projects.

Integrating large consumers (pumped storage) and new non-firm renewable power production in a weak grid will require detailed studies. Operational challenges and necessary investments must be identified in order to insure stable operational conditions at all times.

[5] The focus of this study has been limited to a high level appraisal and the following conclusions are therefore also based on experience from other projects.

9 Attachment

9.1 DETAILED SIMULATION RESULTS

Base case	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average 2002-2012
STATISTICS												
pump 1 work hours / GWH	-3,08	-3,40	-2,98	-3,08	-3,24	-3,38	-2,72	-3,43	-3,23	-3,23	-3,36	-3,19
pump 2 work hours / GWH	-2,23	-2,44	-2,15	-2,34	-2,37	-2,48	-1,94	-2,46	-2,27	-2,44	-2,45	-2,32
pump 3 work hours / GWH	-1,21	-1,39	-1,14	-1,38	-1,30	-1,45	-1,03	-1,40	-1,21	-1,44	-1,39	-1,30
pump 4 work hours / GWH	-0,24	-0,31	-0,32	-0,28	-0,31	-0,33	-0,18	-0,33	-0,33	-0,29	-0,32	-0,29
Total pumping energy GWH	-6,76	-7,55	-6,58	-7,07	-7,22	-7,65	-5,87	-7,61	-7,03	-7,40	-7,51	-7,11
Pelton work hours / GWH	4,98	5,30	4,99	5,21	5,37	5,53	4,73	5,44	4,89	5,23	5,34	5,30
Loss pumped storage												-1,81
Francis work hours / GWH	2,63	2,72	3,71	3,74	3,60	3,59	3,79	3,50	3,38	3,75	3,44	3,44
Total hydropower (GWH)	7,62	8,02	8,70	8,95	8,97	9,12	8,52	8,94	8,27	8,98	8,78	8,62
Wind power production (GWH)	39,34	38,39	34,89	40,41	42,42	40,98	39,34	38,39	34,89	40,41	42,42	39,26
Wasted wind power (GWH)	4,76	4,09	3,31	6,04	6,53	5,35	5,66	4,02	2,86	5,71	6,24	4,96
Consumption - (GWH)	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76
Lacked supply (GWH)	-10,32	-10,97	-12,06	-9,51	-8,12	-8,65	-9,42	-10,06	-12,48	-9,48	-8,30	-9,94

+25% turbine capacity	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average 2002-2012
STATISTICS												
pump 1 work hours / GWH	-3,31	-3,50	-3,04	-3,23	-3,44	-3,59	-2,80	-3,51	-3,25	-3,41	-3,56	-3,33
pump 2 work hours / GWH	-2,38	-2,50	-2,19	-2,47	-2,52	-2,63	-2,02	-2,53	-2,29	-2,60	-2,61	-2,43
pump 3 work hours / GWH	-1,29	-1,42	-1,16	-1,45	-1,38	-1,52	-1,08	-1,42	-1,22	-1,51	-1,44	-1,35
pump 4 work hours / GWH	-0,25	-0,31	-0,31	-0,28	-0,32	-0,34	-0,18	-0,32	-0,33	-0,30	-0,35	-0,30
Total pumping energy GWH	-7,23	-7,74	-6,71	-7,43	-7,66	-8,08	-6,09	-7,78	-7,09	-7,82	-7,97	-7,42
Pelton work hours / GWH	5,24	5,41	5,14	5,53	5,72	5,83	4,96	5,55	4,96	5,58	5,64	5,41
Loss pumped storage												-2,00
Francis work hours / GWH	2,58	2,68	3,67	3,64	3,57	3,58	3,76	3,49	3,38	3,69	3,45	3,41
Total hydropower (GWH)	7,82	8,09	8,82	9,17	9,29	9,41	8,72	9,04	8,34	9,26	9,09	8,82
Wind power production (GWH)	39,34	38,39	34,89	40,41	42,42	40,98	39,34	38,39	34,89	40,41	42,42	39,26
Wasted wind power (GWH)	4,29	3,90	3,18	5,68	6,08	4,92	5,43	3,86	2,80	5,29	5,78	4,66
Consumption - (GWH)	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76
Lacked supply (GWH)	-10,12	-10,91	-11,94	-9,29	-7,80	-8,37	-9,23	-9,96	-12,41	-9,20	-7,99	-9,75

+25% turbine capacity+upper reservoir 725 000 m3 (=lower reservoir)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average 2002-2012
STATISTICS												
pump 1 work hours / GWH	-3,41	-3,61	-3,14	-3,36	-3,66	-3,72	-2,88	-3,62	-3,24	-3,60	-3,71	-3,45
pump 2 work hours / GWH	-2,46	-2,57	-2,26	-2,57	-2,68	-2,71	-2,09	-2,61	-2,27	-2,71	-2,77	-2,52
pump 3 work hours / GWH	-1,37	-1,46	-1,20	-1,52	-1,47	-1,57	-1,12	-1,46	-1,20	-1,62	-1,56	-1,41
pump 4 work hours / GWH	-0,28	-0,32	-0,32	-0,31	-0,36	-0,35	-0,21	-0,33	-0,31	-0,35	-0,38	-0,32
Total pumping energy GWH	-7,52	-7,97	-6,93	-7,76	-8,17	-8,36	-6,30	-8,02	-7,02	-8,28	-8,43	-7,70
Pelton work hours / GWH	5,40	5,51	5,24	5,72	6,00	6,01	5,10	5,70	4,92	5,82	5,94	5,58
Loss pumped storage												-2,13
Francis work hours / GWH	2,55	2,68	3,69	3,62	3,56	3,60	3,76	3,56	3,42	3,66	3,39	3,41
Total hydropower (GWH)	7,95	8,19	8,94	9,34	9,57	9,61	8,86	9,26	8,35	9,47	9,33	8,99
Wind power production (GWH)	39,34	38,39	34,89	40,41	42,42	40,98	39,34	38,39	34,89	40,41	42,42	39,26
Wasted wind power (GWH)	4,00	3,66	2,96	5,35	5,58	4,64	5,22	3,61	2,87	4,83	5,32	4,37
Consumption - (GWH)	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76	45,76
Lacked supply (GWH)	-9,99	-10,81	-11,82	-9,12	-7,52	-8,17	-9,08	-9,74	-12,41	-8,99	-7,75	-9,58

9.2 RESERVOIR VOLUMES AND RESERVOIR LEVELS

The following figures show examples for reservoir filling. The figures show that reservoir volumes in general are sufficient, as the upper reservoir only in short periods is completely full and the lower reservoir rarely is empty. The figures show the year 2012, which is a year with about average inflow.

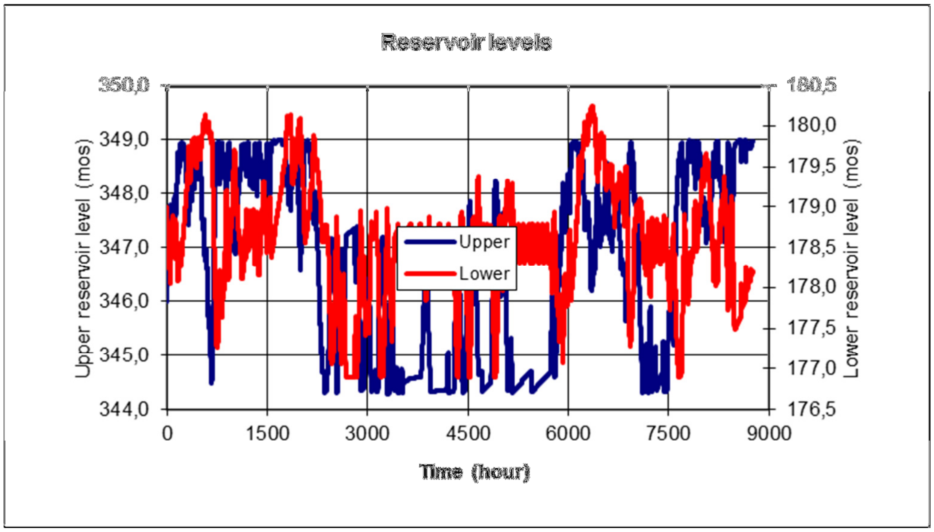


Figure 12 Reservoir levels for the "base case", with 2,5 m^3/s turbine capacity in the PSPP, with an unchanged reservoir volume (upper reservoir: 550 000 m^3, lower reservoir: 725 000 m^3). The read curve show the water level in the lower reservoir, the blue curve shows the water level in the upper reservoir for the year 2012.

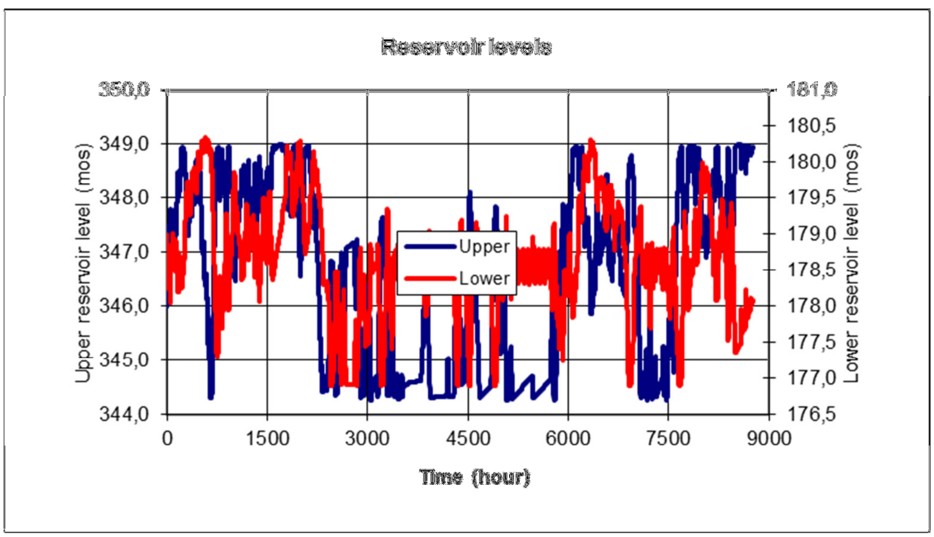


Figure 13 Reservoir levels with 3,125 m3/s turbine capacity in the PSPP, with an unchanged reservoir volume (upper reservoir: 550 000 m3, lower reservoir: 725 000 m3). The read curve show the water level in the lower reservoir, the blue curve shows the water level in the upper reservoir for the year 2012. As the larger turbine empties the upper reservoir more quickly, the reservoir size is more completely filled.

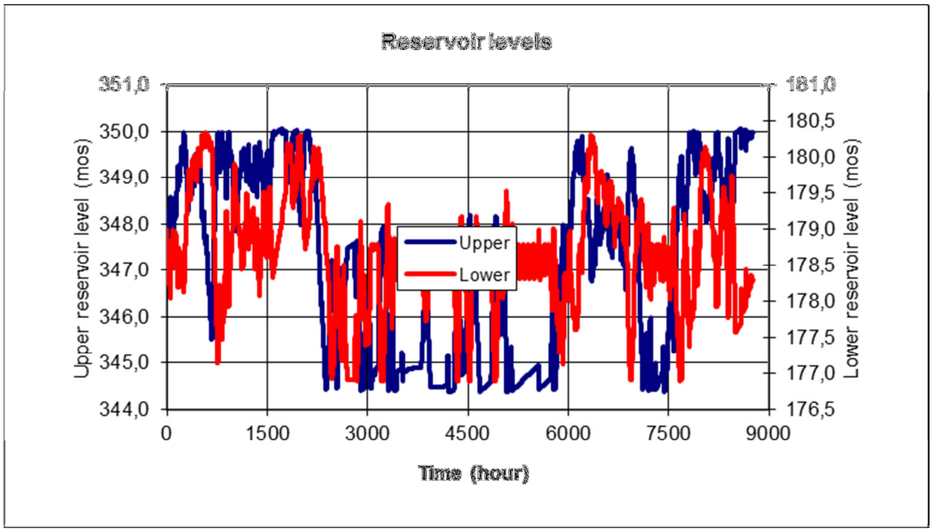


Figure 14 Reservoir levels with 3,125 m^3/s turbine capacity in the PSPP and with a higher upper reservoir volume (725 000 m^3), resulting the same reservoir capacity in the lower and the upper reservoir. The read curve show the water level in the lower reservoir, the blue curve shows the water level in the upper reservoir for the year 2012. In times with much inflow, the reservoir reaches it maximum water level also with the slightly larger reservoir.