TR A7227- Unrestricted

Report

Norwegian hydropower for large-scale electricity balancing needs

Pilot study of technical, environmental and social challenges

Authors
Eivind Solvang (lead author), Julie Charmasson, Julian Sauterleute, Atle Harby, Ånund Killingtveit, Helene Egeland, Oddgeir Andersen, Audun Ruud, Øystein Aas

SINTEF Energy Research
Energy Systems
2014-02-14

CEDREN – Centre for Environmental Design of Renewable Energy: Research for technical development and environmental impact of hydro power, wind power, power lines and implementation of environment and energy policy.

SINTEF Energy Research, the Norwegian Institute for Nature Research (NINA) and the Norwegian University of Science and Technology (NTNU) are the main research partners. A number of energy companies, Norwegian and international R&D institutes and universities are partners in the project.

The centre, which is funded by The Research Council of Norway and energy companies, is one of eleven Centre for Environment-friendly Energy Research (FME). The FME scheme consists of time-limited research centres which conduct concentrated, focused and long-term research of high international quality in order to solve specific challenges in the field of renewable energy and the environment.

CEDREN Centre for Environmental Design of Renewable Energy

FME
CENTRE FOR
ENVIRONMENT-
FRIENDLY ENERGY
RESEARCH

SINTEF

SINTEF Energi AS
SINTEF Energy Research

Address:
Postboks 4761 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 73597200
Telefax:+47 73597250

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

KEYWORDS:
Balance power
Hydro storage
Pumped storage
Environmental impacts
Societal legitimacy

Report

Norwegian hydropower for large-scale electricity balancing needs

Pilot study of technical, environmental and social challenges

VERSION
1.0

DATE
2014-02-14

AUTHOR(S)
Eivind Solvang (lead author), Julie Charmasson, Julian Sauterleute, Atle Harby, Ånund Killingtveit, Helene Egeland, Oddgeir Andersen, Audun Ruud, Øystein Aas

CLIENT(S)
CEDREN

CLIENT'S REF.
CEDREN's Board

PROJECT NO.
12X757

NUMBER OF PAGES/APPENDICES:
100

ABSTRACT

Many European countries are increasing the proportion of wind and solar power generation in their electricity supply. This increases the need for energy storage to compensate for the difference between production and consumption, known as balance power. Hydropower with reservoirs is the only form of renewable energy storage in wide commercial use today. Existing Norwegian hydropower reservoirs have a large balance power potential within the current regulations limits, and this report shows the results from a pilot study of possibilities and challenges.

Implications for the operational schemes of the affected reservoirs when balancing wind power from the North Sea area are analysed. Based on time series of stage and live storage volume of the upper and lower reservoirs, balancing power on daily basis was simulated on top of the current operation of three existing power plants. This was assumed to be realised by installing reversible turbines in addition to the existing ones. The objectives were to compare the current patterns of water level fluctuations to the simulated patterns (season, frequency, rate of change) and to analyse which factors determine how much power can actually be balanced compared to how much is required to be balanced (turbine capacity, free reservoir volumes).

The societal aspects of using Norwegian hydropower reservoirs for large-scale balancing services for Europe are analysed according to how these are expressed by key Norwegian stakeholders. Does this use of Norwegian hydropower have legitimacy, what are the drivers supporting this idea, what are the barriers, and what approaches are necessary to overcome important barriers, are the questions that is addressed.

PREPARED BY
Eivind Solvang

SIGNATURE
Eivind Solvang

CHECKED BY
Michael Belsnes

SIGNATURE
Michael Belsnes

APPROVED BY
Knut Samdal

SIGNATURE

REPORT NO.
TR A7227

ISBN
978-82-594-3524-8

CLASSIFICATION
Unrestricted

CLASSIFICATION THIS PAGE
Unrestricted

Table of contents

List of abbreviations

7Days-Avg	Balancing power scenario based on the deviation of the wind power generation from the moving average over seven days
CEDREN	Centre for Environmental Design of Renewable Energy (http://www.cedren.no/)
Dev-Avg	Balancing power scenario based on a certain percentage deviation of the wind power generation from the long-term average
DN	Norwegian Directorate for Nature Management
DNT	Norwegian Trekking Association
ENTSO-E	European Network of Transmission System Operators for Electricity
HP	Hydropower plant
HRLW	High Regulated Water Level
LRWL	Low Regulated Water Level
LVK	Landssamanslutninga av Vasskraftkommunar (a Norwegian organization for hydroelectricity producing municipalities)
MoE	Ministry of the Environment
MoPE	Ministry of Petroleum and Energy
NGO	Non-governmental organization
NNV	Norwegian Society for the Conservation of Nature
NSCOGI	North Seas Countries Offshore Grid Initiative
NJFF	Norwegian Association of Hunters and Anglers
NVE	Norwegian Water Resources and Energy Directorate
TBM	Tunnel boring machine
TSO	Transmission System Operator
WWF	World Wide Fund for Nature (World Wildlife Fund until 1986)

1 Introduction

This report describes a large pilot study, using relatively simple modeling tools and analysis to assess challenges and opportunities for large-scale balancing and energy storage from Norwegian hydropower. For all the studies conducted, there are more advanced options of modeling and analysis using more comprehensive input data and parameters available. A comprehensive use of models and analysis is not possible in a pilot study, but the pilot study still gives relevant information and analysis based on necessary assumptions and precautions. Most of the activities in this study are further investigated in new projects in CEDREN and at SINTEF Energy Research, using more advanced models to conduct more detailed analysis.

1.1 Balance power from Norwegian hydropower reservoirs

Many European countries are increasing the proportion of wind and solar power generation in their electricity supply. Since it is not possible to store energy generated by such renewables, there will be an increased need for energy storage to compensate for the difference between production and consumption, known as balance power. Hydropower with reservoirs is the only form of renewable energy storage in wide commercial use today. Existing Norwegian hydropower reservoirs have considerable storage capacity that can be exploited for balancing services within the current regulations regarding highest (HRWL) and lowest (LRWL) regulated water levels.

The balance power capacity of Norwegian hydroelectric power stations can be increased by installing larger turbines and generators in some power stations, and by installing (reversible) pump turbines to pump water between two reservoirs. It will be necessary to build new tunnels in parallel to existing ones as well as new power stations in association with existing facilities.

The balance power capacity of hydroelectric power stations depends on how much power can be supplied during periods of shortage and how much power can be absorbed in periods of overproduction. Power can be absorbed if a power station can pump water up to a higher reservoir. In many power stations the capacity of the downstream reservoir will limit the amount of power which can be generated. Pumping at times of the day when the power demand is lowest (e.g. at night) will reduce the capacity restriction effect of the downstream reservoir. Such pumping will also increase the capacity of the upstream reservoir and the periods of power generation can be extended by pumping water back during the part of the day in which the power demand is lowest, to be used at the time when the demand is highest.

Implications for the operational schemes of the affected reservoirs when balancing wind power from the North Sea area are analysed. Based on time series of stage and live storage volume of the upper and lower reservoirs, balancing power on daily basis was simulated on top of the current operation of three existing power plants. The objectives were to compare the current patterns of water level fluctuations to the simulated patterns (season, frequency, rate of change) and to analyse which factors determine how much power can actually be balanced compared to how much is required to be balanced (turbine capacity, free reservoir volumes).This analysis is based on the results from a preliminary case study on large-scale balancing services from Norwegian hydropower (Solvang, Harby & Killingtveit 2012), showing the technical potential to develop 20,000 MW of new hydro where about 10,000 MW includes pumping.

The social acceptance of using Norwegian hydropower reservoirs for large-scale balancing services for Europe are analysed according to how these are expressed by key Norwegian stakeholders. Does this use of Norwegian hydropower have legitimacy, what are the drivers supporting this idea, what are the barriers, and what approaches are necessary to overcome important barriers, are the questions that is addressed. The analysis draws on an analysis of interviews with 22 informants, representing four interest groups, as well as the public authorities concerned. These interests include; energy companies, environmental NGOs, recreational NGOs, as well as the host communities. The interviews performed with the stakeholders focused on the how the idea of Norway as a provider of large-scale balancing services was considered by the different stakeholders in general, and not in relation to concrete projects.

The issue of social acceptance may be understood in several ways. In this report we have chosen to use a broad interpretation which includes environmental and economic aspects, questions of involvement, as well as reflections on the current national framework's ability to take key stakeholder considerations into account. The question of social acceptance is therefore treated as a question of societal acceptance.

The main drivers and barriers for large-scale exploitation of Norwegian hydropower for balancing services for Europe as expressed by the informants are presented according to each stakeholder group.

The timeframe in the current study is set to 2030 and beyond. At the same time it is necessary to pinpoint that the timeframe relevant for several of the key stakeholders is somewhat different. When reflecting upon the question of potential concerning the stakeholders' interests it is important to take into consideration that the question of time should be divided in to short, middle and a long term perspective. On the one hand the NGOs for example address the question of potential by directly referring to the political targets (2020 and 2050). On the other hand the companies (except Statnett who has 2030 as their timeframe) reflect upon the current political uncertainties – both nationally and internationally speaking – concerning political support for further investments in the national and international grid development, as well as for instance the unpredictability related to what is perceived as a time consuming concession process.

1.2 Driving forces

In March 2007 leaders of the European Union (EU) endorsed an integrated approach to climate and energy policy (Ruud & Knudsen 2009). This was followed by a set of specific objectives, known as the '20-20-20' targets – 20% reduction in greenhouse gas emissions compared to 1990 levels, 20% share of EU energy consumption to be sourced from renewable resources, and, finally, a 20% reduction in primary energy use (Ruud, Knudsen & Jacobsen 2011).[1]In addition the European climate Foundation (ECF) has taken the initiative to Roadmap 2050 which has the aim to provide pathways to achieve a low-carbon economy in Europe.[2]

These European initiatives have led to an increase in national efforts to promote further development of renewable energy resources as well as increased exchange of energy between European countries. As a result national action plans have been adopted by the Member states.[3] As an indicator of the need for balancing services, the National Renewable Energy Action Plan for Germany assumes a rise in the annual electricity production from wind energy plants (offshore and onshore) to increase from about 44,000 GWh in 2010 to about 106,000 GWh in 2020.[4] Development of new renewable production that lack energy storage capacity – like for instance wind- and solar energy – creates a backup demand. Hydropower with large reservoir capacity is regarded as one, among several other possible technologies, that can be used for such services. This has, amongst other things led to a renewed interest for Norwegian hydropower.

---

[1] Further details on http://ec.europa.eu/clima/policies/package/index_en.htm

[2] Further details on http://www.roadmap2050.eu/who_we_are

[3] Further details on http://ec.europa.eu/energy/renewables/transparency_platform/action_plan_en.htm

[4] Federal Republic of Germany: *National Renewable Energy Action Plan in accordance with Directive 2009/28/EC on the promotion of use of energy from renewable sources – The RES Directive*.

In Norway the role of hydropower has for more than a century been subject to support as well as controversy. On the one hand hydropower has represented economic development at the local and national level through income, employment opportunities and local social change. On the other hand hydropower – especially large scale hydropower installations – has been subject to controversy due to environmental impacts on biodiversity, landscape, as well as impacts on the local society (e.g. the rights of the Sami people). This has led to many conflicts since the 1960s, which culminated during the 1980s and 1990s with the decision to develop the Alta river watercourse for hydropower, followed by the completion of the National plan for protection of river courses against hydropower development. The lack of support for new large scale hydropower development was further confirmed in the Norwegian Prime Minister Jens Stoltenberg's speech on New Year 2001 where he stated that "(...) the time for new large scale hydropower development in Norway has come to an end."

Over the last decades a shift has taken place where the climate challenge increasingly became an important reference for the Norwegian energy policy in general, and for the management of hydropower in particular (Angell & Brekke 2011). Consequently, the energy policy context has changed from being largely a national issue, to increasingly becoming a part of a larger European context (Angell & Brekke 2011, Knudsen & Ruud 2011).

In the national political discourse the focus on climate change has led stakeholders to argue for new ways of developing Norway's hydropower resources. One major discourse is about how Norwegian hydropower can become a 'green battery' by providing balancing services for other renewable energy sources which has no storage capacity (Solvang, Harby & Killingtveit 2012). On a visit to London in January 2011 the Norwegian Prime Minister Jens Stoltenberg met with the British Prime Minister David Cameron, as well as colleagues from the Nordic and Baltic countries to discuss amongst other things the energy issues in general, and how to secure a better exchange of electricity across the countries. In an interview Stoltenberg proclaimed "-Norwegian hydropower is a unique energy resource. As opposed to coal, nuclear and wind power it can be stored in reservoirs and used in accordance to the need" (NTB, 20.01.2011). Hydropower is therefore given an important role not only in a Norwegian energy policy context, but increasingly also as a part of an international context.

In the public debate contrasting views as to how Norway can meet this challenge becomes apparent. These differences are not so much a result of different understandings of what, in this case, the term 'green battery' refers to, but rather a result, as this analysis will show, of the concerns stakeholders have when discussing the future of energy and environmental policy issues in Norway in general. In this picture the idea of a 'green battery' only poses one, among several, challenges.

1.3 Variation in wind power production

The electricity balancing needs as seen from Norwegian hydropower's point of view are expected to be closely related to the variation in wind power production and the demand for electricity in Northern and Western Europe.

Scenarios for wind power production in Europe were developed in the EU-funded project TradeWind. The variation in wind power production illustrated in Figure 1.1 and Figure 1.2 based on TradeWind's medium wind power capacity scenario year 2030. The offshore wind power part of this scenario in 2030 consist of 94.6 GW (94,600 MW) installed capacity in the North Sea in Belgium (3.0 GW), Denmark (5.6 GW), Germany (25.4 MW), UK (43.3 MW), Netherlands (12.0 GW) and Norway (5.4 MW).

Wind speed data from the 'Reanalysis' global weather model, combined with regional wind power curves and wind speed adjustment factors, is used for constructing synthetic wind power time series for specific grid model zones in the TradeWind project (Tande, Korpås, Warland, Uhlen & Van Hulle 2008). The calculations presented in Chapter 3 are based on time series of hourly electricity generation from the 94.6 GW installed capacity in the North Sea in 2030 from TradeWind with weather data for the years 2000 to 2006.

Figure 1.1 and Figure 1.2 show variation in simulated hourly wind power production (MW) throughout the year 2005 (as an example) based on the TradeWind 94.6 GW scenario. Figure 1.1 shows January – March and April – June, while Figure 1.2 shows July – September and October – December.

Figure 1.3 shows variation in wind power production (MW) throughout a year based on simulated hourly electricity generation for the years 2000 – 2006. The green graph shows the hourly variation for the year 2006 (as an example) and the blue graph shows the average hourly variation for the years 2000 – 2006.

Figure 1.4 shows hourly minimum (green graph) and maximum (blue graph) wind power production (MW) for the years 2000 – 2006. Each minimum and maximum figure is from the year that had lowest and largest production respectively that hour.

Table 1.1 shows average figures for the years 2000 – 2006. "P ≤ 10 %" means that the wind power production (MW) is less or equal 10 % of the installed capacity (0,1• 94.6 GW = 9,460 MW). An occurrence is a period when the production P is ≤ 10 %, ≤ 20 %, ≤ 30 %, ≥ 70 % or ≥ 80 % respectively.

Table 1.1 Average figures for the years 2000 – 2006 for occurrences of production P lower or larger a certain % of the installed capacity (94.6 GW).

	P ≤ 10 %	P ≤ 20 %	P ≤ 30 %	P ≥ 70 %	P ≥ 80 %
Number of occurrences (occurrences/year)	43	76	91	58	41
Average duration (h/occurrence)	21	30	40	28	19
Annual duration (h/year)	888	2276	3593[1]	1649	774
Annual duration (% of 8760h)	10	26	41	19	9
Annual production (TWh/year)	5	25	56	124	62
Annual production (% of tot. annual prod.)	2	7	16	37	18

[1] Quarterly distribution of the annual duration of 3593 h with production lower than 30 % of installed capacity (94.6 GW): January–March (560 h, 15 %), April–June (1109 h, 31 %), July–September (1359h, 38 %) and October–December (565 h, 16 %).

It is 91 occurrences per year when P ≤ 30 %. The average duration is 40 h/occurrence. The annual duration is 3593 h/year (41 %). The annual production when P ≤ 30 % is 56 TWh/year (16 % of the total annual production 339 TWh/year).

The average annual wind power production is 38.7 GW and 339 TWh, lowest in 2000 (37.0 GW and 324 TWh) and largest in 2005 (40.8 GW and 358 TWh). The average GW and the total TWh production are therefore relatively constant from year to year during 2000 – 2006.

The figures and the table show typical variation in wind power production, and demonstrate the need for power balancing. In order to balance this system and maintain a steady supply, of for example 48 GW (50 % of installed capacity), one will need a technology that can provide 29 GW when the wind power production is lower than 20 % (19 GW) of installed capacity. This happen 76 times a year in average (Table 1.1). Average duration time is 30 hours and total duration time is 2276 hours/year (26 %). Capacity factor C_F for the years 2000-2006 varies from 0.39 to 0.43, with an average of 0.41.

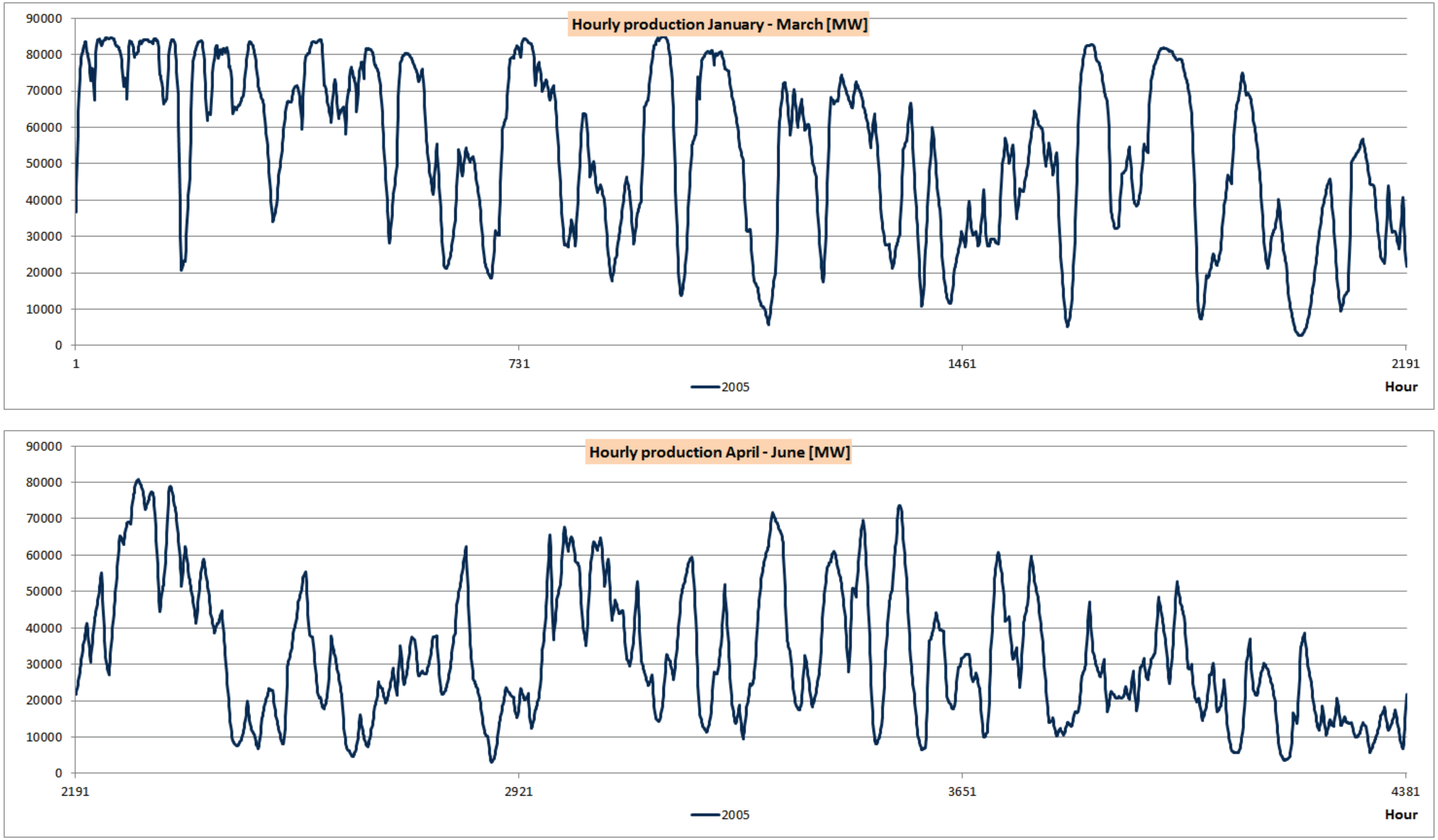
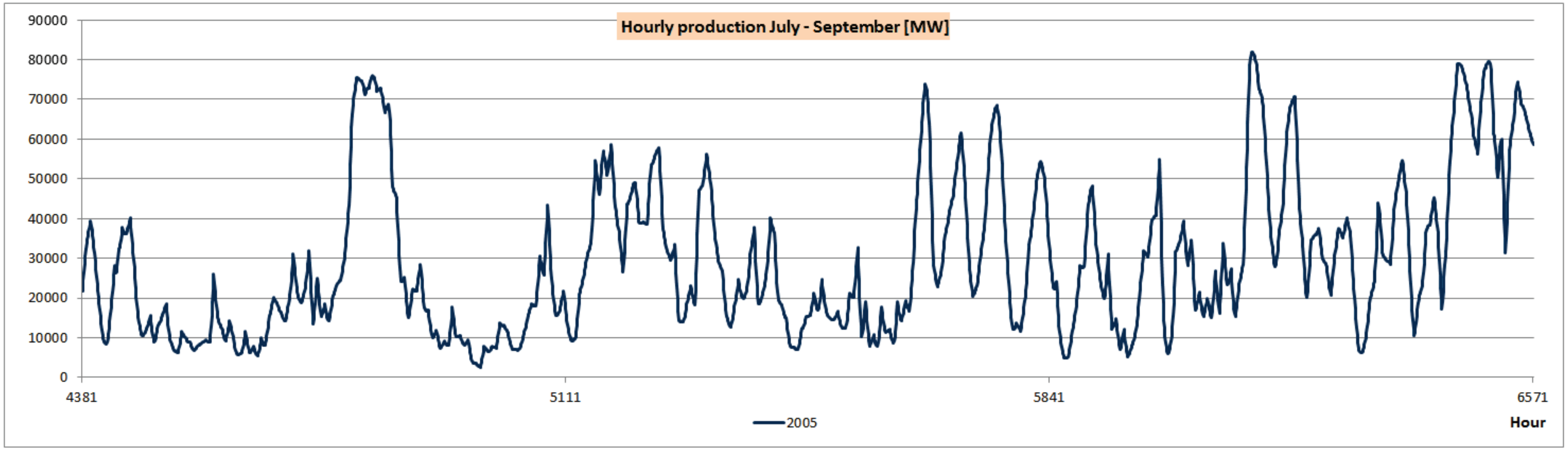


Figure 1.1 Hourly variation in wind power production (MW) throughout the year 2005.



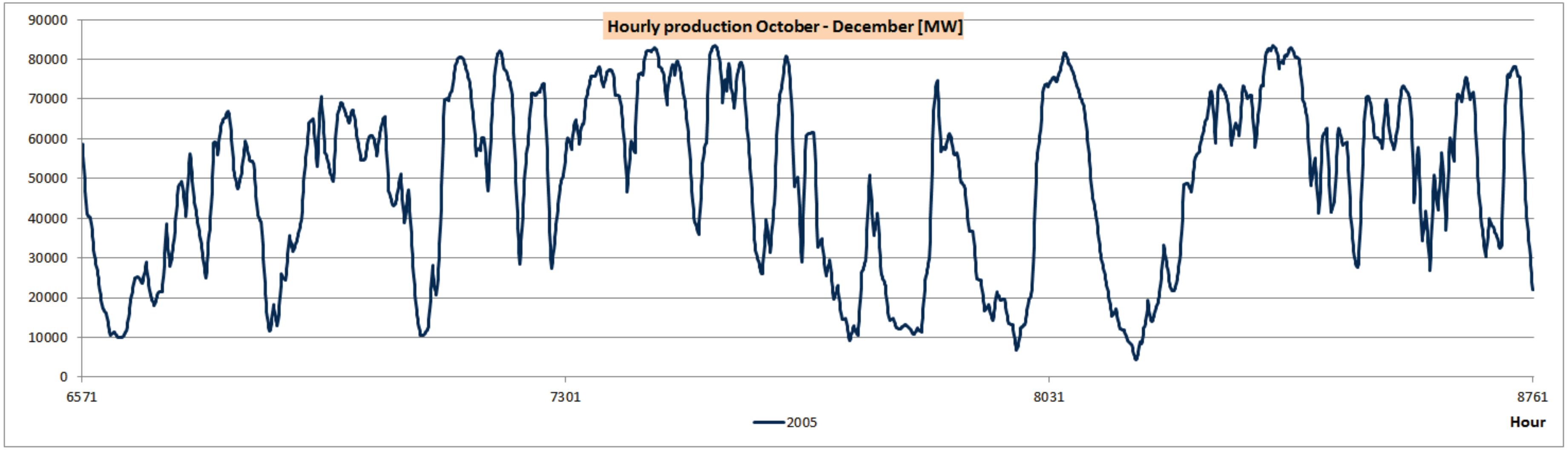


Figure 1.2 Hourly variation in wind power production (MW) throughout the year 2005.

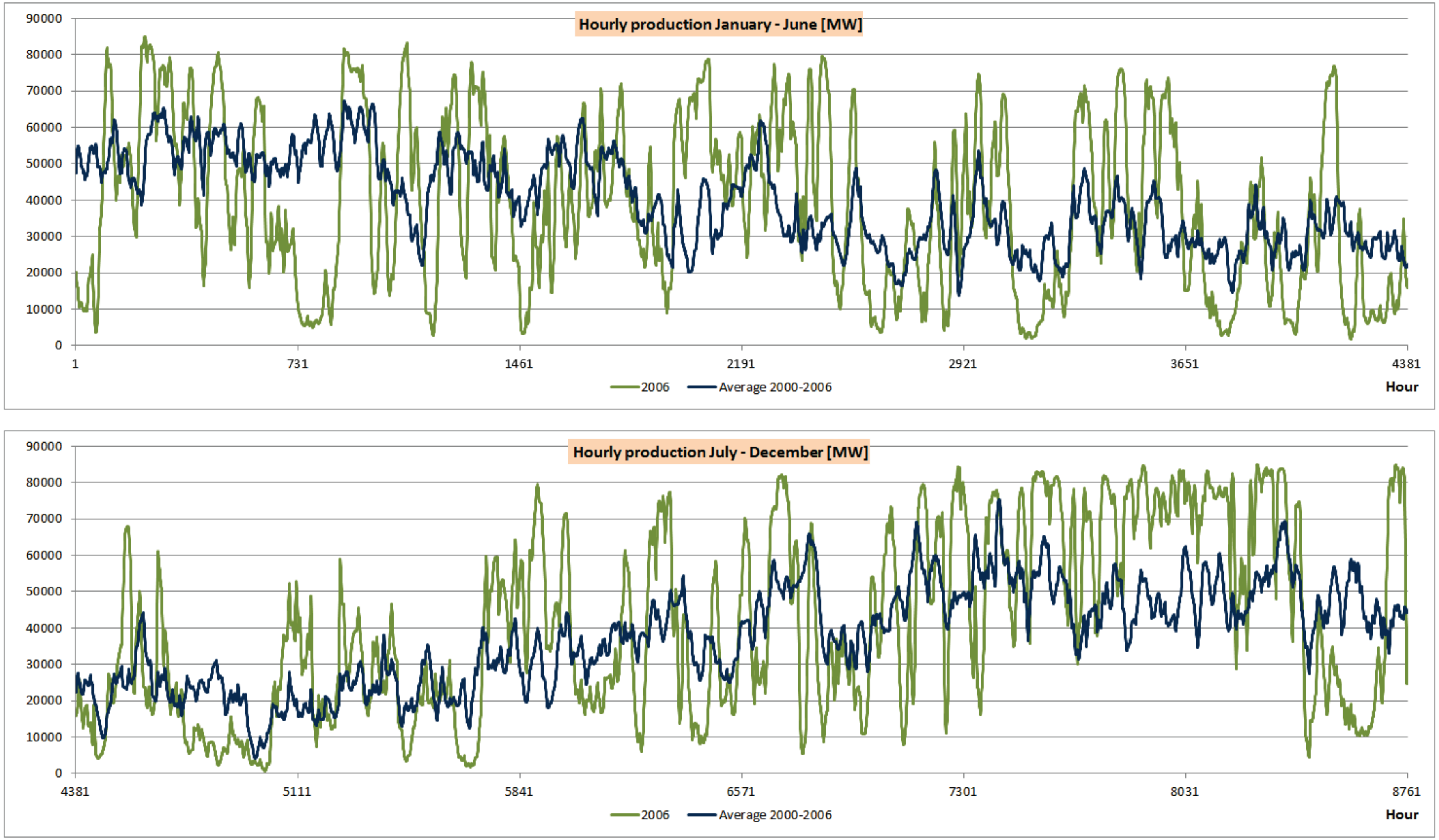


Figure 1.3 Hourly variation in wind power production (MW) throughout a year (2006 and average 2000-2006).

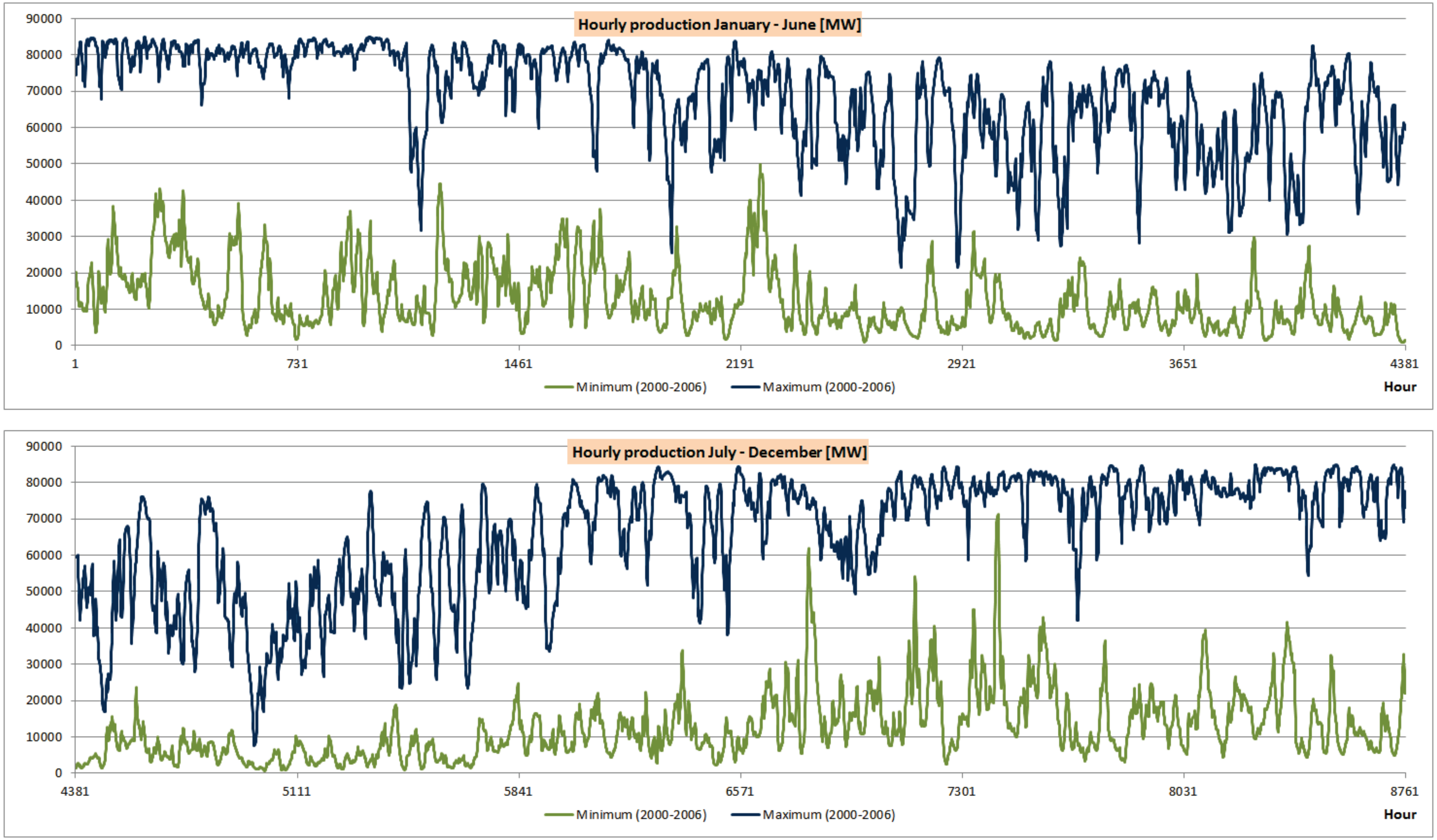


Figure 1.4 Hourly minimum and maximum wind power production (MW) for the years 2000-2006.

2 Large scale hydropower development

2.1 Sites in southern Norway - Examples

Table 2.1 shows results from a preliminary study (Solvang, Harby & Killingtveit 2012) relating to increasing the power output of existing hydroelectric reservoir plants in southern Norway, subject to the constraints of current regulations relating to maximum and minimum regulated water levels (HRWL and LRWL). The main scenario involves twelve new power stations with a combined power output of 11,200 MW. It is envisaged that these power stations would be constructed with new tunnels to an upstream reservoir and to the downstream outflow into a reservoir or to the sea. Five of the power stations are pumped storage power stations with a combined output of 5,200 MW, while the remainder are conventional hydroelectric power stations with a combined output of 6,000 MW, all but one of which (case G2) discharge into the sea. The pumped storage power stations have reversible pump turbines, pumping water between two reservoirs, while conventional power stations are not fitted with such pump turbines.

Table 2.1 New power generation and pump installations – Main scenario.

Case	Power station	Output (MW)	Upper reservoir[1]	Lower reservoir[2]
A2	Tonstad pumped storage power station	**1,400**	Nesjen (14 cm/h)	Sirdalsvatn (3 cm/h)
B3	Holen pumped storage power station	**700**	Urarvatn (8 cm/h)	Bossvatn (8 cm/h)
B6a	Kvilldal pumped storage power station	**1,400**	Blåsjø (7 cm/h)	Suldalsvatn (4 cm/h)
B7a	Jøsenfjorden conventional power station	**1,400**	Blåsjø (7 cm/h)	Jøsenfjorden (sea)
C1	Tinnsjø pumped storage power station	**1,000**	Møsvatn (2 cm/h)	Tinnsjø (1 cm/h)
D1	Lysebotn conventional power station	**1,400**	Lyngsvatn (9 cm/h)	Lysefjorden (sea)
E1	Mauranger conventional power station	**400**	Juklavatn (14 cm/h)	Hardangerfjorden (sea)
E2	Oksla conventional power station	**700**	Ringedalsvatn (12 cm/h)	Hardangerfjorden (sea)
E3	Tysso pumped storage power station	**700**	Langevatn (9 cm/h)	Ringedalsvatn (7 cm/h)
F1	Sy-Sima conventional power station	**700**	Sysenvatn (9 cm/h)	Hardangerfjorden (sea)
G1	Aurland conventional power station	**700**	Viddalsvatn(12 cm/h)	Aurlandsfjorden (sea)
G2	Tyin conventional power station	**700**	Tyin (1 cm/h)	Årdalsvatnet[3]
	Total new power generation capacity	**11,200**		

[1] Water level decrease in parentheses.

[2] Water level increase in parentheses.

[3] Insufficient data to calculate water level increase in Årdalsvatnet.

The water level variations in the upper and lower reservoirs include any inflow and discharge resulting from maximum power generation in other power stations associated with the reservoirs in each case. The power generation outputs (design) in the scenario were chosen mainly so that the water level change in the upper and lower reservoirs does not exceed 13 cm/hour. For two of the reservoirs (Nesjen and Juklavatn) the rate is 14 cm/hour. According to research into the stranding of salmon in rivers, the water level should not sink by more than 13 cm/hour (Harby et al. 2004). Although this is not directly applicable to lakes, this was used as a rule of thumb for acceptable water level reduction in reservoirs.

Table 2.2 New power generation and pump installations – Scenario 3.

Case	Power station	Output (MW)	Upper reservoir[1]	Lower reservoir[2]
A2	Tonstad pumped storage power station	**1,400**	Nesjen (14 cm/h)	Sirdalsvatn (3 cm/h)
B3	Holen pumped storage power station	**1,000**	Urarvatn (10 cm/h)	Bossvatn (12 cm/h)
B6b	Kvilldal pumped storage power station	**2,400**	Blåsjø (11 cm/h)	Suldalsvatn (6 cm/h)
B7b	Jøsenfjorden hydro storage power station	**2,400**	Blåsjø (11 cm/h)	Jøsenfjorden (sea)
C2	Tinnsjø pumped storage power station	**2,000**	Møsvatn (3 cm/h)	Tinnsjø (4 cm/h)
C3	Tinnsjø pumped storage power station	**2,400**	Kallhovd (7 cm/h)	Tinnsjø (4 cm/h)
D1	Lysebotn hydro storage power station	**1,800**	Lyngsvatn (12 cm/h)	Lysefjorden (sea)
E1	Mauranger hydro storage power station	**400**	Juklavatn (14 cm/h)	Hardangerfjorden (sea)
E2	Oksla hydro storage power station	**700**	Ringedalsvatn (12 cm/h)	Hardangerfjorden (sea)
E3	Tysso pumped storage power station	**1,000**	Langevatn (13 cm/h)	Ringedalsvatn (11 cm/h)
F1	Sy-Sima hydro storage power station	**1,000**	Sysenvatn (11 cm/h)	Hardangerfjorden (sea)
G1	Aurland hydro storage power station	**700**	Viddalsvatn(12 cm/h)	Aurlandsfjorden (sea)
G2	Tyin hydro storage power station	**1,000**	Tyin (2 cm/h)	Årdalsvatnet[3]
	Total new power generation capacity	**18,200**		

[1] Water level decrease in parentheses.
[2] Water level increase in parentheses.
[3] Insufficient data to calculate water level increase in Årdalsvatnet

The output of the 12 power stations in the main scenario can be increased to 18,200 MW (see Table 2.2) without the water level changes in the upper and lower reservoirs exceeding 14 cm/hour. How long the power stations are able to deliver this power output will depend among other things on the current regulations regarding highest and lowest regulated water levels (HRWL and LRWL), as well as what strategies are adopted with regard to pumping in the case of pumped storage power stations. By including more cases in southern Norway in addition to some in northern Norway, it will be possible to increase the output of existing hydroelectric reservoirs by a further 1,800 MW to give a total of 20,000 MW for the whole country.

The sites of the twelve power stations in Table 2.1 and Table 2.2 are shown in Figure 2.1. Each of the power stations (400-1,400 MW) will require connection through a separate 420 kV line to appropriate points in the central supply grid if power exchange with other countries is to take place by way of the central transmission grid. As regards the power stations at Tonstad, Lysebotn, Jøsenfjorden, Kvilldal, Mauranger/-Oksla, Sima and Aurland/Tyin, these can in principle be linked directly to international grids via HVDC cables, since they are located close to a fjord or the sea. This is indicated by the solid red arrows in Figure 2.1.

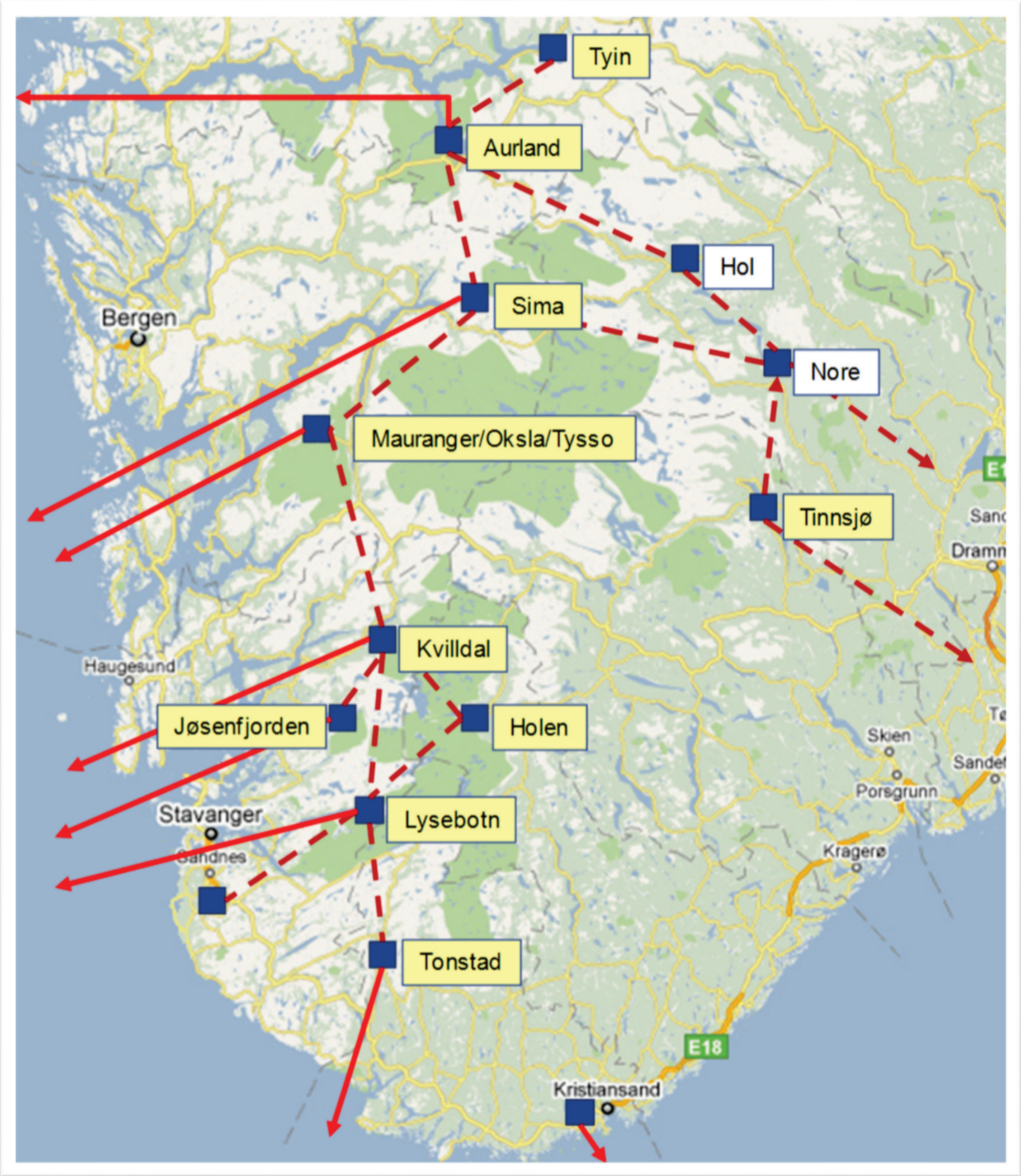


Figure 2.1 Main scenario sites and possible international links.

2.2 Planning and construction

This Chapter consists of, or is based on sections from a report (Grøv, Bruland, Nilsen, Panthi & Lu 2011) prepared for the CEDREN project Hydro PEAK, looking at the potential resources that are required to develop an installed capacity of 20,000 MW of hydro electric power in Norway during a period of 20 years until 2030. The concept is based on utilising the current concessions that exist to the extent possible use of the upper and lower reservoir levels. A development of 20,000 MW constitutes approximately 2/3 of the current total hydro electric power installations in Norway.

It is assumed that the total development of 20,000 MW is split into 5 power plants each with 1,000 MW installed capacity (4·250 MW units), and 60 plants each with 250 MW (2·125 MW units). It is further assumed that the entire process for a 250 MW project will likely take 7 years, whereof 3-4 years are related to the planning and preparation of the project whilst the physical construction is estimated to 3 years.

The construction works is assumed to start in 2015 with an increment of 1,000 MW for 5 years (Figure 2.2). The remaining installation of 15,000 MW is achieved by starting construction of 1,500 MW or 2,000 MW per year during 2020-2028. This means a peak development of 6,000 MW in one given year (2025). The red bars in Figure 2.1 show the annual total capacity under construction given a construction time of 3 years for each plant. The blue bars show the amount of construction that starts each year.

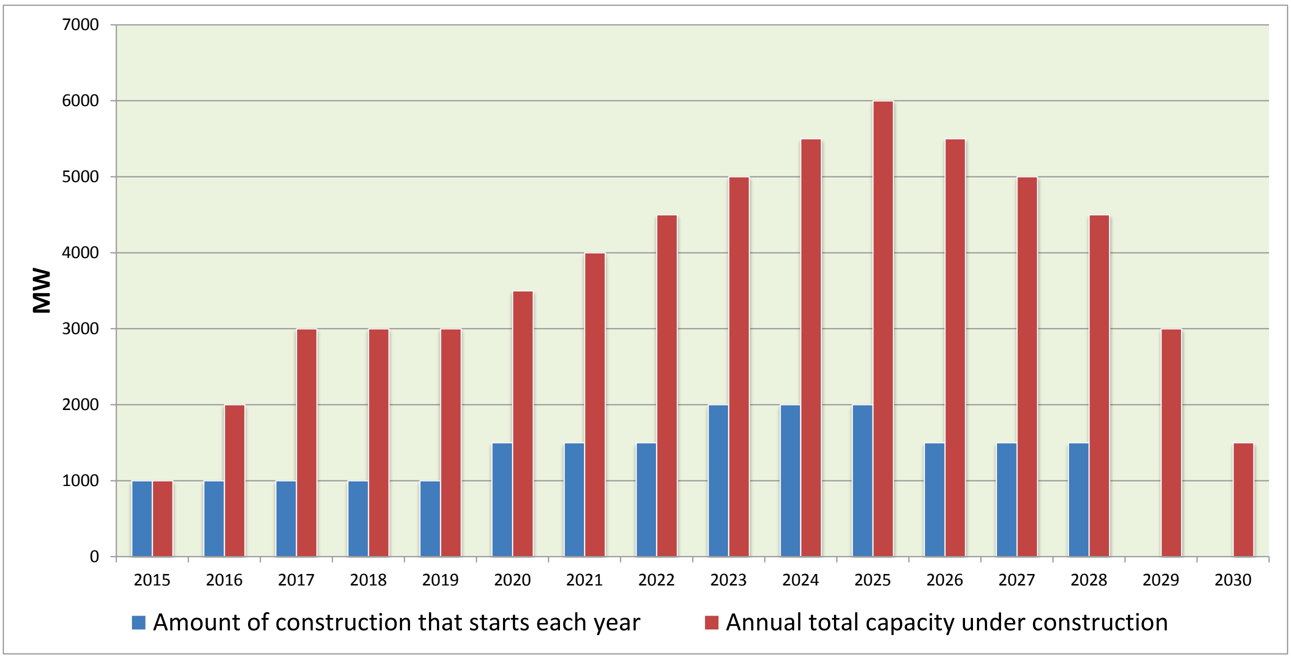


Figure 2.2 Plants under construction scenario (MW).

Assuming a gradual escalation to reach a maximum of production, it is assessed that construction works need to commence at as many as 8 projects yearly for some years when the production is at its peak, meaning that as many as between 24 projects might be under execution simultaneously during some critical years to reach completion by the year 2030.

A very rough estimate of resources in terms of man year necessary for the planning and construction of 20,000 MW of capacity is presented in (Grøv, Bruland, Nilsen, Panthi & Lu 2011). About 10,000 man year in consulting services for the entire scheme of 20,000 MW are needed. During a period of 15 years, this will be 700 man years per year. It means further that at peak production of 6,000 MW a total of 2,000 man years will be needed to cope with the peak demands. The total amount of employees in the consulting services in Norway is estimated in (Grøv, Bruland, Nilsen, Panthi & Lu 2011) to be about 5,000 people. A demand of 700 man years per year to produce 20,000 MW represents 14 % of the total consulting business producing 5,000 man years per year.

They conclude that as far as the consulting services are concerned it is reasonable to expect that this can be served within the current business. However, at peak production there will be a significant stress on the consulting deliveries and careful planning would be strictly required to avoid the consulting services being the bottleneck in the development of 20 000 MW until year 2030.

The average production in tunnelling excavation is expected to be in the range of almost 3 million m^3 per year, with a peak reaching more than 10 million m^3. This production rate will come in addition to the yearly ordinary production volume within the tunnelling industry. Consequently, as the situation is today in this industry it is hardly believed according to the authors that the current parties are able to absorb this amount of work with the current manning and equipment. It would be required to increase the capacity of the industry with significant resources to enable such a development to take place. One may look at the total need of approximately 30,000 man years during the 17 years period of construction works according to the findings.

Other assumptions:

- Longitudinal layout of each plant: long headrace tunnel, surge shaft, 45° inclination high pressure shaft, underground power house, tailrace and access tunnel.
- Length of headrace tunnels: 12,000 m (1,000 MW plants) and 3,600 m (250 MW plants).
- Length of pressure shafts: 712 m (1,000 MW plants) and 500 m (250 MW plants).
- Cross-section of headrace and tailrace tunnels (flow velocity of 2.3 m/s): 125 m^2 (1,000 MW plants) and 48 m^2 (250 MW plants).
- Cross-section of pressure shafts (flow velocity of 8 m/s): 27.3 m^2 (1,000 MW plants) and 13.2 m^2 (250 MW plants).
- Excavation of tunnels: traditional drill-and-blast method.
- Excavation of pressure shafts: TBM (Tunnel Boring Machine) or raise boring.

In the estimation of necessary recourses, an excavation volume of 2,000 m^3 per MW is assumed, applicable for both 1,000 MW and 250 MW plants.

Given that the yearly required production capacity per plant is approximately 1.1million m^3 and with 6.6 sites going on simultaneously, the total demand would be around 60 jumbo drill rigs with a 80 % utilization for the 20,000 MW development. This is 1.5 times the number of jumbo drill rigs in activity today.

3 Impacts on water volume, stage and area in reservoirs

3.1 Introduction

The following simulations of pumped storage operation in reservoirs used for balancing of wind power were conducted on the background of CEDREN's HydroPeak project and the study "Increasing balance power capacity in Norwegian hydroelectric power stations – a preliminary study of specific cases in Southern Norway" (Solvang, Harby & Killingtveit 2012). The former includes a main scenario with 20,000 MW export of balancing power from Norway. The latter shows that it is possible to provide a balancing power capacity of 20,000 MW by installing new hydro peaking capacity and pumped storage power plants, using existing dams and reservoirs only with the current stipulations, meaning that the operation of existing power stations remains unchanged.

For the purpose of more detailed analysis of pumped storage operation, three reservoir pairs were selected from the cases presented in (Solvang, Harby & Killingtveit 2012). The main objectives of the present study were

i) To simulate the water level fluctuations in the reservoirs and compare them to the current ones
ii) To determine the limiting factors for provision of balancing power
iii) To provide a basis for an assessment of environmental impacts of pumped storage

3.1.1 Model description

In order to simulate pumped storage operation of reservoir pairs a model was built in Excel®. The model calculates changes of water volume in the lower and upper reservoirs of hydropower systems which have a pumped storage power plant and can either pump up water into the upper reservoir (electricity consumption, uptake of energy) or release it through turbines into the lower reservoir (electricity generation, output of energy). The main output of the model are calculations of the variations in water volume, stage and area in selected reservoirs pairs, under new potential energy storage scenarios with phases of pumping and generation. The model basically consists of three elements (Figure 3.1):

1. Current operation
2. Balancing power operation
3. Future operation

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

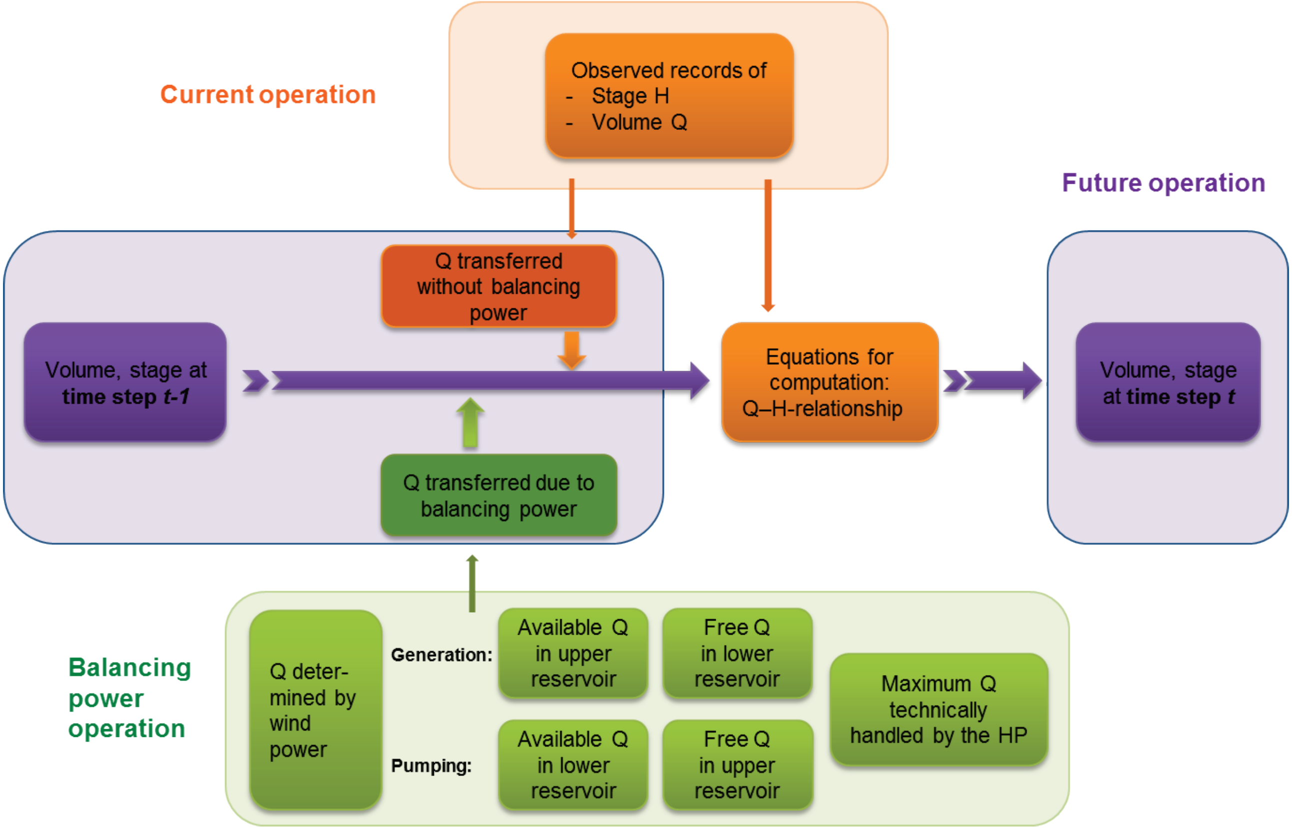


Figure 3.1 Scheme of the model. Pumped storage operation is simulated by combining the current operation (orange) with balancing power operation (green). Future operation (purple) is computed based on the water volumes which are transferred between the reservoirs. For detailed description, see text.

The current operational scheme is based on reservoir Volume-Stage curves which were obtained from regression analysis of observed water volume and stage in the reservoirs. Observed water volume versus water stage is plotted for a period of twenty years. A polynomial curve fitting the data points best is constructed. The fitted curve (Volume-Stage curve) provides the mathematical relationship between volume and stage. The same procedure is applied to obtain the inverse Stage-Volume curve. These curves allow converting water volume to stage and vice versa. They represent the reservoir bathymetry, i.e. how stage varies with changing water volume, depending on the reservoir shape. After conversion of the water volume into stage, the rate of change in water level from time step to time step is calculated. The reservoir surface area is determined for each time step by dividing the difference in volume to the previous time step by the difference in stage to the previous time step. The rate of change in surface area is calculated.

The balancing power demand is determined by fluctuations in electricity generation by wind power (cf. 3.1.3). The goal is, of course, to transfer the amount of water corresponding to the electricity which is necessary to cover the required balancing power. For each time step the amount of water, which needs to be pumped or released through a turbine in order to meet the balancing power demand is computed, using the energy equivalent of the power plant, i.e. the amount of electric energy that is generated/consumed per cubic meter water (kWh/m^3). The energy equivalent depends on the head. Therefore it is recalculated for each time step according to the change in head from the previous time step. Further, the water volumes which can be withdrawn from the lower reservoir (pumping)/upper reservoir (generation) or is free in the upper reservoir (pumping)/ lower reservoir (generation), and the water volume which can be handled by the turbine at maximum are calculated. The smallest of these volumes is selected in each time step and used for further calculations. In this way it is ensured that the current regulations on HRWL and LRWL are not violated. Corresponding to the calculations for the current operation the reservoir surface area and the rates of change in water level and surface area are calculated.

3.1.2 Assumptions

For our simulations we assumed the following:

- Reversible turbines: New turbines installed in power stations are reversible turbines, used for both electricity generation and pumping of water
- Efficiency: The overall efficiency of the new turbines was supposed to be 0.9
- Installed capacity: The capacity of new power stations was determined on basis the previous balancing power study (Solvang, Harby & Killingtveit 2012). Solvang et al. (2012) calculated rates of change in water level for different installed capacities. According to their results, the capacities for this study were chosen so that the rates would not exceed 14 cm/h, as higher rates are likely to be detrimental to fish due to stranding (Harby et al. 2004).
- Share of capacity: The amount of energy to be balanced by the three selected cases was determined as the proportion of their installed capacity to the total balancing power capacity of 20,000 MW in the scenarios given in (Solvang, Harby & Killingtveit 2012).
- Basic operation of hydro power pattern before and after installation of the pump is assumed to be the same.

3.1.3 Balancing power scenarios and energy storage needs

The main idea is that hydropower would compensate for the deficit in electricity generation when electricity produced from wind power plants cannot meet the load. As a consequence electricity would be produced from hydropower plants during periods with little wind, while water would be pumped and stored in upper reservoirs during time periods with strong wind. Variations of volume and water level in reservoirs will depend on both the market demand and the wind power production. Two different balancing power scenarios, which define the schedule for both generation and pumping phases, were established. They are based on simulations of electricity production from wind turbines in the North Sea for the years 2000 to 2006 (Chapter 1.3).

Table 3.1 Cumulated water volume transferred, cumulated number of days and average water volume transferred per day for the time period 2000-2006 for pumping and generation phases under 7Days-Avg and Dev-Avg balancing power scenarios for the cases Tonstad, Rjukan and Holen.

CASES	Scenarios	7Days-Avg scenario		Dev-Avg scenario	
		PUMPING	GENERATION	PUMPING	GENERATION
Tonstad	Volume (Mm^3)	**9941**	**9910.**	**4171**	**4133**
	Nb of days	1192	1220	513	620
	Volume/day	8.3	8.12	8.13	6.67
Rjukan	Volume (Mm^3)	**18976**	**18918**	**8708**	**8597**
	Nb of days	1220	1150	554	615
	Volume/day	15.55	16.45	15.72	13.98
Holen	Volume (Mm^3)	**11335**	**11328**	**5832**	**5814**
	Nb of days	1223	1196	695	720
	Volume/day	9.27	9.48	8.40	8.08

Compensation for short-term fluctuations in energy

The first balancing power scenario, the so called **7Days-Avg scenario**, is defined assuming that hydropower will compensate short-term fluctuations of wind power production up to one week. Since hydropower has the advantage of being available to produce electricity on a short schedule, it can respond to rapid variations of the demand. Thus, assuming that other types of power plants can compensate for the long-term fluctuations in wind power production, hydropower will produce electricity to compensate the short-term fluctuations. This scenario is based on the 7 day moving average of wind power production. It is obtained by computing at each data point the average of the wind power production of the data set starting three days before and ending three days after the considered point of time. Therefore, the difference between the 7 days moving average (weekly fluctuations) and the daily production (daily fluctuations) from wind farms represents the energy needs to be balanced and is implemented into the model as input data.

When the 7 days moving average of wind power production is higher than the daily production, there is a lack of energy: release of water in lower reservoirs is required (Figure 3.2) to generate electricity; when the situation is inverted, there is a surplus of energy: pumping is required to store water in upper reservoirs. In this scenario, generation and pumping phases, meaning number of consecutive days with generation or pumping required, last typically 2 to 4 days. For the 2000-2006 time period, the cumulated water volume transferred between reservoirs is more or less equally distributed between the pumping and the generation phases. Large differences in amount of transferred water appear among cases. For the 7Days-Avg scenario, the volume exchanged between reservoirs is about 9,900 Mm^3 for Tonstad case, which has the smallest volumes of all reservoir pairs; 11,300 Mm^3 for Holen case, which has intermediate reservoir sizes; and 19,000 Mm^3 for the Rjukan case, with the largest volumes.

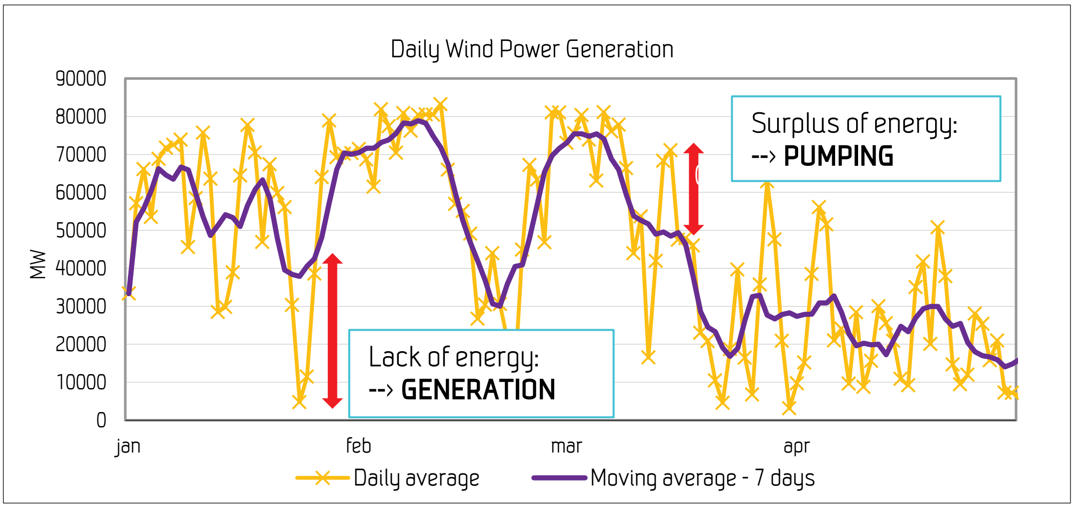


Figure 3.2 Definition of 7Days-Avg balancing power scenario: The orange line represents the daily power generation for the North Sea from January to April. The dark blue line represents the 7 days moving average of the daily power generation for the same period.

Compensation for energy production capacity

The second balancing power scenario, so called **Dev-Avg scenario**, is defined assuming that hydropower balances the large fluctuations in wind power production, while smaller fluctuations up to certain threshold can be compensated by the existing energy system. A high and a low threshold were defined (Figure 3.3), corresponding to the daily average production's value from wind power for 2000 to 2006 plus minus 25 % of the average, respectively. When the daily production from wind is less than the lower threshold, there is a lack of electricity production: electricity generation by hydropower is required; if the situation is inverted, pumping of water is required. In this scenario, generation and pumping phases, meaning number of consecutive days with generation or pumping required, last typically 1 to 2 weeks. For the 2000-2006 time period, the cumulated water volume transferred is also nearly equally distributed between the pumping and the generation phases. However the cumulated volumes transferred between reservoirs are reduced by almost 50 % in all studied cases compared to the 7Days-Avg scenario.

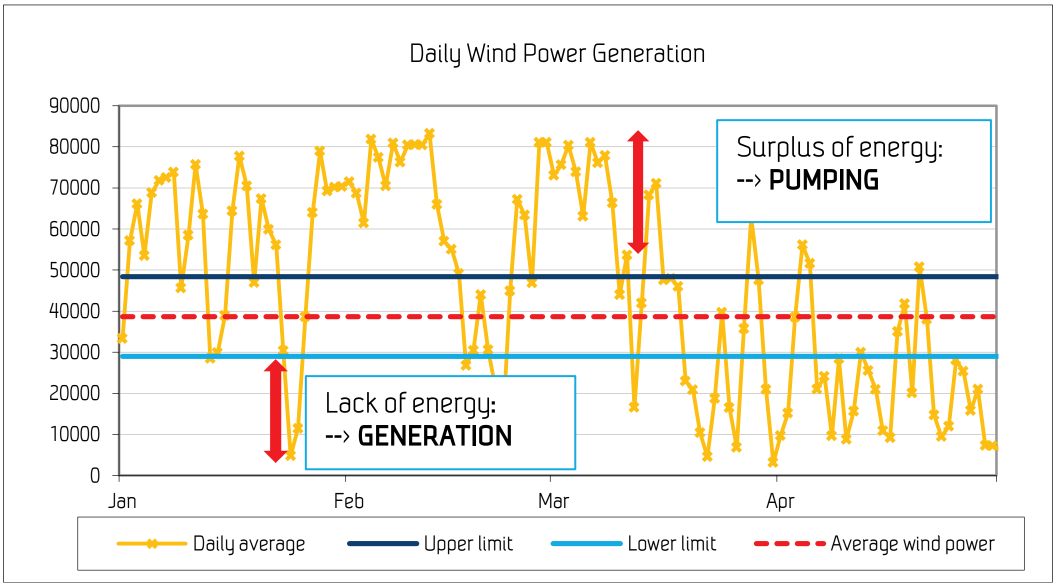


Figure 3.3 Definition of Dev-Avg balancing power scenario: Daily power generation for the North Sea from January to April 2001 and thresholds. The dark blue line represents the upper threshold (daily power average + 25 % of average), over which pumping is required. The blue line represents the lower threshold (daily power average - 25 % of average), under which electricity generation is required.

3.1.4 Main scenarios and description of cases

In the following paragraphs we describe the simulation results of the two main scenarios as described in chapter 3.1.3. We present detailed results for the 7Days-Avg scenario (chapter 3.2) and the Dev-Avg scenario (chapter 3.3), with parameter settings as given in Table 3.2. In chapter 3.4.1 and 3.4.2 the effects of varying the share of capacity in the 7Days-Avg scenario and the threshold in the Dev-Avg scenario are presented, but less detailed.

Table 3.2 Main balancing power demand scenarios.

Two main scenarios		Tonstad	Holen	Rjukan
7Days-Avg scenario	Threshold	Threshold: 7 days moving average		
Dev-Avg scenario		Threshold: +/- 25 %		
In both scenarios	Share of capacity	0.07	0.07	0.14

Description of cases

A larger selection of reservoir pairs, which could be potentially used in a future scenario of balancing energy demand from Europe, was conducted in a report (Solvang, Harby & Killingtveit, 2012). Based on this selection, three pairs of reservoirs were selected because of their difference in volume storage, reservoirs topography, size of turbines, and gap between HRWL and LRWL. These three cases allow understanding in which range stage fluctuations occur in relation to reservoirs characteristics.

Tonstad case is characterized by a lower reservoir smaller than the upper one: Sirdaslsvatn (lower) with a volume of 56 Mm^3 represents only 20 % of the volume of Nesjen (upper), which has a volume of 275 Mm^3. The difference between LRWL and HRWL is only 3.5 m for the lower reservoir, and 38 m for the upper one. The area is 19.47 km^2 for the lower and 15.36 km^2 for the upper reservoir, respectively.

Rjukan case is similar to Tonstad case, as the lower reservoir represents 19 % of the volume of upper one, but this case differs by the larger size of the reservoirs: Tinnsjø has a volume of 204 Mm^3, Møsvatn a volume of 1064 Mm^3. Møsvatn is considered as a relatively large reservoir in Norway, the largest one being Blåsjø with 3105 Mm^3. The difference between LRWL and HRWL is only 4 m for the lower reservoir, and 19m for the upper one. The upper reservoir is relatively shallow compared to Tonstad's upper reservoir.

The third case, Holen, differs from the two others since both the lower and the upper reservoir have similar volumes: 296 Mm^3 for Bossvatn (lower), 253 Mm^3 for Urarvatn (upper). The particularity of that case is also the large altitude difference between LRWL and HRWL: 56 m gap in the lower reservoir, and 34 m gap in the upper reservoir. The latter is relatively deep, with steep banks.

Table 3.3 Reservoirs characteristics.

	TONSTAD		RJUKAN		HOLEN	
	Upper	Lower	Upper	Lower	Upper	Lower
Volume (Mm^3)	**275**	**56**	**1064**	**204**	**253**	**296**
Area (km^2) at HRWL	15.36	19.47	78.43	51.38	13.15	7.70
LRWL (m)	715	51	919	191	1175	551
HRWL (m)	677	47.5	900	187	1141	495
Diff: HRWL – LRWL (m)	38	3.5	19	4	34	56

3.2 Water level fluctuations in reservoirs under 7Days-Avg scenario

The studied cases show modifications of the current temporal variations in the reservoirs' volume, stage and area, when pumping is introduced. These modifications affect mainly:

- Seasonal patterns
- Short-term fluctuations (daily scale)
- Reservoir emptying and filling

The importance of these changes is correlated to the characteristics of the reservoirs and its use to balance energy needs. Thus, to assess qualitative as well as quantitative effects of pumping, we give detailed results of the study for the upper and the lower reservoirs.

3.2.1 Seasonal trend

Upper reservoirs

The current observed seasonal cycle consists of four successive phases: a filling phase (May to July), when reservoirs receive water from snow melting; then a period with relatively high and stable stage (summer); afterwards, an emptying period (autumn and winter), when water is mainly released to generate electricity due to higher demand; finally a short period when the lower level is reached (end of winter, before the spring flood).

This seasonal cycle remains similar under pumping scenario. However deviations appear as follows (Table 3.4).

- For Tonstad, the seasonal cycle is well preserved: 1) during the filling period, the simulated stage remains lower than the current observed stage (up to 3-4 m); 2) during the low stage period, the lowest simulated stage level reached is lower than today.
- For Rjukan, the seasonal cycle is slightly shifted: 1) the high stage period shows lower stage for all studied years; 2) the emptying phase is characterized by a larger rate of stage decrease; 3) the low stage period shows lower stage values for all studied years.
- For Holen, the seasonal cycle is modified, whereas a certain seasonality still appears: 1) in some years, the filling phase is separated into two by a short intermediate emptying phase; 2) the high stage period show lower stages than the current situation and is shorter; 3) the emptying phase is often longer, as it starts before and ends after the current dates.

Table 3.4 Modification of the seasonality cycle of upper reservoirs under pumping.

Phase	Filling phase	High stage period	Emptying phase	Low stage period
UPPER Case				
Tonstad	x (Lower stage)			
Rjukan		X (Lower stage)	X (lower stage)	X (starts earlier, Lower stage)
Holen	X (Lower stage)	X (Shorter period, Lower stage)	X (Earlier, Lower stage)	X (Earlier, Lower stage)

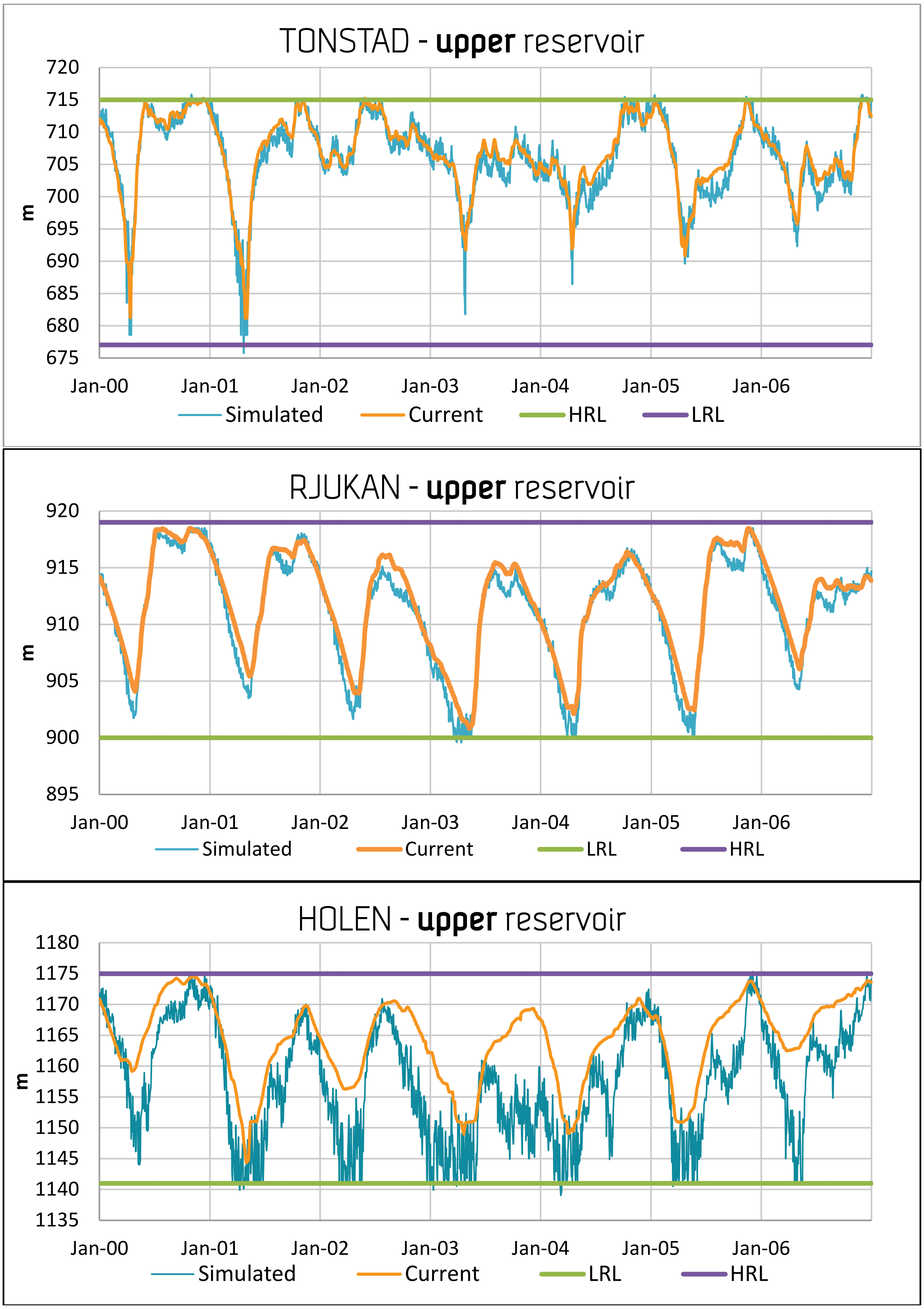


Figure 3.4 **Upper reservoirs. Water level variations for the 2000-2006 period in Nesjen (Tonstad case), Møstvan (Rjukan case), Urarvatn (Holen case) under 7Days-Avg balancing power scenario.**

Lower reservoirs

Current observed variations of stage in the lower reservoirs of the studied cases show that a seasonal pattern is not as clear as it is for the upper ones. We can identify the filling phase, high stage period, emptying phase, and the low stage period. In Holen, that cycle appears twice a year.

Pumping affects heavily the current variations of stage, especially in Tonstad and Rjukan cases where the difference between LRWL and HRWL is relatively small (about 4 meters) compared to Holen's case (56m).

- In Tonstad, fluctuations occur during all year under pumping, and no seasonal cycle can be defined. The lower reservoir is more often filled, and the reason is its relatively small storage volume.
- In Rjukan, fluctuations occur also during all years under pumping, and no seasonal cycle can be defined. The reservoir is more often filled than in the current situation. Fluctuations of stage occur mainly in the first meter under HRWL. It means that the same water volume is successively withdrawn from and released into this reservoir.
- In Holen, fluctuations occur again during all years. They follow roughly the seasonal pattern, except for the "high stage period". Between June and January the water level shows daily variations, but it stays in the 5 first meters under HRWL. It means that the same water volume is successively withdrawn from and released into this reservoir, while the available volume is not used.

Table 3.5 Modification of the seasonality cycle of upper reservoirs under generation/pumping scenario in Tonstad, Rjukan, and Holen case.

Phase	Filling phase	High stage period	Emptying phase	Low stage period
LOWER Case				
Tonstad	x (Higher stage)	X (Higher stage)	X (Higher stage)	X (Higher stage)
Rjukan	X (Higher stage)	X (Higher stage)	X (Higher stage)	X (Higher stage)
Holen		X (Higher stage)		

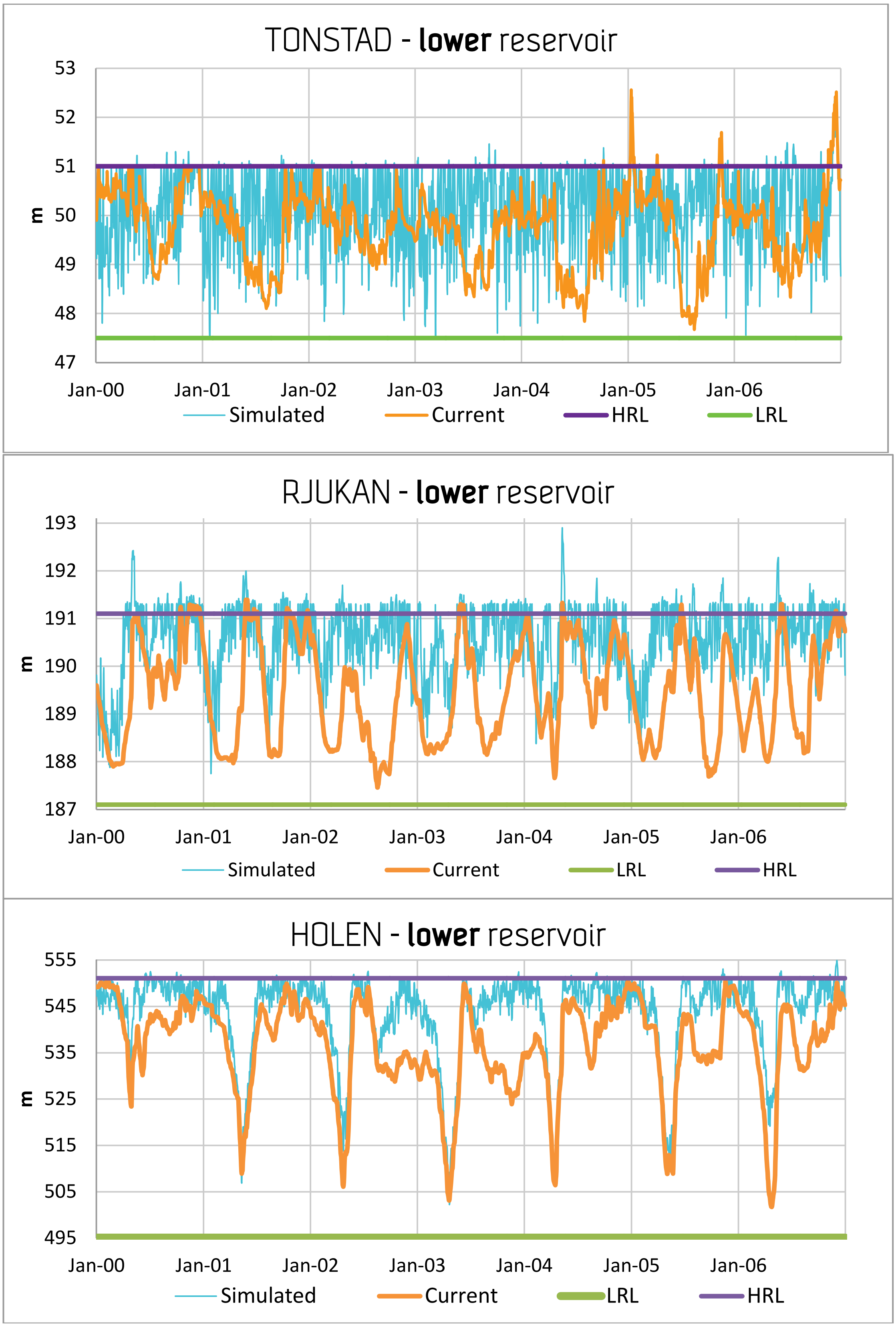


Figure 3.5 Lower reservoirs. Water level variations for the 2000-2006 period in Sirdalsvatn (Tonstad case), Tinnsjø (Rjukan case), Bossvatn (Holen case) under 7Days-Avg balancing power scenario.

3.2.2 Short-term Fluctuations

Upper reservoirs

Whereas the current seasonal filling cycle of upper reservoirs is kept also under the 7Days-Avg balancing power scenario, short-term fluctuations appear in all cases. These short-term fluctuations directly originate from balancing power operation. Withdrawn and released in reservoirs during several hours or days, the water masses induce a direct decrease or increase in water level. The magnitude, frequency, and seasonality of theses fluctuations vary from one case to another, as it depends on reservoir characteristics and the balancing power needs.

a) Frequency

Short-term fluctuations consist in variations of stage on a daily scale. The number of days when the stage is varying in the opposite direction as the day before illustrates the frequency of short-term fluctuations (count of days when the stage is increasing (or stable) or decreasing (or stable) while the stage was decreasing, respectively increasing the day before.

In upper reservoirs of all cases, the water level is fluctuating more under balancing power operation than in the current situation (Table 3.6) and about 40 % of days of the 6 years studied period have short-term fluctuations. The largest change appears for Holen, with a rise from 3.9 to 39.8 % of days with fluctuations when pumping is simulated. A large change in the frequency of daily fluctuations occurs also for Rjukan, increasing from 8.4 to 38.5 %. However in Tonstad, the situation observed today shows that 19.3 % of days have already encountered daily variations; this number rises up to about 39.7 % when 7Days-Avg scenario is simulated.

In lower reservoirs of all cases, the water level is also fluctuating more under balancing power operation than in the current situation (Table 3.6) and about 40 % of days have short-term fluctuations. The larger changes appear in Rjukan and Holen, with a rise from 15.6 to 40.3 %, respectively 17.7 to 39.9 % of days with fluctuations when the 7Days-Avg scenario is simulated. However in Tonstad, 30.9 % of days currently encounter daily variations; this number rises up to 41.9 % when generation/pumping is simulated. The similar values obtained in all cases for the simulated scenario is explained by the same energy demand governing the water masses transfer in the simulation.

Table 3.6 Percentage of days of the whole studied period with a daily variation of stage in upper (left) and lower (right) reservoirs for Tonstad, Rjukan and Holen cases.

% Upper	*Change*	*Current*	*Simulated*
Tonstad	↗	**19.3**	**39.7**
Rjukan	↗	**8.4**	**38.5**
Holen	↗	**3.9**	**39.8**

% Lower	*Change*	*Current*	*Simulated*
Tonstad	↗	30.9	**41.9**
Rjukan	↗	15.5	**40.3**
Holen	↗	17.7	**39.9**

b) Magnitude

In upper reservoirs the magnitude of fluctuations is modified by balancing power operation (Table 3.7). Fluctuations of stage are more frequent, as described above, and in addition they are stronger. The largest rate of change per day occurs in Holen, with a median rise from 8 cm/day today, to 1.17 m/day under by balancing power operation. Holen is the only case with more than one meter change per day. Its large increase is related to the size of the reservoirs: the upper and lower reservoir have equivalent storage volume, which offers the possibility to transfer the same amount of water from one reservoir to the other without any volume limitations. The increase is more moderate for Rjukan and Tonstad cases, but still abstraction and release of water in the reservoirs to balance energy demand induce higher rates of change in stage: rise from 7 to 22 cm / day under balancing power scenario in Rjukan; and 14 to 60 cm / day in Tonstad. The relatively low value for Rjukan in case of balancing operation is probably due to the large volume of the upper reservoir, more than 1000 Mm^3, and its topography. The upper reservoir can have large abstraction and release of water without a large water level variation in the reservoir. The 90th percentile values confirm these rates of change in stage. In Holen, while 90 % of the rates of changes values are lower than 24 cm /day in the observed situation, the 90th percentile would have a value lower than 3.5 m /day.

In the lower reservoirs, fluctuations of stage are stronger when the 7Days-Avg balancing power scenario is simulated, too (Table 3.7). The largest rates of change occur in Holen, with a median rise from 28 cm to 1.2 m per day. This large increase is not only explained by the volume of the reservoir and the turbine capacity, but also by and the topography of the reservoirs. Indeed in Rjukan the rates of stage change are more moderated, and rise from 4 to 26 cm / day under balancing power operation while the turbine capacity is 2 times larger than in Holen. Tinnsjø (Rjukan) is 30 % smaller than Bossvatn (Holen), but the former has a 7 times larger area than the latter. Thus stage variations are larger in Holen than in Rjukan whereas water amount transferred is almost doubled. These examples emphasizes that the topography of reservoirs themselves plays a large role in stage variations.

In Tonstad's case the rates of stage change are moderated, and rise from 7 to 44 cm / day under generation/pumping scenario. In Tinnsjø (Rjukan), 4 m height (difference between HRWL and LRWL) contain 204 Mm^3, while in Sirsdalsvatn, 3.5 m contain only 56 Mm^3. Even if the amount of water transferred is doubled in Rjukan than in Tonstad (turbine capacity doubled and larger reservoirs) the rates of change in stage are lower. 90th percentile values confirm the rates of change in stage. In addition they show that fluctuations are more often high in Holen than in Tonstad, since 90 % of the rates are under 2.87 m/day in the former case and under 1.07 m / day in the latter.

Table 3.7 Daily rates of change in water level for the current situation and under balancing power scenario in upper (left) and lower reservoirs (right) for Tonstad, Rjukan and Holen cases.

m/day Upper		Change	*Current*	*Simulated*
Tonstad	*Median*	↗	**0.14**	**0.60**
	P90		0.43	1.55
Rjukan	*Median*	↗	**0.07**	**0.22**
	P90		0.15	0.58
Holen	*Median*	↗	**0.08**	**1.17**
	P90		0.24	3.48

m/day Lower		Change	*Current*	*Simulated*
Tonstad	*Median*	↗	**0.07**	**0.44**
	P90		0.22	1.07
Rjukan	*Median*	↗	**0.04**	**0.26**
	P90		0.10	0.62
Holen	*Median*	↗	**0.28**	**1.20**
	P90		0.94	2.87

c) Seasonality

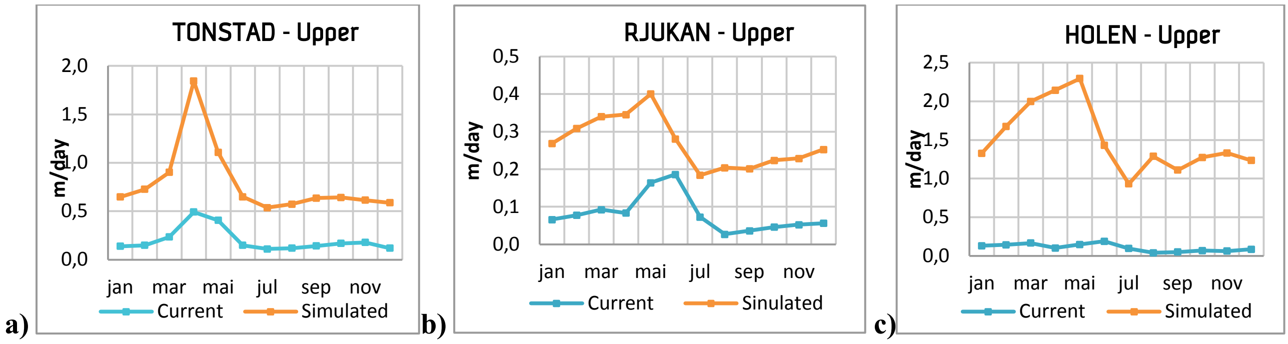


Figure 3.6a-c Averaged monthly variations of rates of change in water level in upper reservoirs for Tonstad (left), Rjukan (middle), and Holen (right) cases.

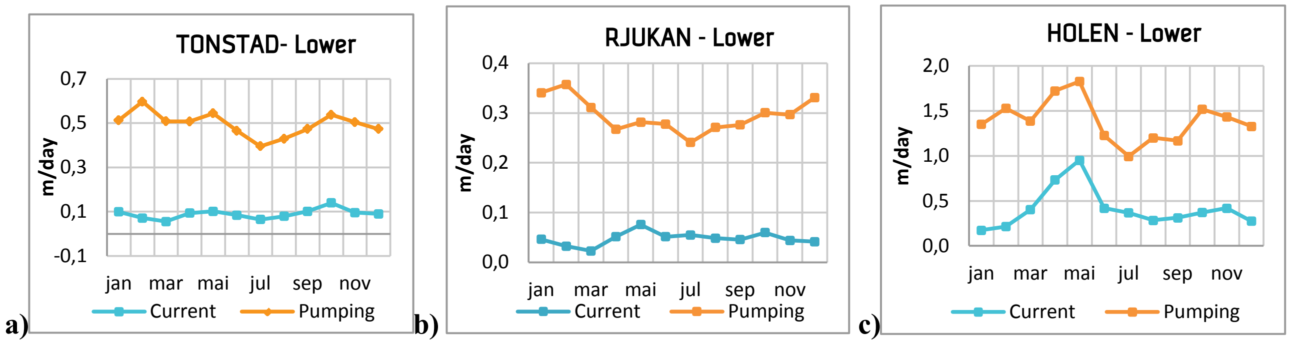


Figure 3.7a-c Averaged monthly variations of rates of change in water level in lower reservoirs for Tonstad (left), Rjukan (middle), and Holen (right) cases.

After looking at the magnitude and the frequency of stage variations, the analysis of monthly rates of change show that in all studied cases, water level variations induced by balancing power operation have monthly variations (Figure 3.6 and Figure 3.7). The monthly average rates of change are higher under balancing power operation for each month in all cases.

In Tonstad's upper reservoir, the rates show a sharper peak in magnitude in April-May under balancing operation, but seasonal variations of the rates is similar to the current situation. In Rjukan, the rates are higher than today, and they show a shift of the peaking period which occurs one month earlier. The very large increase of rates in Holen under balancing operation shows a period with higher rates from March to May, while the current observed monthly variations are insignificant.

In Tonstad and Rjukan's lower reservoirs, new seasonal trend appear since current observed monthly variations are almost insignificant compared to fluctuations under 7Days-Avg scenario. Nevertheless, in Rjukan the seasonal trend is reversed: today higher rates are observed between May and October, while under balancing operation, higher rates occur from December to March. In Holen, the seasonal trend is more preserved since it shows also a peak in rates values in April-Mai. However rates are lower in summer than in winter under generation/pumping while there are in the same range in current observed values.

3.2.3 Reservoir emptying and filling

Upper reservoirs

Physical limits of reservoirs, regarding the volume storage, are more often reached when 7Days-Avg balancing power scenario is simulated (Table 3.8).

For both Rjukan and Holen cases, the number of days when the stage in reservoir reaches the lower regulated water level (LRWL) increases under pumping: it doubles in Rjukan, from 6.3 to 12.0 % ; it is five times higher in Holen, from 5.7 to 28.5 %. The number of days when the stage in the reservoir reaches the highest regulated water level (HRWL) is almost zero in both cases. In both cases the lower reservoir is large enough to receive water from the upper reservoir until the upper one is empty. In Rjukan case however, the upper reservoir is very large and the emptying occurs less. The situation is different in Tonstad. The percentage of days with LRWL reached is stable under balancing power operation, while the HRWL increases slightly. Indeed, the small size of the lower reservoir in that case limits the water that can be released from the upper, and water accumulates in the upper reservoir.

The months when LRWL or HRWL are reached under pumping are almost the same for all cases (Figure 3.8). Time period with emptied reservoirs remains from February to June in Rjukan and Tonstad. However in Holen, the upper reservoir emptying may occur during the whole year, with a peaking period which extends from January to July. Time period with filled upper reservoir occur in Tonstad only during the same time period than it is today, which is between October and January.

Table 3.8 Percentage of days when the LRWL or HRWL is reached in Tonstad, Rjukan, and Holen cases.

% Upper	LRWL			HRWL		
		Current	*Simulated*		*Current*	*Simulated*
Tonstad	-	5.4	5.7	↗	**1.4**	**4.0**
Rjukan	↗	**6.3**	**12.0**	-	0	0
Holen	↗	**5.7**	**28.5**	-	0	0.2

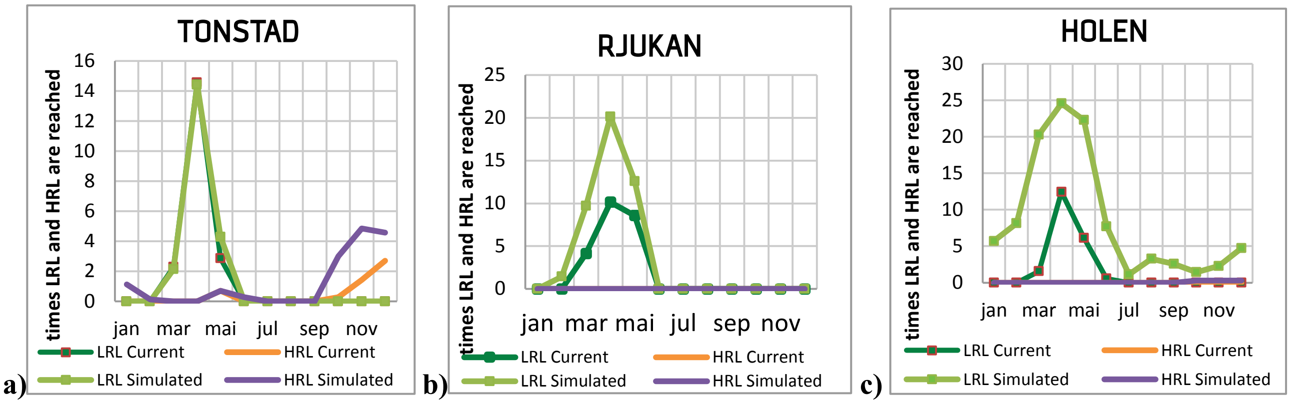


Figure 3.8 a-c Monthly average number of times when HRWL, and LRWL are reached in the upper reservoir in Tonstad, Rjukan, and Holen 's cases.

Lower reservoirs

Physical limits of reservoirs, regarding the volume storage, are more often reached when 7Days-Avg scenario is simulated (Table 3.9).

For both Tonstad and Rjukan cases, the number of days when the stage in reservoir reaches the lower regulated level (HRWL) increases under balancing power operation: it is five times higher in Tonstad, rising from 4.9 to 21.0 %; it is almost six times higher in Rjukan, from 4.9 to 28.1 %. In both cases the free volume available in the lower reservoir is thus a limiting factor to water transfer during generation phases while water is still available in the upper reservoirs (lower reservoirs' volumes are about 20 % of the upper's ones). The LRWL is however never almost reached, which means that pumping phases don't lead to emptied reservoirs in these cases. The reason could be either the energy demand itself (more water is still available for pumping), or a limiting turbine capacity (too small to meet the required water transfers).
In Holen however, the number of days with HRWL reached rises barely form 0 to 3.5 %, while the LRWL is still not reached under the simulated scenario. In that case, more water is available in the reservoirs and could be transferred during both pumping and generation phases.

Regarding the seasonal variations, Rjukan and Holen present two periods with HRWL reached (Figure 3.9): May to July, and September to December. These months are periods with higher energy demand and thus more exchange of water volumes. Apart from these periods, HRWL is reached during the whole year in Rjukan. In Tonstad case, HRWL is also reached all year, with a higher frequency in winter. But Tonstad seem to follow less the seasonal trend for energy needs since its lower reservoir's size is clearly smaller than the others cases and is often a limiting factor to the exchange of water between reservoirs.

Table 3.9 Percentage of days when the LRWL or HRWL is reached in Tonstad, Rjukan, and Holen cases.

% lower	LRWL			HRWL		
		Current	*Simulated*		*Current*	*Simulated*
Tonstad	-	0	0.12	↗	**4.9**	**21.0**
Rjukan	-	0	0	↗	**4.9**	**28.1**
Holen	-	0	0	↗	**0**	**3.5**

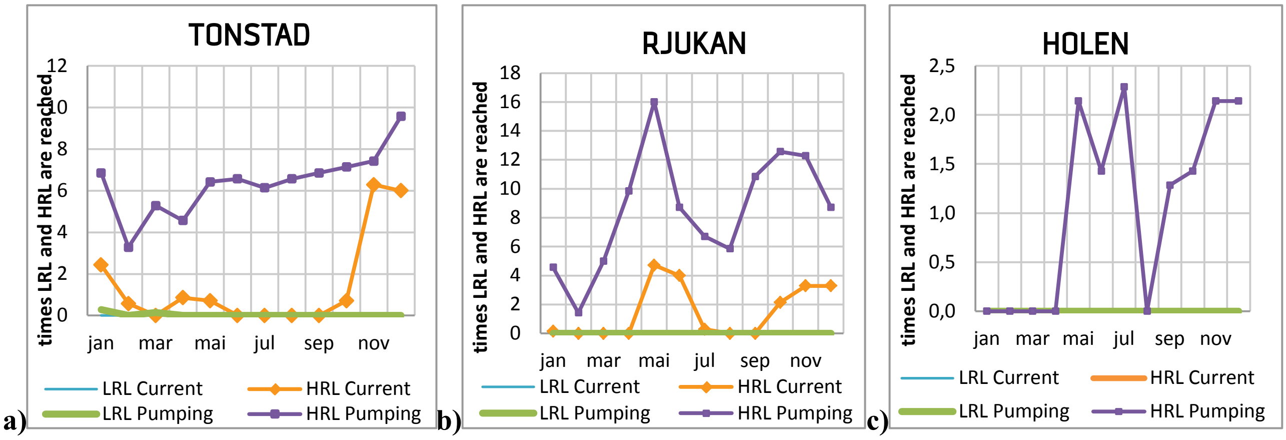


Figure 3.9 Monthly average number of times when HRWL, and LRWL are reached in the lower reservoir in Tonstad, Rjukan, and Holen 's cases.

3.3 Water level fluctuations in reservoirs under Dev-Avg scenario

When applying the second balancing power scenario to the three cases and comparing to the 7Days-Avg scenario, results mainly defer regarding the frequency, the magnitude of short-term fluctuations, and reservoirs' emptying and filling. Results are briefly described below.

3.3.1 Seasonal pattern

In upper reservoirs, the seasonal trend is basically the same as in the 7Days-Avg scenario, except for Holen there is a new seasonal trend. In all studied cases, the maximum and minimum stage reached in the reservoirs is higher and lower, respectively, and they are reached some months later than in the current pattern.
In the lower reservoirs, contrary to the 7Days-Avg scenario, there is still a seasonal pattern which repeats every year. However this seasonal trend differs from the current one. In the Dev-Avg scenario, the water level reaches often the LRWL during the "low stage period". The stage reaches often the HRWL during the "high stage period".

3.3.2 Fluctuations

Frequency

In all cases, water levels fluctuations in both the upper and lower reservoirs are less frequent in the Dev-Avg scenario than in the 7Days-Avg scenario (Table 3.10). The largest gap appears in Rjukan's case: in the Dev-Avg scenario 20.0 % and 25.6 % of the days of the studied period encounter stage fluctuations in the upper and lower reservoir, respectively, while it was 38.5% and 40.3 %, respectively, in the 7days-average scenario. This difference can be explained by the definition of the energy demand itself. In the Dev-Avg scenario, the principle is to either pump or release water when the electricity production from wind turbines is over or under a certain threshold, respectively, while in the 7Days-Avg scenario, water is transferred when there is a difference between daily and weekly wind power production. Therefore the Dev-Avg scenario leads to less frequent but often longer periods with water pumped or released. We can note that the percentages of days with fluctuations differ from one case to another in the Dev-Avg scenario. Indeed, relatively long periods of pumping or releasing of water found in that scenario induce that reservoirs' volumes are more often a limiting factor to water transfer (Chapter 3.5.2). These limits depend on each reservoir.

Table 3.10,a-b Percentage of days of the whole studied period with a daily variation of stage in upper reservoirs (left) and lower reservoirs (right) for Tonstad, Rjukan, and Holen cases.

% Upper	*Change*	*7 days average*	*DevAvg*
Tonstad	↗	39.7	27.4
Rjukan	↗	38.5	20.0
Holen	↗	39.8	23.7

% Lower	*Change*	*7 days average*	*DevAvg*
Tonstad	↗	41.9	35.4
Rjukan	↗	40.3	25.6
Holen	↗	39.9	26.7

Magnitude

The magnitude of rates of changes in stage is lesser in the Dev-Avg scenario than in the 7Days-Avg scenario in upper and lower reservoirs (Table 3.11). This can be explained by less amount of water transferred by pumping and generation in the former scenario than in the latter, while the current changes in stage (current production and lateral inflows) are the same in both scenarios.

Table 3.11,a-b Daily rates of change in water level for the current situation in upper reservoirs (left) and lower reservoirs (right) under balancing power scenario for Tonstad, Rjukan and Holen cases.

m/day Upper		*7 days average*	*DevAvg*
Tonstad	*Median*	**0.60**	**0.21**
	P90	1.55	1.19
Rjukan	*Median*	**0.22**	**0.09**
	P90	0.58	0.42
Holen	*Median*	**1.18**	**0.29**
	P90	3.48	1.90

m/day Lower		*7 days average*	*DevAvg*
Tonstad	*Median*	**0.44**	**0.12**
	P90	1.07	0.88
Rjukan	*Median*	**0.26**	**0.07**
	P90	0.62	0.55
Holen	*Median*	**1.20**	**0.59**
	P90	2.87	2.77

3.3.3 Emptying and filling of reservoirs

In the upper reservoir of Rjukan and Holen, the stages reach the LRWL less often in the Dev-Avg scenario, and it is stable in Tonstad (Table 3.12). The HRWL is however more often reached in Tonstad and Holen. Thus the upper reservoirs are in general less often emptied, but more often filled in the Dev-Avg scenario.

In the lower reservoir, the stage reaches the HRWL more often than in the 7Days-Avg scenario, which means that it is more often filled, except for Holen (Table 3.12). That results from longer periods of continuous release of water in the Dev-Avg scenario. The LRWL is also reached often, while it is hardly ever reached in the 7Days-Avg scenario.

These results show that the Dev-Avg scenario lead to more often filled or emptied reservoirs, and thus the balancing needs are frequently not met due to reservoirs size.

Table 3.12,a-b Percentage of days when the LRWL or HRWL is reached in upper reservoirs (left), and lower ones (right) in Tonstad, Rjukan, and Holen cases.

% Upper	LRWL		HRWL	
	7Days-Avg	*Dev-Avg*	*7Days-Avg*	*Dev-Avg*
Tonstad	5.7	5.40	**4.0**	**9.78**
Rjukan	**12.0**	**9.67**	0	0.55
Holen	**28.5**	**17.26**	**0.2**	**20.78**

% Lower	LRWL		HRWL	
	7Days-Avg	*Dev-Avg*	*7Days-Avg*	*Dev-Avg*
Tonstad	0.12	**15.93**	**21.0**	**32.44**
Rjukan	0	**10.29**	**28.1**	**36.95**
Holen	0	**14.32**	**3.5**	**2.9**

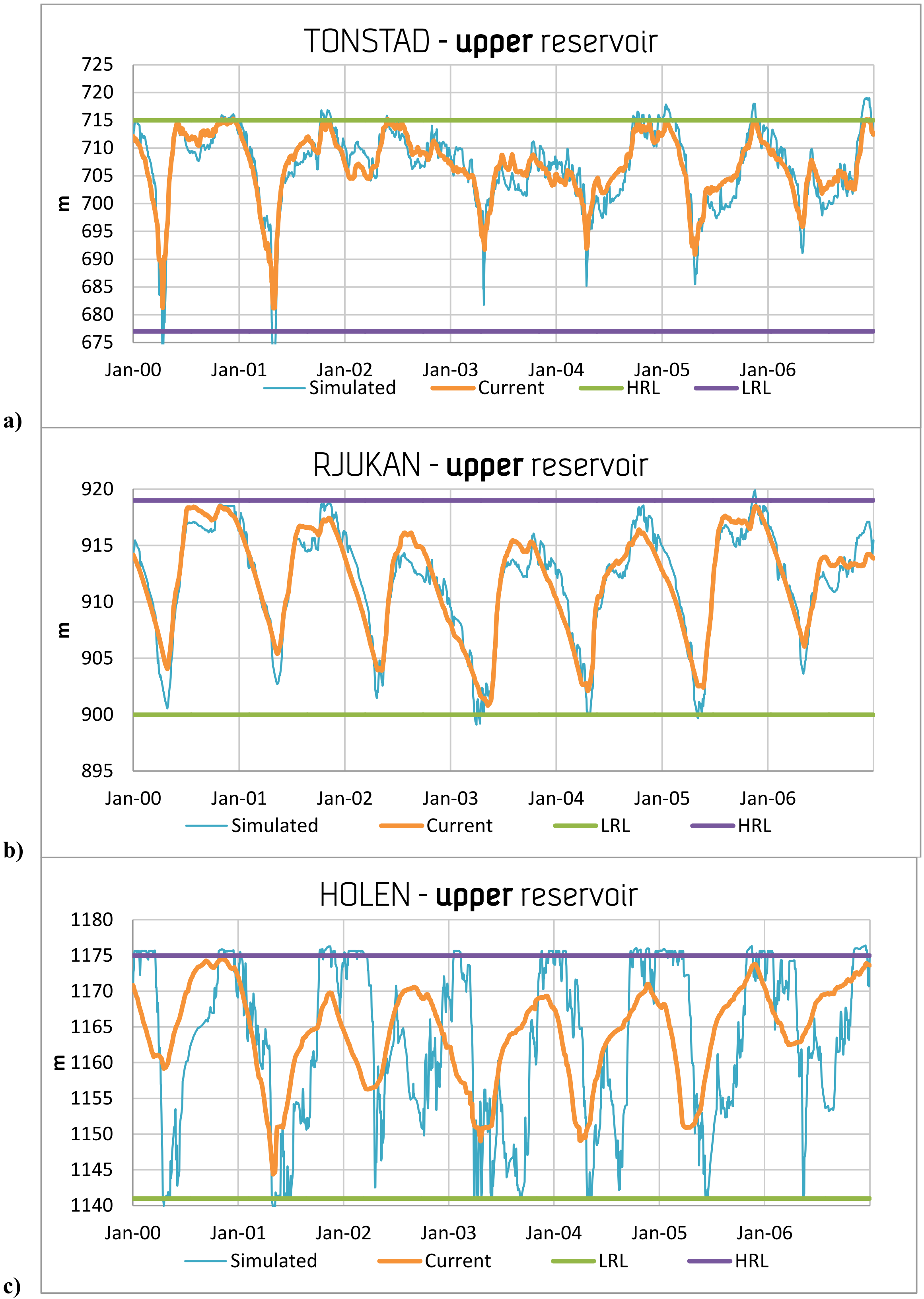


Figure 3.10, a-c **Upper reservoirs. Water level variations for the 2000-2006 period in Nesjen (Tonstad case), Møstvan (Rjukan case), Urarvatn (Holen case) under Dev-Avg balancing power scenario.**

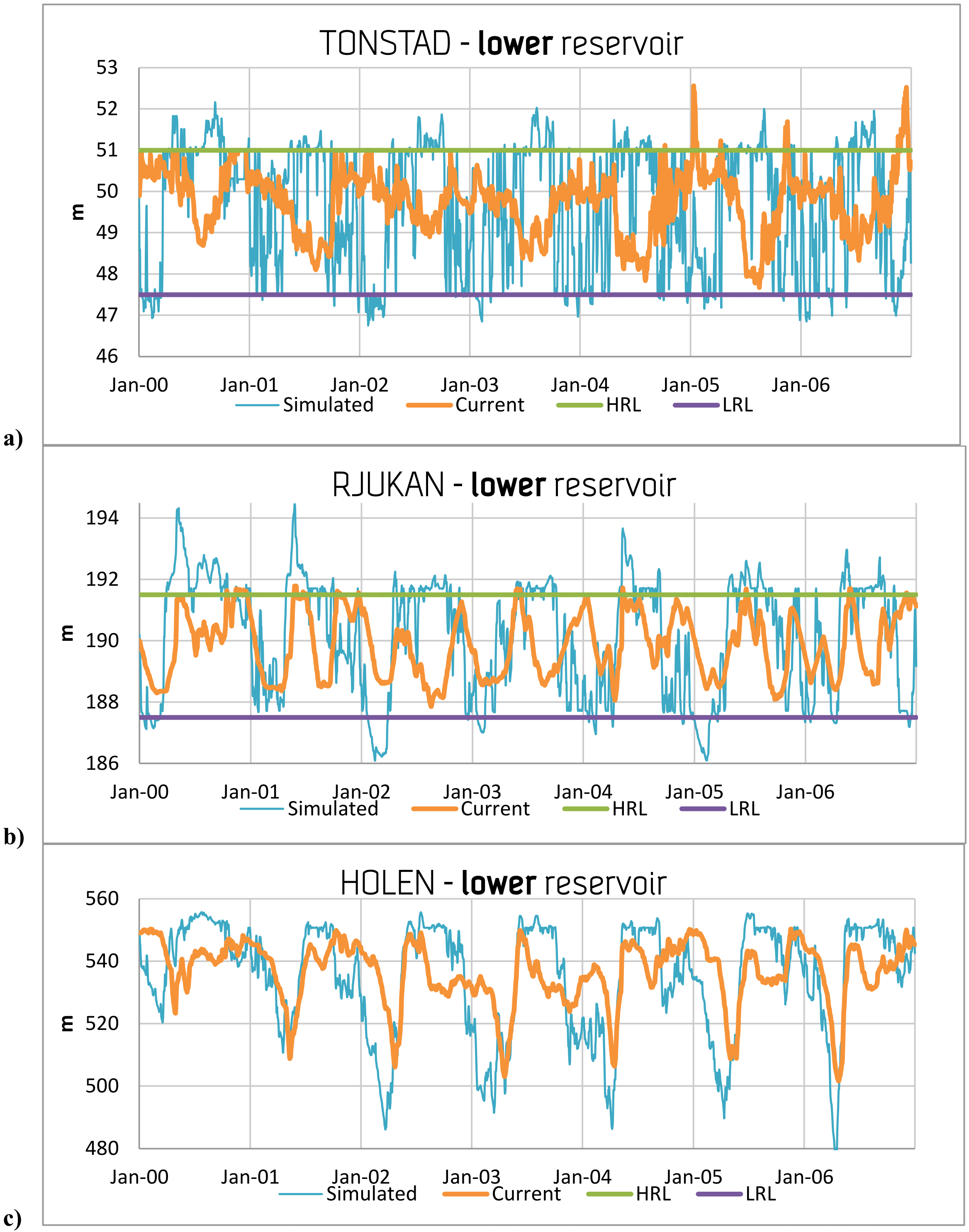


Figure 3.11, a-c **Lower reservoirs. Water level variations for the 2000-2006 period in Sirdalsvatn (Tonstad case), Tinnsjø (Rjukan case), Bossvatn (Holen case) under the Dev-Avg balancing power scenario.**

3.4 Effects of increased balancing power demand

3.4.1 Increased share of capacity

Increasing the ratio of the required balancing power a single reservoir pair has to provide leads to higher rates of change of water level for upper and lower reservoirs (Table 3.13a). When doubling the ratio the rates of change increase by 50 to 60 % for the upper reservoirs, and by 70 to 75 % for the lower reservoirs, mainly because of the increase of the volume transferred between the reservoirs per day. The values of the rates of change are still less than 1m per day, except for Holen. However, the number of days with fluctuations remains relatively stable in all cases (Table 3.13b).

Table 3.13,a-b Rates of changes (left) and percentage of days with fluctuations (right) in the upper and lower reservoirs for the initial turbine capacity set-up in the model, and a doubled capacity.

Rates of changes in water level		*Upper*		*Lower*	
m/day		*Main scenario*	*Doubled capacity*	*Main scenario*	*Doubled capacity*
Tonstad	*Median*	**0.60**	**0.91**	**0.44**	**0.75**
Rjukan	*Median*	**0.22**	**0.36**	**0.26**	**0.46**
Holen	*Median*	**1.17**	**1.78**	**1.20**	**2.10**

Fluctuations	*Upper*		*Lower*	
%	*Main scenario*	*Doubled capacity*	*Main scenario*	*Doubled capacity*
Tonstad	**39.7**	**41.3**	**41.9**	**42.3**
Rjukan	**38.5**	**40.2**	**40.3**	**40.6**
Holen	**39.8**	**40.6**	**39.9**	**40.9**

3.4.2 Altered threshold for balancing power demand

Increasing the threshold determining the required balancing power above a certain amount of wind power generation leads to less stage fluctuations and lower rates of change in water level per day (Table 3.14). When doubling the percentage of deviation from the average wind power generation, the rates of change decrease somewhat in the upper reservoir: Tonstad: from 21 to 16 cm /day, Holen: from 26 to 12 cm/day, Rjukan: from 9 to 8 cm day. The number of days with fluctuations in the upper reservoirs decreases from 27.4 to 24.5 % in Tonstad, 20.0 to 15.9 % in Rjukan, 23.7 to 20.8 % in Holen. The same tendency appears in the lower reservoirs.

Decreasing the threshold leads to more stage fluctuations and lower rates of change in water level per day. When halving the percentage of deviation from the average wind power generation, the rates of changes increase somewhat in the upper reservoir: Tonstad: from 21 to 26 cm /day, Holen: from 26 to 44 cm/day, Rjukan: from 9 to 11 cm day. The number of days with fluctuations increases from 27.4 to 24.5 % in Tonstad, 20.0 to 15.9 % in Rjukan, 23.7 to 20.8 % in Holen. The same tendency appears in the lower reservoirs. The impact of varying the threshold of the balancing power scenario depends on the characteristics of the reservoirs pairs, where Rjukan case is least affected.

Table 3.14,a-b **Rates of changes (up), and number of days with fluctuations (low) for upper and lower reservoirs for different thresholds set-up in the Dev-Avg scenario.**

Rates of changes in water level		*Upper*			*Lower*		
m/day		*12.5 %*	*25 % Main scenario*	*50 %*	*12.5 %*	*25 % Main scenario*	*50 %*
Tonstad	*Median*	**0.26**	**0.21**	**0.16**	**0.15**	**0.12**	**0.08**
Rjukan	*Median*	**0.11**	**0.09**	**0.08**	**0.10**	**0.07**	**0.05**
Holen	*Median*	**0.44**	**0.26**	**0.12**	**0.75**	**0.59**	**0.42**

Fluctuations	*Upper*			*Lower*		
%	*12.5 %*	*25 % Main scenario*	*50 %*	*12.5 %*	*25 % Main scenario*	*50 %*
Tonstad	**27.8**	**27.4**	**24.5**	**34.4**	**35.4**	**33.1**
Rjukan	**22.5**	**20.0**	**15.9**	**26.9**	**25.6**	**24.2**
Holen	**24.3**	**23.7**	**20.8**	**27.9**	**26.7**	**24.5**

3.5 Origin of limitations in balancing power provision

3.5.1 Types of limitations

The amount of energy which can be provided by a pumped storage power plant may be determined by the following factors:

1. Turbine capacity
2. Reservoir volumes

The power plant's maximum capacity (electricity generation) or consumption (pumping) is limited to the power that corresponds to the water discharge the turbine is designed for. If the balancing power demand exceeds this power the turbine capacity becomes the limiting factor for the provision of balancing power. Further, the amount of available balancing power may be limited by the water volumes which are available/free in the reservoirs. In case of pumping it may be limited by the available volume of water in the lower reservoir or the free volume in the upper reservoir. Correspondingly, it may be limited by the free volume in the lower reservoir or the water volume available in the upper reservoir in case of power generation. The various types of limitations are illustrated in Figure 3.12 and Figure 3.13 by plotting the actual energy generation/uptake of the pumped storage power plant against the balancing power demand. Values in the second quadrant correspond to generation (delivery of balancing power), while values in the fourth quadrant correspond to pumping (storage of water/energy). Values on the straight line (green) mean that the balancing power demand (storage and generation) can be met. The red straight lines represent cases having the turbine capacity as limiting factor. Blue and yellow dots stand for the lower or upper reservoir, respectively, limiting the provision of balancing power.

3.5.2 Comparison of cases based on different wind balancing scenarios

Wind balancing power scenario 7Days-Avg

In the baseline scenario the balancing power demand (storage and generation) can be provided at 71, 77 and 76 % of the time for Tonstad, Holen and Rjukan, respectively (Figure 3.12). Considering both generation and pumping, the free or available volume in the lower reservoirs and the turbine capacity are the main limiting factors for providing balancing power in all three cases, while the upper reservoirs play a minor role. The free volume in the lower reservoir is the dominating limiting factor during electricity generation, especially in the case Tonstad (16 % of all days vs. 7 and 11 for Holen and Rjukan). This is related to the total live storage volume of the lower reservoirs (Table 3.3). Considering pumping only, the upper reservoirs' free volumes limit the balancing power provision in the case Tonstad (4 %) and Rjukan (1 %), whereas the available water volumes in the lower reservoirs are not limiting. However, the main limiting factor is the turbine capacity in all three cases (16-17 %). In the cases Tonstad and Rjukan limiting is basically, apart from the turbine capacity, that the stage of the upper and lower reservoir is occasionally close to the HRWL (Figure 3.4 and Figure 3.5), meaning that there is no free volume in the lower reservoir during generation and no free volume in the upper reservoir during pumping (Figure 3.12). In the case Holen in contrast, the free/available reservoir volumes do only limit the balancing power amount during generation, i.e. the HRWL of the lower reservoir and the LRWL of the upper reservoir are reached at times (Figure 3.4, Figure 3.5 and Figure 3.12).

Wind balancing power scenario Dev-Avg

Compared to the 7Day-Avg balancing power scenario, the percentages for the time the balancing power demand (storage and generation) can be provided at, are lower for the Dev-Avg scenario (Tonstad 53 %, Holen 53 %, Rjukan 57 %). This is due to increased numbers of days on which free/available reservoir volumes limit the balancing power provision. Regarding Tonstad and Rjukan, the percentage increases for the lower reservoir (from 16 % to 34 % and 11 % to 26 %, respectively; Figure 3.13), while regarding Holen it increases both for the lower reservoir (from 3 % to 20 %) and the upper reservoir (from 7 % to 14 %). In the cases Tonstad and Rjukan the percentage of days with the lower reservoir being limiting is larger during both generation and pumping mode. In the case Holen the percentage is higher for the upper reservoir during pumping and for the lower and upper reservoir during generation.

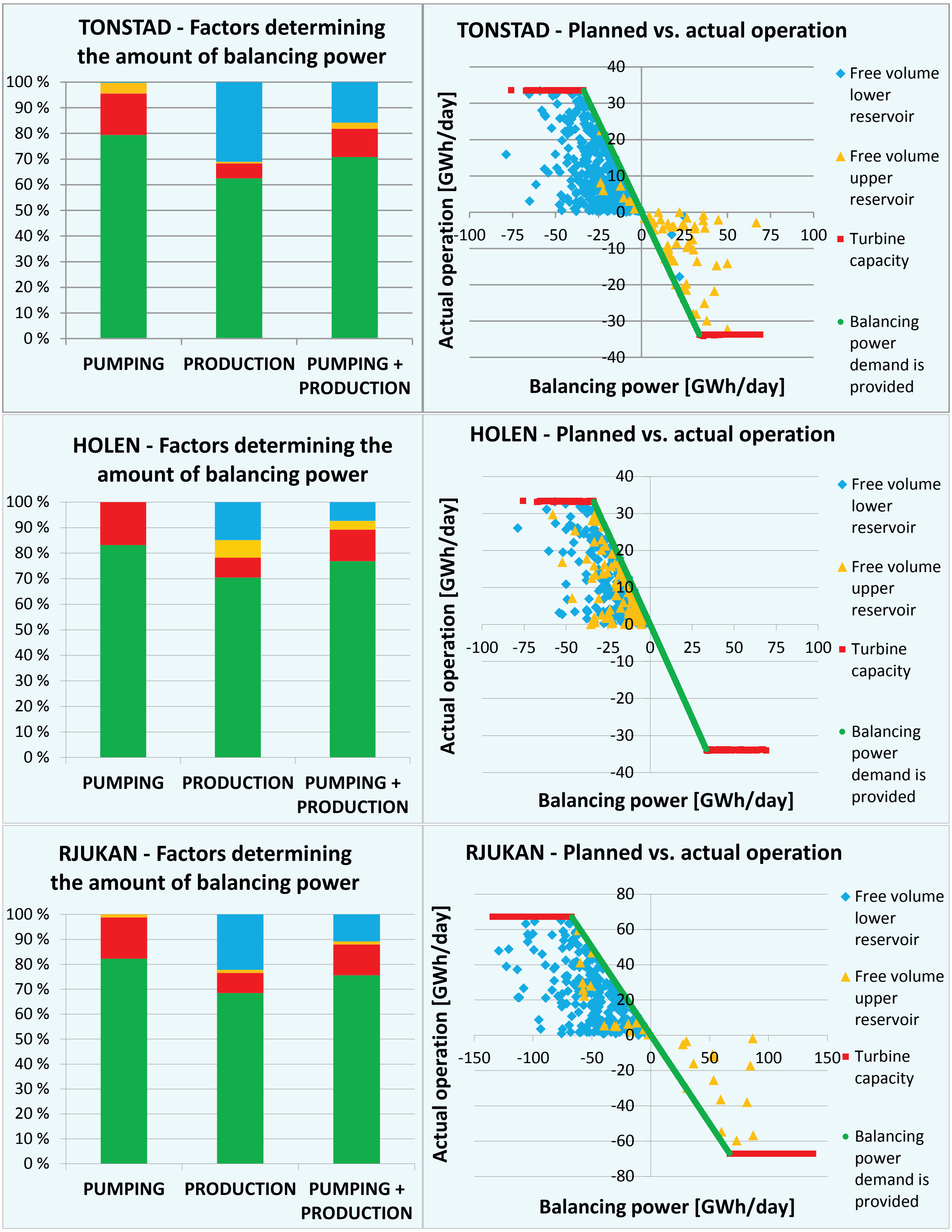


Figure 3.12 7Days-Avg scenario. Factors determining the amount of balancing power provision (left) and planned vs. actual operation (right) for Tonstad (top), Holen (middle) and Rjukan (bottom).

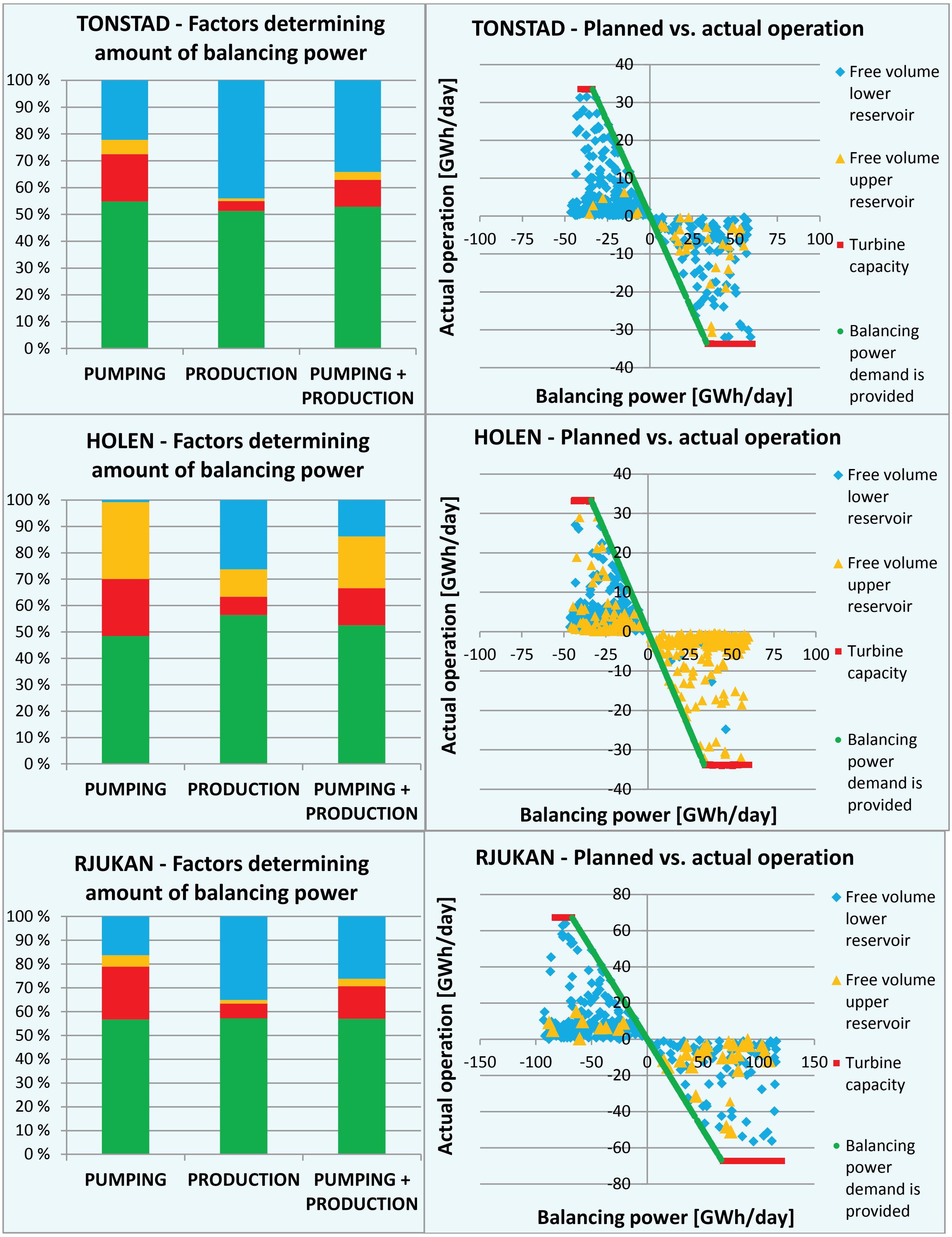


Figure 3.13 Dev-Avg scenario. Factors determining the amount of balancing power provision (left) and planned vs. actual operation (right) for Tonstad (top), Holen (middle) and Rjukan (bottom).

3.5.3 Effects of increased balancing power demand

Based on the 7Days-Avg and the Dev-Avg balancing power scenarios, effects on the limiting factors are described when varying the share of capacity and the threshold for providing balancing power in the Dev-Avg scenario. The former affects the amount of balancing power which is to be provided in general, the latter the amount of balancing power which is to be provided by a single reservoir pair.

Increased share of capacity

Increasing the ratio of the required balancing power a single reservoir pair has to provide leads to lower percentages of days on which the balancing power demand can be met. When doubling the share of installed capacity the percentages decrease strongly (Tonstad: from 71 % to 43 %, Holen: from 77 % to 47 %, Rjukan: from 76 % to 44 %), mainly due to the turbine capacity increasingly limiting the balancing power provision (Figure 3.14), whereas the reservoir volumes are less significant. In order to achieve a situation in which the turbine capacity is no longer limiting the share of installed capacity has to be halved.

Altered threshold for balancing power demand

Decreasing the threshold determining the required balancing power above or below a certain amount of wind power generation leads to lower percentages of days on which the balancing power demand can be met, but the effect is not strong. When halving the percentage of deviation from the average wind power generation the percentages of days decrease somewhat (Tonstad: from 53 % to 47 %, Holen: from 53 % to 48 %, Rjukan: from 57 % to 51 %), mainly due to the turbine capacity increasingly limiting the balancing power provision (Figure 3.15). When doubling the threshold the percentage of days the turbine capacity limits the balancing power provision diminishes, while the influence of the reservoir volumes remains about the same.

3.5.4 Typical limitations for different types of hydropower plants and reservoirs

Overall, the factor limiting the provision of balancing power most is the volume of the lower reservoir, especially during electricity generation, i.e. the HRWL is reached. This is mainly due to the current regulations and way the reservoirs are operated at present, meaning that there are periods with high water levels in the reservoirs. At these times there is no additional capacity in the lower reservoirs for taking more water during generation. In addition, the size of the reservoirs' live storage volumes plays a role. In the case of Holen, having a lower reservoir with a large volume, the percentage of days on which the upper reservoir is limiting is therefore larger than in the two other cases.

The second important limiting factor is the turbine capacity. It limits the provision of balancing power during both generation and pumping, where the influence during pumping is higher than during generation in all cases. The turbine capacity becomes primarily limiting when the amount of required balancing power is varied, while the significance of the free/available volumes in the reservoirs remains about the same. Increasing either the amount of balancing power that is totally required or the demand a reservoir pair has to cover, implies an increased percentage of days on which the turbine capacity limits the provision of balancing power.

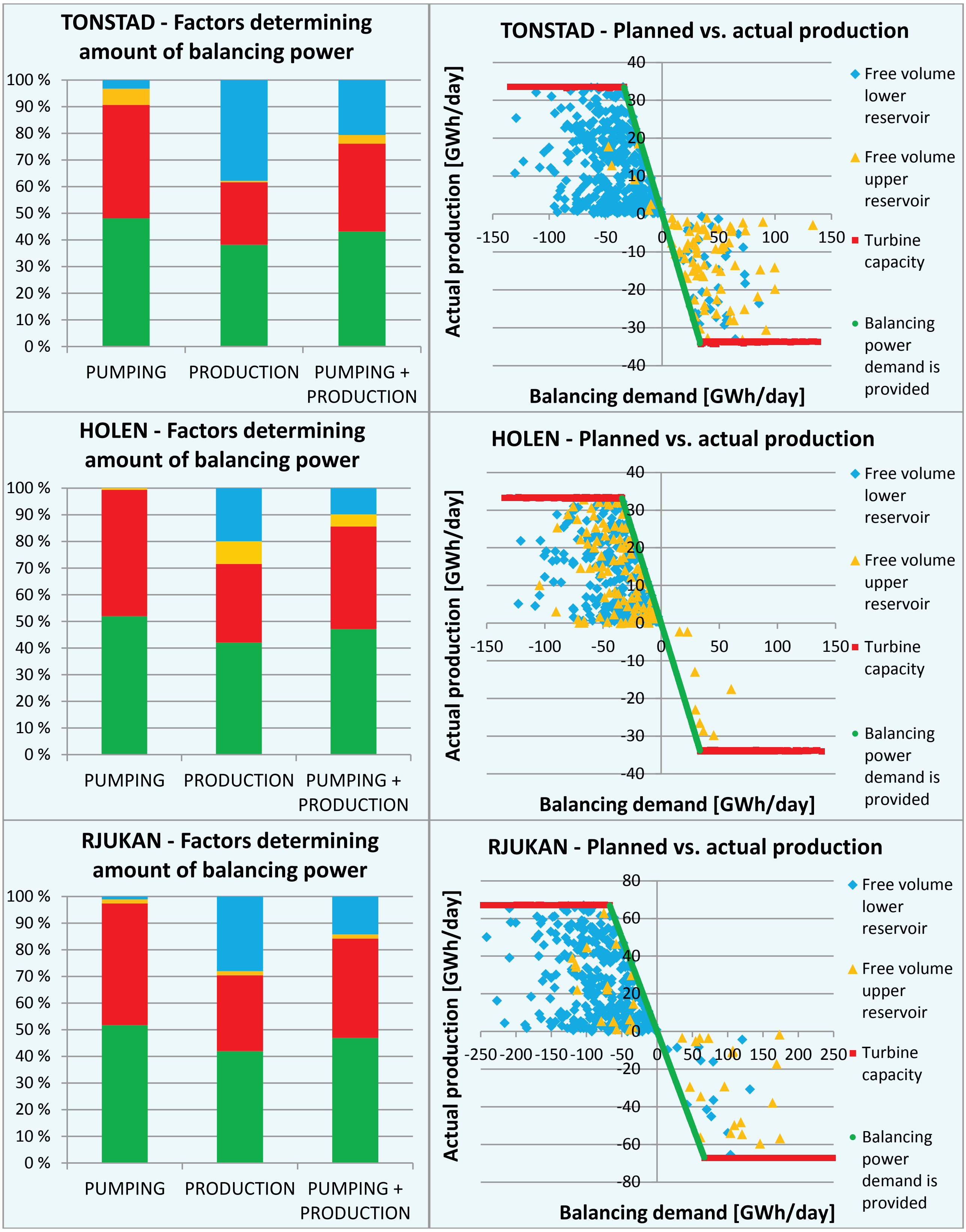


Figure 3.14 7Days-Avg scenario, doubled share of installed capacity. Factors determining the amount of balancing power provision (left) and planned vs. actual operation (right) for Tonstad (top), Holen (middle) and Rjukan (bottom).

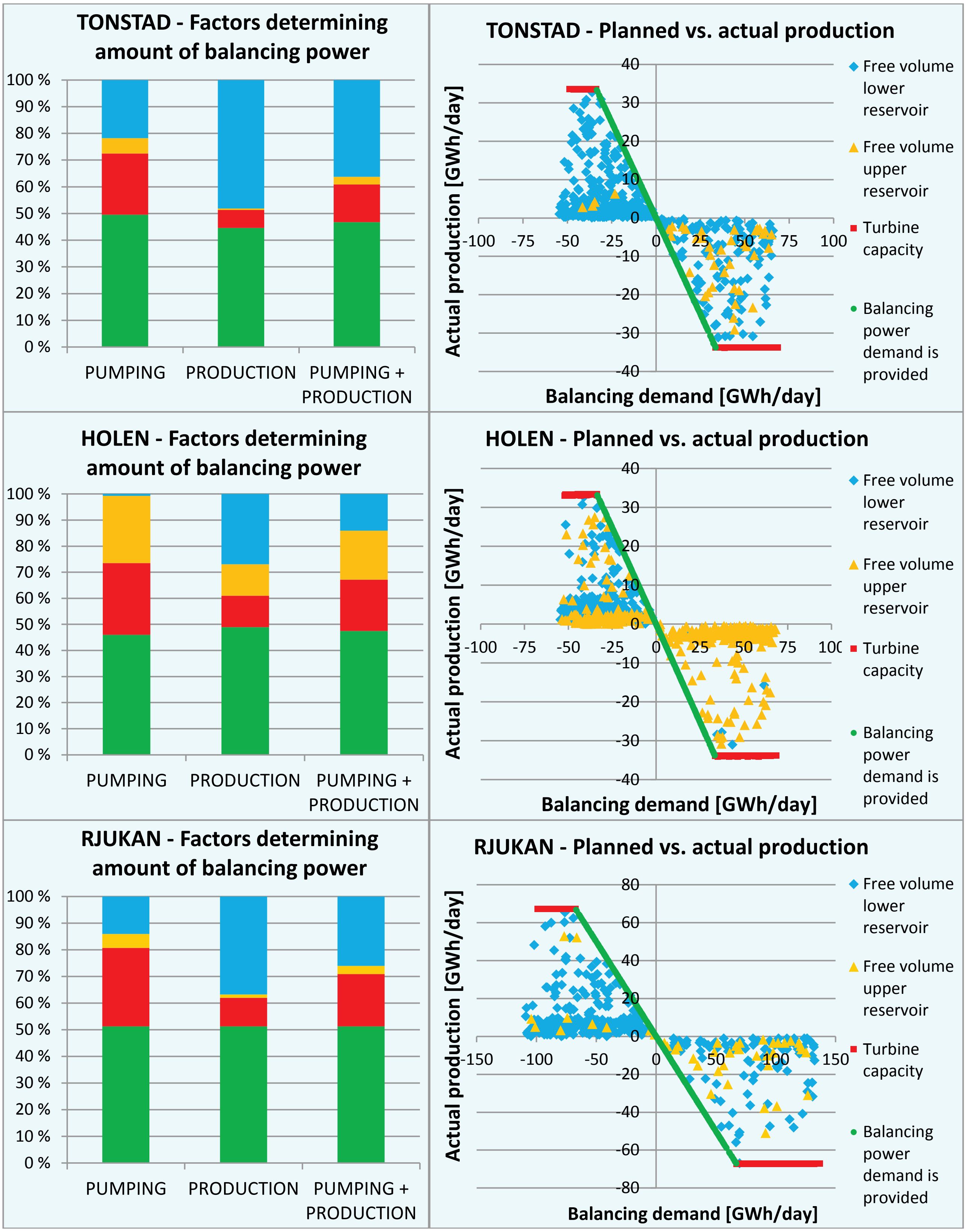


Figure 3.15 Dev-Avg scenario, halved threshold for balancing power demand. Factors determining the amount of balancing power provision (left) and planned vs. actual operation (right) for Tonstad (top), Holen (middle) and Rjukan (bottom).

3.6 Environmental impacts

Construction of pumped storage power plants will modify the current patterns of reservoir operation by introducing more frequent and greater fluctuations in water volume, level and wetted area in the upper and lower reservoirs, as described for the three cases in this study (Chapter 3.2 – Chapter 3.5). Changes in seasonal and monthly variations of stage, more frequent and stronger fluctuations as well as more frequent emptying and filling of reservoirs will be direct consequences of the use of reservoirs for the means of balancing power. New operational regimes could have both direct/immediate and indirect/long-term abiotic and biotic impacts in affected reservoirs as well as downstream rivers.

The abiotic factors include changes in water level, water temperature, erosion, circulation and ice cover. Increased magnitude, frequency and rates of variations in stage, volume and wetted area are direct impacts, and may lead to changes in the hydrodynamics and water quality of reservoirs. Modifications of circulation patterns may occur in the long-term, induced by occurrence of strong currents, particularly near the outlet of the turbines (Anderson, 2006; Gailiusis, 2003). Another consequence of a regularly occurring alteration between discharge and abstraction of water is the weakening of the water column stability, which may lead to more vertical mixing and affect thermal stratification (Anderson, 2010; Potter et al., 1982) as well as dissolved oxygen concentration and turbidity (Bonalumi et al., 2011). Hence, water quality and temperature in downstream water bodies, which are dependent on the thermal and chemical stratification of a lake, may be modified. Further, the water level fluctuations may induce shoreline erosion, affecting substrates characteristics and amount, as well as re-suspension of nutrients (Zohary, 2011). High velocities may occur in the neighbourhood of pumped storage power plant inlets and create local currents. Moreover, ice formation, ice cover stability and break-up may be affected in lakes with ice cover during winter time (Liu, 1999).

These abiotic factors are expected to influence lake organisms and interactions between species (Stanford & Hauer, 1992; Helland et al., 2011) by affecting the food web, habitat area, population dynamics and nutrient level. The timing of the water level fluctuations as well as when the littoral and pelagic zones are reduced are of vital importance for the biological communities in reservoirs. A direct impact of water level fluctuations is stranding of juvenile fish, which may not be capable to follow the water line and return to deeper areas if the water level decreases rapidly (Bell et al., 2008). Reservoirs which are already impacted by drawdown zones of tens of meters annually due to existing regulation, have typically barren shorelines with few terrestrial and aquatic organisms living in or using the littoral zone (Zohary, 2011). Jonsson & Jonsson (2011) studied salmonids and found that water level fluctuations reduce the connectivity of lakes to their tributaries and consequently, since the fish may spawn in tributaries, accessibility to vital habitats in adjacent streams. It is also possible that new operational regimes may improve these conditions if water levels are maintained high in key periods. Frequent water level fluctuations may lead to more homogenous water temperature profiles and increased circulation, causing a reduction in ice cover, which may affect fish population dynamics (Helland et al., 2011). Furthermore, pumping water from a downstream system may increase the nutrient level in reservoirs and change the population dynamics of plankton communities as well as in some cases increase the fish production (Stockner & Macisaac, 1996).

3.7 Summary of results

The analysis of the three reservoir pairs shows to which extent the current patterns of fluctuations in water volume, water level and surface area in the reservoirs are modified when introducing balancing power operation. In case of the 7Days-Avg scenario these changes affect both the seasonal pattern of the storage volume in the upper and lower reservoirs and introduce short-term fluctuations. The average rates of change in water level are obviously higher than during the current operation, but they are still below the range of critical rates as defined by Halleraker (2003) and Saltveit (2001). The simulation results of the Dev-Avg scenario show the same tendency in terms of water level variations. However, the short-term fluctuations are less frequent and have slightly lower magnitude. The factors limiting the provision of balancing power most are the turbine capacities and the live storage volume of the lower reservoirs.

The analysis shows that water level fluctuations are site-specific. Hence, for the purpose of detailed planning, each case should be studied individually. Water level variations depend on the load, the characteristics of each reservoir pair (live storage volume, steep/gentle bank slope, size of lower reservoir compared to upper one) and the installed capacity.

3.8 Needs for further research

CEDREN's project EnviPEAK, focusing on environmental impacts of hydropeaking (i.e. frequent changes in power production by hydro-electric facilities) mainly in rivers, showed that water level fluctuations can have impacts on organisms (e.g. Noack et al., 2010; Puffer and Berg, 2010; Zakowski et al., 2010). However, only few studies have focused on the potential impacts of pumped storage power plants on the aquatic ecosystem of reservoirs.

Results published in the present report constitute the first step in investigations of environmental impacts of using reservoirs as a battery to balance intermittent energy sources. The model used here allows considering changes only in terms of transferred water volumes and fluctuations in stage. Further research is needed to assess physical and biological consequences of operating pumped storage power plants in reservoirs, based on both numerical modelling and field studies.

Potential physical changes occurring in reservoirs can be assessed in detail by the use of 2D/3D hydrodynamic numerical models for case-specific studies in order to simulate effects of new operational regimes on abiotic factors, such as hydrodynamics (currents, vertical and horizontal mixing, stratification, etc.), water quality (water temperature, oxygen, sediment concentration, etc.) and ice formation. A large set of input data must be collected on-site and over several years to set up and calibrate numerical models. The more field data are available, the more accurately the model can be calibrated, and the more precise the simulation results will be. Detailed topography of the reservoirs must be surveyed. Local meteorological stations need to be installed on the shore of the reservoirs in order to collect the corresponding meteorological data (wind speed, wind direction, cloud coverage, air temperature, radiation, etc.). All inflows and outflows into the reservoirs as well as the water temperature must be recorded at a regular time step (at least daily values) by installing sensors and loggers. Water quality parameters should be collected at various depths from the water surface to intermediate layers, ideally throughout the entire water column. It should be subject of field studies to examine impacts of frequent changes in reservoir water levels on processes related to erosion (interaction between ground and surface water, geo-morphological conditions, etc.).

A large range of simulations should be carried out with various input scenarios to study how pumped storage power plant operation can affect environmental conditions in the corresponding reservoirs. Effects of inflows into the reservoirs and discharge or abstraction by pumped storage power plants on water temperature, the location and depth of the intake and outlet as well as the length of pumping and generation phases are some of the parameters to be studied. Further, technical characteristics and limitations (e.g. up- and down-ramping of pumped storage power plants) should be included in the simulations.

Apart from the abiotic factors it is essential to examine biotic parameters, investigate the interactions and dependencies between these factors and assess their impacts on the reservoir ecosystem. Physical consequences, such as erosion, changes in water temperature, stratification and ice cover, etc. are important biological factors affecting aquatic organisms in reservoirs. There is a complex relationship between various abiotic and biotic factors, including the food web and intra- as well as inter-specific competition, for instance. Organisms have differing requirements on their environment depending on the species, life stage, habitat and season. Further research is needed to understand these complex interactions. In particular, it is important to record data in field studies across relevant gradients (e.g. climate, species composition, lake morphology) as basis for biological models.

Finally, it is of great importance to combine results from numerical studies/simulations/models with observations from field studies, both within biological studies and studies on abiotic factors, but especially across both fields. Emphasis should be put on identifying mitigation measures against negative impacts. As an example, optimisation of pumped storage power plant regimes to fit environmental needs best should be investigated (e.g. seasonal thresholds for rates of change in water level or selective abstraction of water from reservoirs to control water temperature).

4 Societal legitimacy

4.1 Research questions

In this report the analysis of the societal aspects involve analysis of the political, economic and environmental concerns of using Norway as a 'green battery', according to how these are expressed by key Norwegian stakeholders. When the EU Renewable Directive (2009) was promoted, The European Commission initiated a study on how to increase social acceptance in order to promote renewable energy projects.[5] The issue of social acceptance may be understood in several ways. In this report we have chosen to use a broad interpretation which includes environmental and economic aspects, questions of involvement, as well as reflections on the current national framework's ability to take key stakeholder considerations into account. In the following, the question of social acceptance is therefore treated as a question of societal acceptance.

We want to answer the following question:

- Does the idea of a using Norwegian hydropower as a 'green battery' for Europe have legitimacy among key Norwegian stakeholders?
- What are the drivers supporting the idea of Norway as a 'green battery', and what are the barriers?
- And what approaches are necessary to overcome important barriers?

4.2 Method

The analysis draws on an analysis of interviews with 22 informants, representing four interest groups, as well as the public authorities concerned. These interests include; energy companies, environmental NGOs, recreational NGOs, as well as the host communities. The interviews have been performed during October and November 2011.[6]

The informants were chosen according to a set of different criteria. First of all we include those companies that had been involved in Energy Norway's project "Norway as a green battery for Europe". The companies included in the study are Agder Energy, E-Co Energy, Norsk Hydro, Lyse energy, Sira-Kvina energy, Statkraft and Statnett.[7] Secondly, other interest groups at the national level that represent environmental, economic and social interest that might be affected by further development of the Norwegian hydropower system, were approached. The Environmental NGOs included in the study are Norwegian Society for the Conservation of Nature (NNV), Nature and Youth, Bellona and WWF.[8] Thirdly The Norwegian Trekking Association (DNT) and Norwegian Association of Hunters and Anglers (NJFF) were contacted since they both represent two major recreational outdoor interest organisations in Norway. Fourthly the Norwegian organization for hydroelectricity producing municipalities, LVK, was also included in the study, along with two mayors representing the Sirdal and Kvinesdal municipalities. The two municipalities are located in southern part of Norway. In this region there exist several reservoirs with large hydropower storage capacity. Finally, the environmental and energy public directorates (DN and NVE) were included since the idea of Norway as a green battery may pose a challenge for the current concession system, as well as for the overall regulatory framework regarding energy policy concerns at large.

---

[5] For further information: http://www.erec.org/projects/other-projects/reshare.html

[6] During the interviews an interview guide was used, see attachment 1.

[7] BKK was also contacted.

[8] *Fremtiden i våre hender* and *Zero* were also contacted.

The interviews performed with the stakeholders focused on the how the idea of Norway as a 'green battery' was considered by the different stakeholders in general, and not in relation to concrete projects.[9] In accordance with the conditions set by the Norwegian Social Science Data Services, the informants have all been offered the possibility to comment the representation of their views (part 3.1 and 3.2).

4.3 Drivers and barriers

In the following the drivers and barriers are presented according to each stakeholder group. The reason for choosing such a strategy is that the drivers are directly related to the barriers that are identified by each stakeholder and possibilities each respective stakeholder sees for overcoming these barriers.

4.3.1 The companies

The companies view the possibilities for using Norwegian hydropower as balancing services for Europe quite differently. This is due to a range of factors. First of all six out of the seven companies interviewed are involved in hydropower production, while one of the companies – Statnett – is responsible for Norway's main grid transmission system (TSO – the transmission system operator). Secondly the companies are different in terms of their size. Statkraft is for example by far the largest company when it comes to hydropower production. Consequently the companies have different opportunities to invest in further hydropower development. Thirdly, the companies are different when it comes to their business interests. Whereas five of the six companies are focused on hydropower production and other renewables – like wind power – Norsk Hydro also have industrial interests (aluminium production). Fourthly, the companies have different abilities to develop balancing services both due to the location of the reservoirs, in terms of distance to the coast, in terms of reservoir capacity, and in terms of technical possibilities.

Having these differences in mind the following presentation of the drivers and barriers focus on considerations made, without focusing on a specific company's interest. The reason for choosing this strategy is that the goal of the analysis is not to focus on the differences between the companies, but rather to get an overall picture of possibilities and challenges that the idea of Norway as a 'green battery' represents from a company perspective.

The idea of using Norwegian hydropower for balancing services for Europe has legitimacy among the stakeholders in the sense that it is generally viewed as representing a way of contributing to a more climate friendly energy system. Even though the companies themselves have no obligation to follow international commitments regarding the political goals to increase the renewable energy share in the European energy market, the companies generally find that Norwegian companies should make such a contribution. However, the differences are significant between those seeing it as a solution for their company and those doubting the possibility that neither their company – nor any hydropower company in Norway for that matter – can contribute in realizing the 'green battery'. This is related to the perceived risks and uncertainties that such an investment pose, both economically and politically. Despite the reservations made, the idea of a 'green battery' in itself is viewed as a legitimate challenge.

Even though the companies reflect upon the climate change as a driver promoting the idea of a 'green battery', it is the possibilities for creating a new business product and thereby how the Norwegian hydropower system can be further developed, that is the most important driver for the companies who find balancing services or back-up services representing a desirable future for the companies. In other words it is

---

[9] Se attachment 1, Interview guides

the commercial interests that drive the companies. At the same time many of the companies question the economic foundation of a 'green battery'. The scepticism is related to a disbelief in the future of the price differences. Several of the companies find that the positive calculations draw on historical data that will not be relevant for the future energy market since it is expected that a better energy flow will reduce the peaking in prices that is seen as the foundation for such a system – economically speaking.

The disbelief in the commercial potential has also several other aspects. One aspect is the fear that countries like Germany will find other ways to balance wind and solar energy. Many of the informants find it likely that Germany will choose pumping storage now developed in Switzerland, Austria and Germany in order to avoid the long transport of energy, as well as the possibilities of getting such services at a lower cost. Secondly the technological development on the continent is also seen as a challenge since new back-up solutions will open up for other ways of storing electricity other than using water storage from reservoirs. Thirdly the capacity payment system which currently is adopted in many EU countries in order to promote new renewable, is suspected to change the market situation. At the same time, some of the companies regard public subventions representing a possibility for guaranteeing the financial capacity needed in order to establish new interconnectors.

Another uncertainty regarding a possible “green battery” future is related to the need to build new interconnectors. So far it is Statnett who is responsible for the cables that have been constructed as well as of the new ones that are planned. There is a fear that the grid connection to the continent will be delayed due to Statnett's obligation to sustain the national grid. National grid development is therefore seen as representing a hindrance for realizing new cables since the needs for transport of specific balancing services – effect, goes beyond Statnett's current mandate – thus to secure delivery of electricity in Norway. There is also a resistance from some of the companies regarding who should pay for further cable development. As the system is currently designed, it is the consumers that finance grid development through a grid tariff. New costly cables will challenge this system.

The environmental effects are generally viewed to be limited, even though the companies also express considerations regarding some potential negative effects, a point to which we will return later. Among positive effects, pumping storage is seen as a technology that might lead to a situation where the extremes (lowest water level in the reservoirs granted in the concession) might be less, even though this is not guarantied. Another positive effect is that the water level in the reservoirs is expected to be higher in the summertime compared to the current situation. Furthermore new tunnels that lead cold water from the reservoirs directly to the sea or lower reservoirs, is seen as positive in areas where cold water today affects rivers where fishing interests are important. Possible new pumping projects are also generally viewed as an opportunity to improve landscape values, although such possible adjustments have to be considered in a case-by-case approach.

At the same time several of the companies believe that pumping storage may lead to erosion problems, as well as insecure ice conditions. Some of the informants are also concerned that the extended grids will demand the construction of new overhead lines in virgin areas. This is, from some companies view, one of the main problems with the current organisation of the power-supply system, new grid lines is to a large extent the companies' responsibility, and Statnett cannot plan new overseas cables without expanding the onshore grid capacity. There is also a concern among all the production companies concerning the mass volume that excavation from new tunnels will result in and how this might affect the local environment. Finally several of the companies express uncertainty as to what the Biodiversity Act, as well at the Water Framework directive will mean for further hydropower development, including balancing services.

Despite some potentially positive aspects regarding environmental impacts of increased efficiency and pumping storage might result in, this question is, however, seen as a task on-going research should give an answer to.

In the cases where the companies are generally positive to the idea of a Norway as a 'green battery', they are all reluctant when it comes to the scale of the services Norway will be able to deliver. Most of the companies express that even in the cases where they see possibilities, the question of scale is important not only from a financial aspect, but also from an environmental aspect. Even though on-going research will give input as to how they find they might design new projects, the companies are of the opinion that the consequences has to be assessed in each concrete project.

Finally the idea of using Norway as a 'green battery' is seen as legitimate among most of the companies due to the contribution the income from such an investment will cause from a societal perspective. Not only are the local municipalities seen as benefiting from further hydropower development, especially during the construction phase, but also the society at large is seen as a part who will benefit economically form such development. At the same time there is an expressed worry among the companies that possible future projects involving pumping storage will not be met positively by the host municipalities since the existing taxation system is based on production. Since pumping involves energy consumption, the net income for the host municipalities might in fact be reduced.

Even though most of the companies find the idea of using Norwegian hydropower to balance further development of wind and solar energy on the continent as representing an opportunity, the risks associated with such a development of hydropower is regarded as being high. The risks are related to the uncertainties regarding the lack of sufficient cable development, as well as uncertainties regarding the commercial potential and the regulatory framework. These issues are seen partly as a consequence of a lack of political clarification regarding the future of the Norwegian energy policy. From the companies point of view there is a need for a new energy policy that clarifies whether or not Norway should become a 'green battery'. Such a clarification, and especially the role of Statnett, should, according to several of the companies, involve a grid policy that is more oriented towards an international market. In general the future of a 'green battery' is seen as a governmental responsibility that also should involve a risk sharing – especially economically speaking – where the state takes on a responsibility for such a development. Further more the national framework regarding renewable development is seen as a challenge due to the time consuming concession process.

4.3.2 Environmental NGOs

There are several different environmental organisations i Norway. The organizations differ when it comes both to what they regard as the main environmental challenge (reducing CO_2 emissions and/or protection loss of biodiversity), as well as how they are organized. When it comes to hydropower the NGOs also differ when it comes to the extent they have been involved in hydropower concerns, and which needs hydropower production should cover (inland consumption for households and industry, export to other countries etc.) Export of power has not been on the agenda for a long time for most of the NGOs, a fact that also influences the way they view the idea of using Norway as a 'green battery' for a Europe. In order to get a better understanding of the differences between the different environmental concerns we chose to interview four different environmental organisations that represent partly divergent positions in the environmental discourse. The organizations are the Norwegian Society for the Conservation of Nature (NNV), Nature and Youth, Bellona and WWF. The Norwegian Society for the Conservation of Nature is Norway's oldest and largest nature and environmental protection organization. The organization is based on a democratic membership structure, and has regional branches in all the country's counties, as well as several local groups across the country.[10] Nature and Youth is the only member based environmentalist youth organisation in Norway, and is considered the youth organization of The Norwegian Society for the Conservation of Nature. The organisation has about 80 local groups.[11] The Bellona Foundation is an international environmental

---

[10] http://naturvernforbundet.no/about/

[11] http://www.nu.no/english/

NGO based in Norway. The organization has a technology and solution-oriented approach to environmental issues.[12] World Wildlife Foundation Norway (WWF) is an environmental NGO which is part of the international WWF organisation. The organisation focuses on the protection and conservation of nature as well as biodiversity and work to improve Norwegian climate and energy policies.[13]

Even though the organizations are different they all viewed the idea of Norway as a 'green battery' for Europe, as legitimate – at least to a certain degree. The arguments that were used to support such a view were that Norway should contribute to more sustainable energy systems in Europe. According to the organisations there is no necessary conflict between taking care of environmental concerns in Norway – primarily biodiversity – and at the same time contributing to the promoting of an enlarged share of renewables on the continent as long as proper environmental concerns are taken into account. However the lack of an overall energy policy is seen as a structural challenge. The possible future of a 'green energy' project is further seen as weakened due to a lack of political commitment to such a development, especially in the existing energy policy in Norway.

Despite the fact that they all are positive to the idea of Norway as a 'green battery' for Europe, the legitimacy of such a scenario is only valid to the extent it will lead to a reduction in the use of non renewable resources and thereby reducing the CO_2 emission rate. Bellona operates with a timeframe of forty years (2050).

The Norwegian Society for the Conservation of Nature and WWFs both emphasize that increased use of hydropower resources might lead to increased overall consumption of electricity. A guaranty that a 'green battery' will replace non renewable resources is therefore seen as vital. Nature & Youth, WWF and The Norwegian Society for Conservation of Nature are all concerned with multiple approaches as to how to solve the climate challenge. As a way of dealing with the climate change they focus on both the need to reduce the use of non-renewables energy resources in Norway as well as in Europe. It is this context that Norway as a'green battery', is seen to represent one of the solutions. Because of the expected increase in renewable electricity production in Norway in the coming years as well as the expected growth in precipitations, they find that both exports of hydropower energy as well as efficiency improvements are possible.

The organisations further express that they have different priorities in the environmental discourse. Whereas for example Bellona is first and foremost concerned about the climate change, and the Norwegian Society for the Conservation of Nature is more concerned about biodiversity and nature values, all organisations share a common concern for both the climate challenge, as well as for the loss of biodiversity. This common view of the environmental challenges also affects the way they view the idea of a 'green battery';it is seen as a possible way to contribute to solve the climate challenge. At the same time they all have a concern about the extent to which Norway should contribute to solving the backup needs in Europe due to a concern for the consequences on biodiversity.

As a way of mitigating the negative consequences, the organizations stress the need to carefully choose areas suitable for increased efficiency use, as well as pumping storage and grid development. These concerns are related to the impact on the ecosystems. Further grid development – both when it comes to national grid development as well as cable connection to other countries – is seen as vital in order to increase the renewable share in Norway as well as in Europe. At the same time there is an expressed preference that such development should not take place in areas where the natural resources are vulnerable.

In order to be able to choose between the best projects – also concerning possible future development of balancing services, the organisations stress the need for an improved knowledge base when it comes to how

---

[12] http://www.bellona.org/subjects/1140449074.91/aboutussection_view

[13] http://www.wwf.no/om_wwf/hvem_er_vi/

environmental concerns are taken into account in the concession process. The reason for this concern is to be found in the organizations' focus on the importance of a knowledge based concession system that are able to balance energy and environmental issues in a more sustainable manner.

In generally the environmental NGOs find the idea of Norway as a 'green battery' legitimate if it leads to a reducing of CO_2 emissions and take into account necessary environmental precautions. Using Norwegian hydropower for balancing services is seen as one of the possibilities that can be used in order to increase the renewable energy share in Europe. In order to make this possible an overall energy-policy is needed, as well as increased transmission-capacity to Europe, and as long as knowledge of the long-term effects of operating a hydropower system is taken into account.

4.3.3 The host community interests

The host municipalities have played an important role in the Norwegian concession system regarding hydropower production for more than a century – a stronghold which was confirmed by the legal acts adopted in 1917 where the municipalities where entitled a part of the outcome from the hydropower production. In 1977 the Norwegian organization for hydroelectricity producing municipalities (LVK, Landssamanslutninga av Vasskraftkommunar), was established. According to the historian Lars Thue (2003) the organization has – until recently – proved being an efficient interest- and lobby organisation, although the internationalization of the energy market, as well as the possible integration of Norwegian supply of power into a European market is seen as a possible challenge.

The idea of Norway as a possible 'green battery' addresses some of the concerns the organization has regarding the municipalities' role in future hydropower development. In the following we will look at exactly how these challenges are seen by LVK, and, further morehow these challenges are suggested solved in order to make a 'green battery'-scenario possible.

The idea of Norway as a 'green battery' has legitimacy in the sense that Norway is seen as a country that has an opportunity – technically speaking – to contribute to solve the climate challenge, even though the Norwegian contribution is seen to be limited when measured towards the needs in Europa. Further more practical issues have to be mapped (environmental consequences) and specified (Norway's contribution to reduce the carbon footprint). In order for Norway to become a 'green battery' the following two conditions are seen as important. First of all consequences on the natural resources has to be taken into account. An important principle for LVK is the local consequences of Norwegian hydropower development when it comes to loss of natural resources, a fact that according to LVK should be recognized at the national level. This situation entitles the host municipalities to play a crucial role for further hydropower development. Secondly – and as a consequence of the first condition, the host municipalities should be compensated for the loss of natural resources through economic compensation measures in order to secure the future for coming generations in the municipalities where the natural resources are exploited.

Whereas the environmental organisations argues for the importance of preserving natural resources amongst other things due to national obligations regarding avoiding loss of biodiversity at a global level, the concern of the host municipalities is linked to recreational values as well as concerns for the natural values in their local surroundings.

As LVK sees it, the legal system is not designed to meet the current and future challenges that for instance increased use of pumping represent. As the system is designed today, the host municipalities get their income from four pillars: concession power (compulsory power), concession fee (licence fee), natural resource tax and property tax. Concession power and concession fee is granted in accordance with the Industrial

Concession Act of 1917. Since most of the new hydropower licences are given in accordance with the Water Resources Act of 2000, which does not include concession power, the income has been reduced for new licences. When it comes to further income reduction, the idea of a 'green battery' poses two particular challenges regarding the natural resource tax and the property tax. Both of these taxes are based on production. Since pumping storage in reality reduces the total production, income opportunities may be reduced for the host municipalities. The changes in the hydropower system that the 'green battery' implies (export of effect) therefore challenges a long tradition in the Norwegian concession system where the host communities have been given a prominent role.

Two municipalities who have especially been engaged in the discussions regarding the potential for Norway – or rather Southern Norway – as a 'green battery for Europe' are Sirdal and Kvinesdal. They are both located in the Lister-region where many of the possible pumping projects and interconnectors might be realized in the future. In 2011 a report was published by Agder Research, on behalf of Listerrådet, focusing on the drivers and barriers regarding the Lister regions potential for becoming a 'green battery' for Europe.[14] In the report the potential for import and export of efficiency between Norway and Europe is viewed as an opportunity to develop the region given the necessary political clarifications that is needed regarding income distribution as well as the financing of the interconnectors needed (Røed, Skaaland, Imenes & Knudsen 2011).

Sirdal and Kvinesdal municipalities have had hydropower for decades. According to both the mayors, the income from hydropower production has contributed to the welfare in the region. The power company, Sira-Kvina, is one of Norway's largest producers of electricity. The production from the seven hydropower stations, all of them located in Sirdal and Kvinesdal municipalities, represents about 5% of the total hydropower production in Norway, in a normal year (Røed, Skaaland, Imenes & Knudsen 2011) Both mayors find the idea of Norway as a 'green battery' particular relevant from a climate point of view, and for the Lister region in particular because of its technical potential (reservoir capacity located in high altitudes) as well as geographically (closeness to the European energy market). Despite the welfare growth the region has got from hydropower– during the construction phase, and later through taxation income – the region faces challenges when it comes to population development, education level, employment opportunities and infrastructure. The mayors therefore are concerned that not only future hydropower projects related to export of efficiency, but also other energy projects (wind, small scale hydropower and grid development) will not contribute to a sustainable development for the communities. In the understanding of sustainability, the economic aspects are only one among several challenges. According to the mayor of Kvinesdal, the effects on biodiversity and landscape are – with reference to the Biodiversity act – seen as important in order for the municipalities to be able to consider the total effects of all the different energy projects. Both mayors therefor call for not only a national clarification regarding the energy policy, but also for an improved concession system where all the effects of different projects can be taken into account. Finally in order to make a 'green battery' possible – as well any other energy projects in the region – the mayors call for a stronger cooperation between institutions, stakeholders and entrepreneurs.

The idea of Norway as a 'green battery' has legitimacy both from a climate point of view, but not lest from a regional development point of view, given that the identified barriers – consideration of biodiversity and landscape values, income opportunities, regional development, and an improved concession system that takes the accumulated effects of different energy projects into account – are overcome.

---

[14] The Lister Council is a regional political and administrative co-operation between six municipalities in the Lister region. The Vest-Agder county is also represented in the council as an observer. For more information: http://www.lister.no/listerradet

4.3.4 Outdoor Recreation NGOs

The Norwegian Trekking Association (DNT) and Norwegian Association of Hunters and Anglers (NJFF) represent two important recreational interest organisations in Norway. Both organisations have more than 100 000 members nationwide, and have existed for more than a century. Their engagement in environmental issues concerning hydropower represent what is often referred to as the 'classic environmental interest' – thus traditionally focusing on experience of landscape as well as fishing interest (Nilsen & Thue 2006).

From DNTs point of view the idea of Norway as a 'green battery' in itself is seen as legitimate when it comes to the climate argument. However, this is only the case if there is a guarantee that effect deliverances will have a climate affect, thus shutting down power stations using non renewable energy resources in Europe. But at the same time as a 'green battery' is seen to have a legitimacy, the barriers, especially concerning the possible negative affects of such a project is valued as hard to overcome when taking the landscape values into account. DNT fears that a realization of Norway as a 'green battery' will exploit the landscape even more due to especially the expected over-headlines that future export of effect will demand. This fear is not just related to the idea of Norway as a 'green battery', but even more to wind mill parks, as well as grid development in general. According to DNT the power supply sector has dominated the climate debate in Norway, and by doing so has affected the current energy policy. In order to take the landscape values into account, there is, according to DNT, a need for a new planning instrument which identifies which areas are more vulnerable, and which areas are more suitable for future energy projects.

As DNT, NJFF also expresses scepticism towards the idea of Norway as a 'green battery'. To NJFF the current debate does not take into account the price the Norwegian nature has to pay in order to meet the renewable energy goals in Europe. The barriers are seen as hard to overcome concerning the environmental interest if downstream watercourses were affected. In order to overcome these barriers, pumping storage should not be realised in areas where the fisher interest would be affected. NJFF pinpoints that there is 'quite good' documentation of the environmental effects of regulations, especially in anadromous rivers, where the socio-economic interests are strong and also important. As examples, hydropower companies should avoid rapid drops in water level or take water from the bottom of intake basins instead of surface water, because water temperature also affects water fauna. To NJFFs opinion, it is acceptable that some large reservoirs which already are subject to heavily regulated can be used for pumping purposes. On the other hand it is not viewed as acceptable if pumping should be carried out on a large scale in many reservoirs. Further more NJFF stresses that local knowledge should also be considered as this is providing important information concerning mitigation efforts.

Both DNT and NJFF have opinions concerning the current concession-procedures. To their opinion, the environment is not given enough weight. There is generally scepticism towards the system where the Norwegian Water Resources and Energy Directorate (NVE) has the responsibility to assess environmental affects in hydropower, wind and grid projects. According to DNT and NJFF, the Norwegian Directorate for nature Management (DN) should be involved more formally in the concession process in order to guarantee a better consideration of the environmental interests. DNT suggests that NVE should give permission according to the energy-aspects, whereas DN should give permission according to the environmental aspects. Energy aspects as well as environmental aspects should be considered equally. In general DNT and NJFF call for an overall approach to energy issues that better takes environmental aspects into account.

4.4 The authorities concerns

It is the Ministry of Petroleum and Energy (MoPE) that has the overall responsibility for the energy policy in Norway. The Norwegian Water Resources and Energy Directorate (NVE) conducts the initial assessments in large scale hydropower cases (more than 10 MW) – thus considering the applications, knowledge assessments, input from the hearings, as well as input from public meetings – that later on is put forward to MoPE which in turn prepares the case for the Government. The final conclusion is signed by the King in Council. The Ministry of the Environment (MoE) is responsible, along with the Norwegian Directorate for nature Management (DN), for coordinating and approving environmental assessments in large scale hydropower issues (Knudsen & Ruud 2011). The Norwegian energy policy is therefore strongly influenced by a sectorial divided responsibility where energy issues are formally separated from environmental issues. The differences between the authorities concerns – in this case NVE and DN – to a strong degree mirrors the sectorial divide.

According to NVE the possible future of Norway as a 'green battery' for Europe is seen as possibility for value creation for the Norwegian society at large. At the same time NVE underlines that the Norwegian contribution – deliverances of effect services from hydropower storage – can only serve as part of the solution when it comes to how energy production from renewable energy resources in Europe can be increased in the future. In order to make this possible, NVE sees two main challenges. First of all national and international electricity grid connection has to be strengthened through upgrading of the national grid, as well as the establishment of interconnectors to the continent. Secondly the current market situation is seen as a problem. In order to make it possible for hydropower companies to make such investments, a predictable benefit sharing system has to be designed that guaranties the companies that make such investments get part of the income and not just the grid company, as the case is today.

DN, on the other hand, is concerned about uncertainties regarding substitution effects on non-renewables (climate reduction effects), resulting from development of balancing services. According to DN such substitution is necessary to justify the negative effects on nature from such developments and probably needed in order to give public legitimacy to the idea of Norway as a 'green battery'.

Both DN and NVE comment on the importance of including the environmental costs – concerning erosion, environmental degradation, removing and translocate species, impacts on aquatic ecosystems as well as consequences on landscape. Environmental concerns should therefore be carefully assessed on a strategic level in every case. NVE finds that the current environmental assessment system is sufficient in order to meet such challenges. According to NVE the concession system makes the relevant trade-offs between competing concerns. DN, on the other hand, calls for a more transparent assessment over larger geographic areas, as well as the need for thematic considerations beyond each development project. In order to guarantee such an assessment DN argues for a system where the environmental authorities are given a more formal role to verify the environmental effects (e.g. according to the biodiversity act). This call is supported in the interviews among the environmental organisations.

Both DN and NVE see the possibility for positive environmental effects of pumping storage on landscape and fish in large scale reservoirs, although reservations are made concerning whether or not this will be the case since such possible effects have to be clarified in every project and restrictions made in the license.

According to NVE, formal improvements regarding the questions of involvement is seen as unnecessary as this is regarded as a company responsibility where most companies today are aware of the need to involve affected parties at an early stage. Regarding involvement DN also finds that it should be of interest to the companies to involve the host societies at an early stage in order to design the best projects. The question of acceptances is furthermore, according to NVE, seen as a general challenge in all European countries, and not a problem that can be related to the particular concerns in Norway.

NVE, as DN, acts according to the mandate they are given by current politics. It is seen as a problem that there is no overall energy and climate politics that goes beyond the sector responsibilities. Such clarification is necessary, according to NVE, in order to follow up the commitments of the EU Renewable Directive. Norway has adopted commitments that require a more predictable policy on issues such as cables and grid policies. DN is also positive to an overall energy and climate policy that involves all sectors. According to DN such a policy statement must, when it comes to the energy policy, be clear on whether the current goal – security of supply – should be extended to include Norway's possible contribution to an international energy market. However, it must balance this energy targets with other international obligations as e.g. the Water Framework Directive and Biodiversity targets. Even though Norwegian hydropower has been subject to export since the 1960s, the main objective of the energy policy has always been to secure the national energy supply. In order to make it possible for Norway to contribute to an increased share renewable energy production in Europe through export of effect, such a clarification is seen as important in order to avoid local resistance.

Whereas NVE finds the current concession system sufficient, DN, on the other hand, calls for a need for regional strategic plans in order to get an overall picture of the effects on the environment. Such plans are seen as relevant in order to find where the best projects could be realized, according to environmental concerns. DNs interest for area based plans, which they argue would make it easier to prioritize between projects, is driven by the environmental concerns stated in the Biodiversity Act (adopted in 2009) as well as the implementation of the Water Framework Directive (WFD). There is, however, no common view between NVE and DN as to how such concerns should affect the current concession system concerning, in this case, the future of hydropower development.

4.5 Opportunities and the question of societal acceptance

Drawing on the results presented so far, the idea of using Norwegian hydropower as a 'green battery' is viewed as legitimate due to the potential positive climate affect that such a battery might have in terms of reducing the need for non-renewable energy resources. At the same time reservations are made concerning the uncertainty related to the actual climate impacts such a battery might have. Furthermore the lack of an overall national energy policy, environmental concerns, and risks related to commercial opportunities and grid development, are regarded as barriers that have to be overcome if the idea of a 'green battery' is to become a reality', a point to which we will return in the last section. In this section we will focus on the question of social acceptance. The importance of social acceptance in achieving renewable energy ambitions are increasingly recognized as a vital issue to be addressed.

The environmental impacts are of vital concern to all the informants in this study. There are, however, different views regarding how environmental concerns should be taken into account, and whether or not the current concession system needs to be improved in order take better into account new challenges that balancing services might pose. According to the host municipalities, environmental and recreational NGOs, an improved documentation and assessment of the environmental impacts is seen as necessary in order to consider where pumping storage would be acceptable. In general, water courses which are already highly modified due to hydropower production are seen as more suitable for further development Furthermore, most of the stakeholders hold the view that the environmental impacts of pumping storage will be less in areas where the pumping can be carried out between high capacity reservoirs, than between small ones.

In general mitigation measures that may improve the environmental state concerning biodiversity, or landscape qualities, are seen as important when considering possible future projects in already regulated watersheds. Despite the uncertainty regarding environmental impacts on biodiversity if pumping between reservoirs is introduced, some of the stakeholders hope that pumping between high capacity reservoirs may lead to a more stable water level through the year which in turn will improve the conditions for fish and reduce impacts on landscape values. Concerning expected grid development, a positive consequence that is being suggested by some of the stakeholders is replacement of low-voltage lines in order to reduce the risk of bird coalitions. The uncertainties regarding the environmental impacts, however, make the concerns for both positive and negative consequences quite open ended.

The uncertainties are also related to potential social and economic benefits of possible further development of the hydropower system in order to export balancing services. This is not just related to the challenges such services represent when looking at the host municipalities' income from hydropower, as previously described. The uncertainty is also related to whether or not drilling of new tunnels and construction and development of new turbines, pumps and power stations will represent jobs that may create opportunities for local entrepreneurs thus resulting in local development.

In order to overcome some of the environmental, social and economic challenges, as these are identified by the host municipalities, environmental and recreational NGOs, and authorities, a close dialogue between all involved parties is regarded as vital. Involvement at an early stage – before the projects are announced formally – is generally regarded as important by all stakeholders. It is supposed that such involvement will reduce the level of conflict, as well as resulting in projects that are better, especially seen from an environmental and local community point of view.

Societal acceptance is further linked to a need for a clarification of the goals of the projects that developers may suggest. Societal acceptance is based on trust, transparency, fairness, and also closely linked to clear documentation that balancing services actually contributes to a more climate-friendly energy system for Europe. At the same time the responsibility for committing such clarifications is not all together seen as a company responsibility. The call for such a clarification is first and foremost directed towards the national level, thus the Norwegian government and parliament.

4.6 Final discussion: the societal possibilities for Norway as a green battery

Despite the fact that Norway as a 'green battery' has legitimacy among the stakeholders due to the hope that deliverances of balancing services will increase the renewable share of energy production in Europe, this analysis has shown that the barriers identified are several, especially if the timeframe is set within 2020. The views, as these are expressed by the stakeholders, including the assessment of the possibilities, mirrors the need for a clarification regarding the current framework – politically and regulatory, commercially and technically speaking.

In summary, the interviews showed that:

- All stakeholder supported the idea that Norway could play a role in reducing climate change by offering balancing services from hydropower
- At the same time there is widespread doubt that this is realistic – at least within the timeframe of 2020, because a range of political clarifications and regulatory frameworks that are considered crucial to proceed with planning for balancing services are presently lacking
- Despite the overall support of considering Norwegian hydropower as balancing services in a European context, stakeholders agree that the likely contribution will be minor, because of

limitations set by environmental values, as well as commercial and financial constraints or uncertainty

- Among some of the energy companies, there exist uncertainty about the commercial basis for pumped storage as this depend on that energy prices continue to vary significantly. Some companies question if this will last, especially if the European grid is developed further
- The most concrete barrier within the 2020 timeframe is the existing grid policy. Statnett's current mandate focuses on national services and currently not on contributing to grids that make it possible for large scale transmission of balancing services to Europe
- The existing grid policy is also seen as insufficient regarding the distribution of benefits and costs from new cables
- Representatives from the environmental NGOs stress that Norway must contribute to reduce climate change but at the same time live up to biodiversity commitments
- Better involvement of stakeholders and local communities is seen as crucial in further planning of balancing services but there are different views on how and who should be responsible for better involvement
- There is general agreement that host communities must get their share of benefits from production of balancing services, and that the current legislation must be changed to take this into account
- Balancing services should avoid sites where rivers or smaller downstream reservoirs are affected. Nearby transmission cables is also seen as a prerequisite in choosing suitable projects

From an environmental interest point of view several of the stakeholders have expressed doubts if deliverances of balancing services will de facto have a climate effect, especially in the short run. At the same time there are differences in the views of the timeframe the value of a 'green battery' is to be measured against.

Another concern expressed by all the stakeholders is regarding *the extent* to which the Norwegian hydropower system actually will be used to balance wind- and solar energy in Europe. Even if the barriers concerning environmental, economic and social interest in Norway are possible to overcome, the Norwegian contribution to the need for balancing services in Europe is considered as rather limited. It depends on a clearer specification of what kind of services this idea of becoming a 'green battery' calls for.

The idea of a 'green battery' is furthermore, from an environmental point of view, seen as legitimate only if it takes other environmental concerns (other than climate) into account. From the environment NGOs point of view, as well as for the host municipalities', an important condition that has to be met is Norway's obligation for conservation of biodiversity. It is therefore argued that further planning of balancing services should be based on a systematic assessment of which areas that are most suitable for further exploitation. The call for better integration of various environmental concerns, however, does not undermine the idea of Norway as a 'green battery', but it points to a barrier that is seen as fundamental to several of the stakeholders included in this study.

More surprisingly, the extent to which Norway can become a 'green battery' is not just questioned from an environmental point of view. There are also concerns related to commercial risks identified by the companies. The disbelief in the future of the price difference, as well as the uncertainties regarding the cost- and income sharing regarding the cables needed, makes several of the companies reluctant when considering a 'green battery' as a business opportunity.

Furthermore there are also local concerns regarding the idea of Norway as a 'green battery'. In light of the history of hydropower development in Norway where there has been a tradition – manifested through the legal framework – of compensating the host municipalities, the development of these new hydropower services is seen as a threat to this social contract. This is related to the fact that the current legal framework still is designed for the traditional ways of exploiting hydropower. Even though this argument is related to the economic/commercial risks, it is also seen as seen as a larger social concern amongst the host municipalities. They have expressed doubt if development of hydropower services in the direction of balancing services will result in regional and local development for the coming generations. Generally, these rural municipalities face challenges regarding population decline, an ageing population, educational level and availability of jobs and is under pressure to maintain attractive for people as a place to live and work (Røed, Skaaland, Imenes & Knudsen, 2011).

Finally, the risks the stakeholders identify are not just seen as environmental, economic and social concerns per se. In order to overcome the barriers, the stakeholders in unison call for a national political clarifications regarding the energy policy. Despite their different roles and goals, they all agree that Norway lack an updated and integrated energy policy. It is considered as a national political responsibility to decide whether or not Norway de facto should become a 'green battery', and if so, the regulatory framework needs to be adjusted accordingly. Thus, it is important for the Norwegian political decision makers – government and parliament, to clarify whether and on what premises Norway should contribute to the promotion of renewable electricity development in the EU countries. As part of this, a clarification is called for regarding the grid development towards Europe (Statnett's mandate, on how to finance the cables needed, as well as benefit sharing on revenue generated and so forth), as lack of grid capacity is one of the most concrete and immediate barriers to the idea of Norwegian hydropower as a green battery for Europe.

4.6.1 Need for further research

This study merely expresses concerns among a number of central stakeholders, and further studies are needed both on local specific challenges, regional considerations – including coordination among different municipalities, national policy coordination as well as selected EU matters.

The main driver creating this idea of becoming a 'green battery' for Europe is found in Europe itself as a direct result of recent energy and climate policy efforts. Further studies ought to better understand more in detail what is actually taking place in relevant countries and to what extent they are promoting intermittent renewables for electricity generation that triggers an increasing need for balancing services – potentially from Norway. In particular, further studies ought to be conducted on the specific renewable policy implementation efforts in Germany, The Netherlands and Great Britain – thus extending the comparative case studies reflected in Lafferty & Ruud (2008).

Regardless of European on-shore policy efforts also reflected in the National Renewable Energy Actions Plans to implement the targets specified in line with the Renewable Energy Sources (RES) Directive, there is also further need for studies on how the interconnectors are to be realized and de facto connected to the National Grids. There is also a need for further developing the domestic grid, a challenge which highlights the need to focus on issues related to public acceptance.

The energy policy efforts undertaken by individual member states are significantly influenced by EU policy dynamics at large. It is therefore vital to analyse the third energy market package which further promotes a liberalization of European electricity markets as this is expected to influence further grid development in Europe, both on- and offshore. Consequently we also need to follow closely the policy efforts undertaken within the North Sea Countries offshore grid initiative (NSCOGI) of 2010 as this to a large extent is expected to influence the actual opportunities for realizing balancing services from Norway.

The concerns related to public acceptance are expressed through many of the statements reflected in this study, but more studies are needed on the details on what works, where, when and how. Climate concerns remain a driver, but the global concerns are to a large extent manifested in national commitments while locals are paying the price – ecologically, socially and economically. Climate change might produce more precipitation and thus more production capacity in hydropower plants, but the increased revenues must be better related to the totality of costs and benefits. This relates both to the financial compensatory schemes as well as the relative influence on specific policy efforts undertaken. Norwegian energy policy needs a revision on a number of policy procedures and further studies are thus needed on multi-level energy governance at large.

As we have seen, also at the local level a range of concerns and possibilities have been raised, both regarding business opportunities and ecological and landscape impacts, which all will influence on local impacts, benefits, acceptance or opposition. However, as long as the concretisation of how and where “green battery” power plants remains vague, it is challenging to propose a concrete research plan to assess pros and cons as such. Better scoping of sites, technical solutions and regulatory schemes are needed before it is fruitful to assess concrete impacts and mitigating actions more closely. Consequently, at this stage we find it more relevant to stress the need to explore what processes and dialogues will be satisfactory for all stakeholders.

5 Pumped storage power plants

This Chapter is based on sections from a master student specialization project (Sætre 2012) connected to the preparation of this report.

5.1 Main characteristics

Pumped storage is the method capable of storing the largest amount of electrical energy, as well as having the largest generation capacity. A pumped storage plant consists of two water reservoirs at different heights. At the lower reservoir, a reversible pump turbine is placed. Alternatively, both a turbine and a pump are mounted on the same generator.

An electric motor drives a pump or pump turbine, pumping water from the lower reservoir up to a higher storage reservoir. To produce electricity water is released back through the turbine or pump turbine. The turbine is used to drive the generator and electricity is generated and fed into the grid. Figure 5.1 shows a typical pumped storage layout.

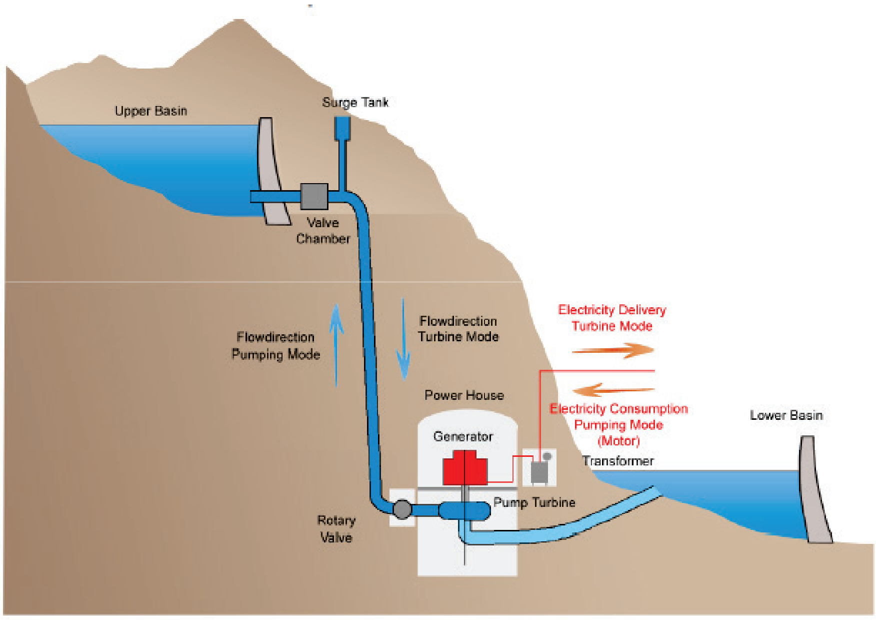


Figure 5.1 Typical pump storage layout (Hydro Equipment Association 2012).

The amount of energy that can be stored depends on the height difference between the reservoirs and the volume of the reservoirs, while the power capacity depends on the size of the pump/turbine. Pumped storage is a mature technology with high efficiency. It is possible to recover more than 80 % of the energy that is put into the system, which is very high in comparison to all other storage technologies (Fornybar 2012).

Pumped storage power plants are able to react within short time to grid fluctuations. Modern systems can start pump/turbine operation in just 30 seconds from standstill. In the event of a power failure, pumped storage power plants can re-establish the power supply to the network without an external energy supply.

In Norway, pumped storage power plants have so far only been constructed for seasonal storage.

From a turbine/pump and generator/motor point of view, there are basically two main properties to consider (Nysveen and Molinas 2012):

- Reversible turbine/pump or twin system
- Fixed or adjustable speed

These will be further discussed in the following sections.

5.2 Pump and turbine configurations

This section describes the two main solutions to obtain both pumping and turbine operation in the same power plant. A pumped storage plant can either use a reversible pump turbine or be designed as a twin system that consists of separate generating and pumping equipment. The impeller on a reversible pump turbine is designed both for turbine and pump operation. For a twin system the impeller is designed only for turbine operation while the pump is designed exclusively for pump operation.

5.2.1 Twin system

Twin systems (also called ternary systems) consist of a motor-generator and a separate turbine, typically high pressure Francis or Pelton turbines (Hamnaberg 2011) and pump set (Figure 5.2). Since the turbine and pump are separate, the rotational direction of the motor-generator can be the same in both operational modes, making the electrical system simple. This system is more expensive and mechanically complex than the single turbine reversible system, but has some operational advantages (Nysveen and Molinas 2012):

- Increased efficiency in both turbine and pump mode
- Simplified start-up in pump mode
- Shorter start-up time in pump mode

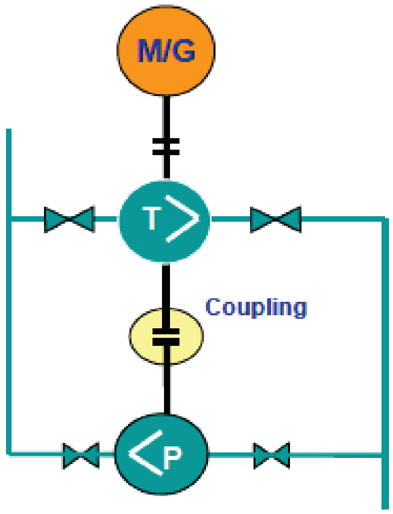


Figure 5.2 Line-diagram of a twin system (Amler 2010).

Switching between turbine and pump operation can be achieved by a clutch, a starting turbine or a synchronizing torque converter (Voith 2012). The torque converter provides extremely short switching times between turbine and pump operation. Within seconds the storage pump can be connected or separated from the shaft system. It transmits torque and/or power from the motor-generator to the pump shaft by being filled with process water (Voith 2012).

A special configuration, which is possible with a twin system, is a hydraulic short circuit system, which has a pump and a turbine operating simultaneously. The short circuit results in a larger range of capacities for the system. For example a 50 MW turbine power and a -45 MW pump power result in a 5 MW power generation. Following this principal, the whole range of capacities (+/-100%) can be achieved (Hamnaberg 2011) (Huber and Gutschi 2010). Twin systems are most often used for pumped storage plants with large heads (h > 400 - 600 m) (Hamnaberg 2011).

Francis turbines are primarily used for medium heads up to 600 m. Their special hydraulic characteristics enable relatively high-speed compact units, up to the highest power outputs.

5.2.2 Reversible turbine/pump system

Reversible turbine/pump systems consist of a motor-generator and a reversible pump-turbine that works either as a pump or as a turbine depending on the direction of rotation (see Figure 5.3 and Figure 5.4). The dominating turbine type is the Francis turbine. This design allows for compact power houses, which saves both investment costs as well as costs related to maintenance and operation. Pump-turbines can operate at a wide range of specific speeds and are therefore installed at sites with heads from less than 50 to more than 800 m. The unit capacities can range between less than 10 to over 500 MW (Voith 2012).

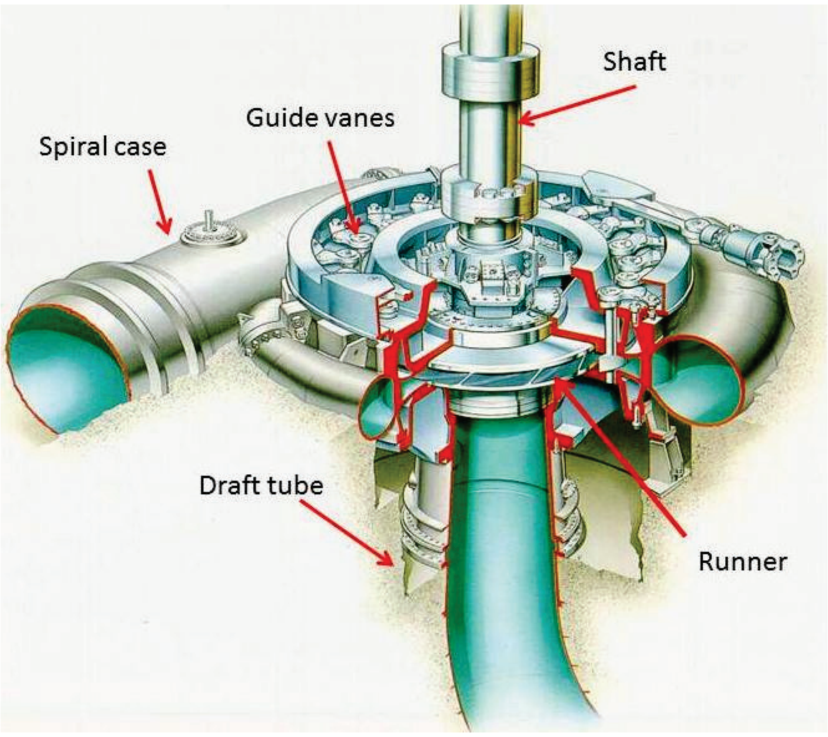


Figure 5.3 Reversible pump-turbine.

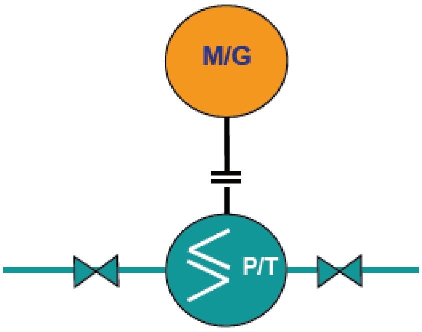


Figure 5.4 Line-diagram of a reversible turbine/pump system (Amler 2010).

Starting up in turbine mode is done by letting the water accelerate the turbine to a satisfactory speed. Starting up in pump mode, requires electrical power from the power system. Normally the water is blown out from the turbine such that the runner is rotating in air during start up.

If an induction (asynchronous) motor-generator is used, the rotational speed of the pump-turbine can be varied (see Section 5.3.2). This allows for efficient stabilization of the grid as the pump capacity can be adjusted to using the exact amount of energy available.

The critical design parameter is the maximum pressure head in pump operation. This parameter decides the design of the pump turbine (e.i. impeller diameter, rotational speed). Due to head losses the total pump head is larger than the static head, while the total head seen by the turbine is decreased, seen in Figure 5.5. This decreases the turbine efficiency, so in order to achieve maximum efficiency, the turbine should be driven at a lower speed than design speed ($n_{opt} < n_{sync}$) (Hamnaberg 2011). Reversible Francis turbines are designed in the same way as conventional Francis turbines. By changing the direction of rotation they can be used for both turbine and pump operation.

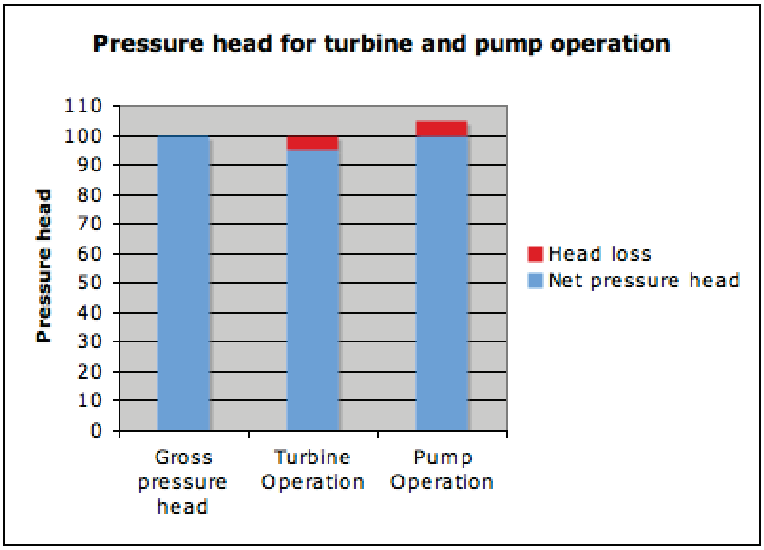


Figure 5.5 Pressure head loss for turbine and pump operation.

Head loss is about 5 % of the gross pressure head in pump and turbine operations (Hamnaberg 2011).

> *Difference between pressure heads = pressure loss in turbine operation + pressure loss in pump operation*

During turbine operation the reversible Francis turbine is operated as a conventional Francis turbine. The delivered power for a constant pressure head can be controlled by the amount of water run through the turbine. During pump operation, the power is defined by the pump characteristics (as for a conventional pump). The pump characteristics give a correlation between pressure head, intake capacity and power for a given pump. For a given pressure head, the intake capacity is decided by the characteristics, which means that the power during pump operation cannot be controlled. Controlling the power during pump operation is a motivation to use adjustable speed systems, which are discussed in Section 5.3.2.

Figure 5.6 shows the operational area of pump turbines. According to the figure the maximum head is nearing 1,000 m while the operating capacity is nearing 1,000 MW. Goulds Pumps (Goulds Pumps 2012) deliver pumps with heads up to 1,067 m that can handle capacities up to 15,900 m^3/h. The pump turbine technology is constantly being developed to meet new market needs and to ensure and enhance reliability, availability, maintainability and safety of the power plants (Avellan 2011). A description of the trend regarding maximum pumping head can be found in (Ikeda, Inagaki, Niikura and Oshima 2000). Reversible pump-turbines are most often used for pumped storage plants with heads less than 400 - 600 m (Hamnaberg 2011).

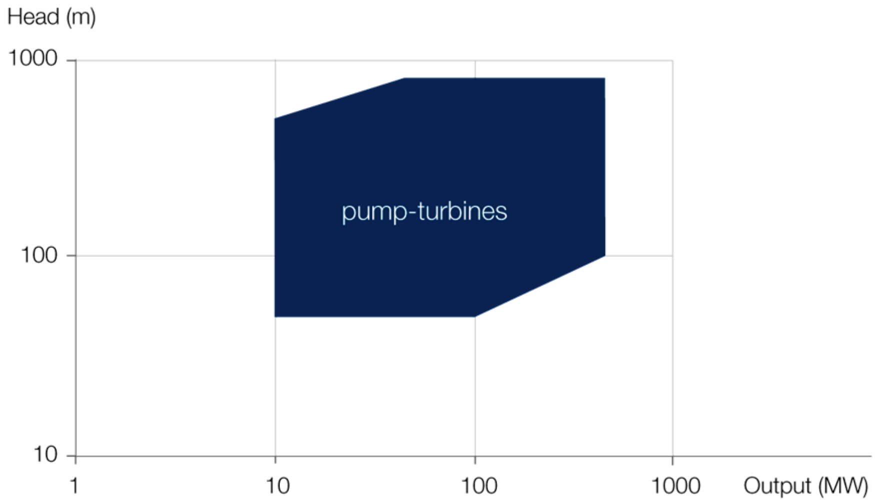


Figure 5.6 Pump-turbine operating limits (Voith 2012).

5.2.3 Twin systems verses reversible turbine/pump systems

A comparison between the two main technical solutions is shown in Table 5.1.

Table 5.1 Comparison of twin systems and reversible pump turbines (Huber and Gutschi 2010) (Hamnaberg 2011).

	Twin system	Reversible pump turbine
Investment	-	+
Size	-	+
Efficiency	+	-
Installation depth	+	-
Pressure head	+	-
Transition time pump to turbine and turbine to pump modes	+	-
Operation cost	-	+
Maintenance	-	+
Technical risk	-	+

A pump and a pump turbine in pump operation have similar efficiency, while a pump turbine in turbine operation has a lower efficiency than a turbine. This is a huge factor deciding which of the alternatives is the most economic. In Norway the most common choice has been a pump turbine (Øygard 2008).

5.3 Generator/motor configurations

This section briefly presents the various generator/motor configurations applicable for pumped storage plants. The configurations can be categorized into three different groups given by the generator and the converter technology:

- Fixed speed synchronous machine (SM)
- Adjustable speed synchronous machine (SM) with full rated frequency converter
- Adjustable speed induction (asynchronous) machine (IM)

A pump turbine is designed for pump operation, so it is not optimized for turbine mode. By increasing the rotational speed in turbine operation a better efficiency can be achieved (Øygard 2008).

Both the synchronous and the asynchronous machine adjustable speed systems require frequency converters. The rotational speed of a synchronous motor is decided by the grid frequency and the number of poles in the machine. The rotational speed of an unloaded induction motor is controlled by the number of pole pairs and the frequency of the voltage supply. Loading the motor (adding resistance to the rotor windings) reduces the rotational speed.

Three phase induction motors are self-starting and produce torque even at standstill. A synchronous motor cannot start on its own due to the inertia of the rotor. The rotor should be rotated near to the motor's synchronous speed to overcome the inertia. Once it nears synchronous speed, the field winding is excited, and the motor pulls into synchronization. The following techniques are used to start a synchronous motor:

- A separate motor is used to drive the rotor before it locks into synchronization.
- The field winding is short-circuited so the motor starts like an induction motor.

- Reducing the input electrical frequency to get the motor starting slowly, by use of f.ex variable-frequency drives.

5.3.1 Fixed speed synchronous machine

The fixed speed system consists of a synchronous machine connected directly to the power system. This is the simplest solution and also the most dominating in use today. These systems run at constant speed.

If it is used with a reversible turbine, a soft-starter or start-up motor is used. When the machine reaches synchronous speed, it is connected directly to the power grid by a circuit breaker. State-of-the-art within starting methods is to use static frequency converters (soft-starters) (Alstom 2012). Soft-starters reduce the load both on the machine and the power grid due to excellent controllability (Nysveen and Molinas 2012).

Advantages and drawbacks of the fixed speed system based on a synchronous machine are summarised in Table 5.2.

Table 5.2 Pros and cons for the fixed speed synchronous machine (Hamnaberg 2011).

Advantages	Drawbacks
Conventional and reliable technology	Limited operating area
Energy recovery during braking (with start-up converter)	Constant load in pump mode (no power control)
Low cost	

5.3.2 Adjustable speed systems

One of the most important advances during the last decades has been the development of adjustable speed systems to allow for controllable power in the pumping mode. Such systems use a reversible Francis-turbine and a power electronically controlled machine. Pumped storage plants with high degree of controllability both in generating mode and in pumping mode are needed to improve the daily balance between production and load, as well as to improve the frequency control of systems with large share of nuclear, thermal, wind or photovoltaic. Adjustable speed operation has several advantages (Nysveen and Molinas 2012):

- Improving the efficiency
- Optimal speed during turbine and pump operation
- Load/frequency control in pumping mode, as well as turbine mode
- Less vibrations and noise (especially at partial load)
- Lower minimum generation limits for the turbines

Adjustable speed improves the turbine efficiency, since the speed corresponding to maximum efficiency is different for turbine and pump operation. The efficiency also varies for different heads, and adjustable speed may be necessary for plants with large variations in water head.

Adjustable speed systems allow power control in pumping mode, as well as extending the allowable operation range in generator mode (Nysveen and Molinas 2012). This means that for a given pressure head, the power delivered to the pump can be varied, and therefore also the water flow. If the speed can be varied to +/- 10% of synchronous speed, the power can be varied to +/- 30% with today's technology (Nysveen and Molinas 2012). This allows the power station to adjust to various needs in the power grid.

5.3.2.1 Synchronous machine with full rated frequency converter

This configuration consists of a full rated frequency converter connected to the stator of the synchronous generator. With increased rating of semi-conductor switches and available high-power motor drives based on the voltage source converter topology, this configuration is an attractive solution (Suul, Uhlen and Undeland 2008). The layout is shown in Figure 5.7, and as shown it will be possible to bypass the converter and operate the machine directly connected to the grid (see Section 5.3.1). This can provide redundancy for the converter in the case of operational problems (Nysveen and Molinas 2012).

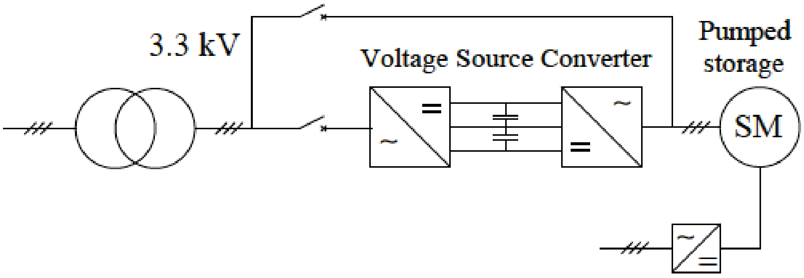


Figure 5.7 Schematic configuration of a full rated converter system with a synchronous machine (Nysveen and Molinas 2012).

Advantages and drawbacks of the full rated frequency converter system based on a synchronous machine are summarised in Table 5.3.

Table 5.3 Pros and cons for the full rated converter with synchronous machine (Hamnaberg 2011).

Advantages	**Drawbacks**
Flexible operating area in turbine and pump operation	Expensive frequency converter
No need for start-up converter	Generation limit at about 100MW
Energy recovery during braking for frequency converter	
Synchronous generator has low cost	
Low maintenance requirements for synchronous generator	
Operation direction can change with filled water way	

Due to design constraints, frequency converters only exist for power ratings up to about 100 MW. For medium and large systems, a design based on an induction (asynchronous) machine will be economically preferable (Hamnaberg 2011).

5.3.2.2 Induction (asynchronous) machine

This configuration consists of a partially rated frequency converter connected to the rotor of the asynchronous generator. With this configuration, variable speed can be obtained with a partially rated frequency converter (less than the generator rating). This is the preferred system in large scale implementations of pumped storage, since the converters rating does not limit the total system rating. Another advantage is that the reactive power to and from the grid can be controlled. This can be utilized for voltage control in the grid and contribute to improve the stability and the operating conditions in the rest of the power system (Nysveen and Molinas 2012). Figure 5.8 shows two basic configurations. Solutions with cycloconverters are suitable solutions and can be made with rugged design for high capacity and low losses (Nysveen and Molinas 2012). However, today the most preferred topology is the back-to-back voltage source converter, and it has been used in some of the most recent pumped storage implementations.

The back-to-back converter system is able to generate power both above and below synchronous speed. The configuration is often called doubly-fed induction generator (DFIG) or doubly-fed asynchronous machine (DFAM), which emphasizes the ability to transfer power into or out of the rotor, as well as out of the stator. The back-to-back converter is connected between the rotor of the DFIG and the three winding transformer (to the grid), while the stator is connected directly to the transformer and then to grid. In this topology, the power converter is partially scaled requiring a rated power of about 30 % of the overall generated power.

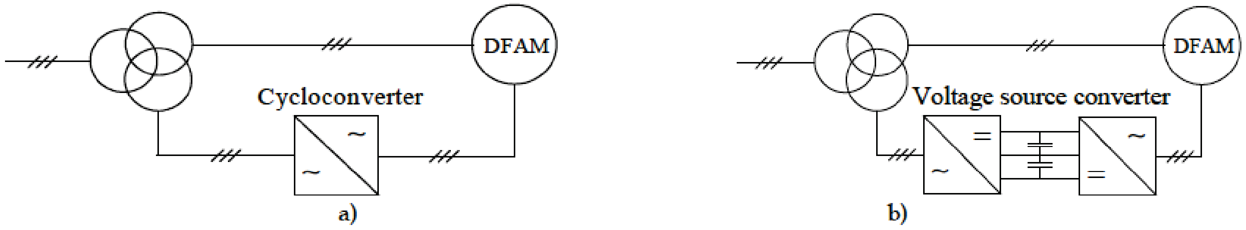


Figure 5.8 Basic configurations of doubly-fed asynchronous machines: a) system with a cycloconverter, b) system with a back-to-back voltage source converter (Nysveen and Molinas 2012).

Advantages and drawbacks of the doubly-fed induction machine system are summarised in Table 5.4.

Table 5.4 Pros and cons for the doubly-fed induction machine system (Hamnaberg 2011).

Advantages	**Drawbacks**
Flexible operating area in turbine and pump mode	More complicated maintenance for asynchronous machines
Possible for generator ratings > 100 MW	Needs separate rotor transformer and converter
Energy recovery during braking	Asynchronous machines are more expensive
Reactive power control to/from grid	

5.4 Overview of large pumped storage plants

In 2009 world pumped storage generation capacity was 104 GW. The EU had 38.3 GW net capacity (36.8 % of world capacity) out of a total of 140 GW of hydropower. Japan had 25.5 GW net capacity (24.5 % of world capacity). Table 5.5 lists pumped storage plants in Europe with capacities larger than 1,000 MW, while Table 5.6 is a list of some of the largest pumped storage power plants in the world with plant capacities larger than 1,500 MW.

Table 5.5 Pumped storage plants with capacities > 1000 MW in Europe.

Station	Country	Capacity [MW]	Head [m]	Year	Reference
Malta-Reisseck	Austria	1,026		1977	1
Coo-Trois-Ponts	Belgium	1,164	275	1978	1
Grand'Maison	France	1,800	955	1985	1
Goldisthal	Germany	1,060	302	2003	2
Markersbach	Germany	1,046	288	1979	2
Edolo	Italy	1,000	1265	1985	1
Entracque	Italy	1,317	1048	1989	1
Presenzano	Italy	1,000	495	1991	1
Roncovalgrande	Italy	1,016	736	1973	1
Vianden	Luxembourg	1,096	291	1976	1
Kaishador	Russia	1,600		1993	3
Zagorsk	Russia	1,200		2000	1
Linth-Limmern	Switzerland	1,000	623	1964	1
Dniester	Ukraine	2,268	38,7	1996	1, 3
Dinorwig	United Kingdom	1,728	545	1984	1, 4

[1](Wikipedia 2012), [2](Vattenfall 2012), [3](Daily 2012), [4](Grøv 2011)

Table 5.6 Pumped storage plants with capacities > 1500 MW in the world.

Station	Country	Capacity [MW]	Head [m]	Year	Reference
Tumut 3	Australia	1,500	155	1974	1
Baoquan	China	2,448	563	2011	2, 3
Guangzhou	China	2,400	535	2000	4
Huizhou	China	2,448	420	2007	2, 3
Tianhuangping	China	1,800	887	2004	5
Grand'Maison	France	1,800	955	1985	3
Kannagawa	Japan	2,820	625	2005	5
Kazunogawa	Japan	1,648	714	2001	5
Okutataragi	Japan	1,932	387	1998	5, 6
Kaishador	Russia	1,600		1993	7
Mingtan	Taiwan	1,602	380	1995	3, 8
Dniester	Ukraine	2,268	38,7	1996	3, 7
Dinorwig	United Kingdom	1,728	545	1984	3, 6
Bath County	United States	3,003	385	1985	9
Castaic	United States	1,566	323	1978	3, 7
Ludington	United States	1,872	110	1973	10
Raccoon Mountain	United States	1,530	310	1979	7, 11

[1](Griffiths 1990), [2](Alstom 2012), [3](Wikipedia 2012), [4](CLP 2012), [5](Avellan 2011), [6](Grøv 2011), [7](Daily 2012), [8](IEA Hydropower 2006), [9](Dominion 2012), [10](DTE Energy 2012), [11](Mock 1072)

6 Grid transmission capacity in Europe

Deployment of the potential hydro storage and pumped storage capacity in Norway for balancing electricity on large-scale has to go hand in hand with integration of these facilities into the power grid. Both internal and trans-national grid investments, such as connections from Norway to Central Europe, Great Britain and wind farms in the North Sea, would be required. This chapter briefly describes the present situation in the European grid with respect to existing transmission capacities between countries, as well as the potential grid development over the next decades. Based on a review of available grid studies by Sauterleute (2013), the current and future cross-border transmission capacities in the European power grid are summarised.

In the light of climate mitigation and efforts to achieve a low-carbon economy on the long-term in Europe (ECF, 2010; EC COM/2011/0885, 2011), the European energy system is facing a transformation from a transmission infrastructure with the major purpose of assuring the security of supply by mutual assistance between national sub-systems to an interconnected and flexible transmission grid with the ability to exchange growing power flows across the continent and integrate variable renewable energy sources (UCTE, 2007). The shift in the generation mix in combination with spatial distribution of sites for building new renewable energy capacities as well as sites for energy storage not matching centres of power consumption will lead to larger and more volatile power flows over large distances across Europe and will require expansion of the power grid (ECF, 2010; Eurelectric, 2010; ENTSO-E, 2012).

The need for expansion of the cross-border transmission capacities in a European power system with high penetration of renewable energy sources depends on the type and amount of renewable energy generation units, the electricity consumption and the geographical distribution of these factors in particular, since the need for power transmission results from spatial mismatch between generation and load (Bakken & Graabak, 2012). Other important factors are the public attitude, e.g. concerning social acceptance of transmission line projects, future settings of the political framework (such as licencing/commissioning processes of transmission line projects) and economic conditions (e.g. investment incentives, power market design).

Regarding the need for large-scale storage of electric energy it can be assumed that, on the one hand, the required amount of storage depends on the extent of the transmission grid expansion. Less transmission capacity may require storage of electricity to equal out regional imbalances in power generation and consumption. On the other hand, establishment of large-scale energy storage may imply grid transmission expansion, since storage facilities have to be integrated into the grid. The latter is the case for balancing electricity on large-scale by the use of Norwegian hydropower. Several subsea cables from Norway to countries around the North Sea, in particular the UK, the Netherlands, Germany and Denmark would have to be constructed.

Sauterleute (2013) reviewed and summarised three studies on grid transmission capacities across borders in Europe, covering different time horizons and geographical focus. ENTSO-E's 10-Year Network Development Plan 2012 (ENTSO-E, 2012) addresses the present situation as well as the short-term grid requirements until the year 2022, the Twenties study (Farahmand et al., 2013) the mid-term grid expansions in 2020 and 2030, and the SUSPLAN study (Bakken & Graabak, 2012) the development on the long-term up to the year 2050.

The existing transmission capacity between countries is characterised by the net transfer capacity (NTC), the capacity available for market participants to use in cross-border electricity trade. The NTC values are assessed and published online by ENTSO-E twice a year (ENTSO-E, 2011). They are results of network model simulations and take into account security margins. The assessment procedure of those values and its limitations are briefly summarised in Sauterleute (2013) and described in detail in ENTSO-E (2001). According to ENTSO-E (2012) the highest NTC values are found in Central Europe, where the grid density is highest, the population is most dense and the major consumption as well as generation is located. This corridor with a high level of power exchanges stretches from the UK and the Benelux countries over France, Germany and the Alpine countries to Northern Italy. South-Eastern Europe shows a consistent pattern of transmission capacities between all its countries, but at a lower level; also within the Nordic power system there is some exchange, first of all between Norway, Sweden and Finland. Those net transfer capacities are illustrated in Figure 6.1. The map shows directions and amounts of cross-border transmission capacities between European countries.

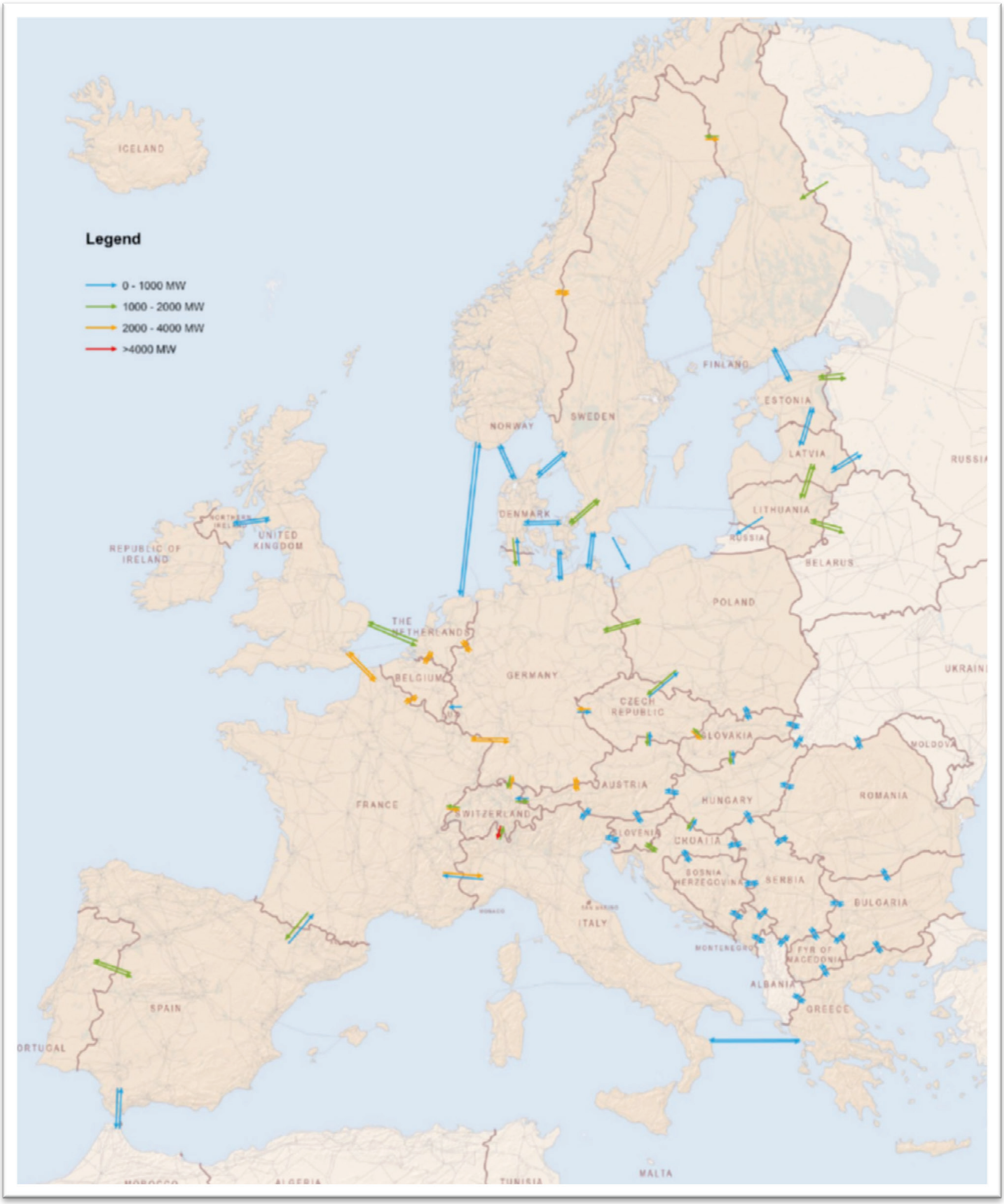


Figure 6.1 Net Transfer Capacities between countries in Europe (NTC values from winter 2010/2011, working day, peak hours). The arrows indicate directions and amount of power exchanges. Denmark is separated into West and East, since it has two synchronous systems. Adopted from ENTSO-E (2012).

Results of market and network studies, which are documented in the Regional Investment Plans of the 10-Year Network Development Plan Package (ENTSO-E, 2012), show that some regions lack appropriate interconnections in the power grid and that many regions face congestions despite existing interconnections. Strong interconnections are lacking in Central Europe (e.g. Germany, Austria, Switzerland, Northern Italy), in South-West Europe (Iberian Peninsula) and around the North Sea (e.g. France, Belgium, the Netherlands). In South-East Europe transit power flows cause congestion (e.g. Slovenia, Serbia, Macedonia). In some regions, integration of RES into the grid is expected to challenge the existing grid. Consequently, grid congestion is anticipated to occur to a large extent in the future. For instance, this applies in the case of transit flows caused by wind power in Northern Germany, Denmark, the North Sea and the Baltic Sea, which have led to grid congestions already in recent years.

With respect to the future need for investments to increase the grid transmission capacities between European countries, studies show different levels of detail and varying results, dependent on the underlying scenarios, methodology, time horizon and geographical focus. However, the common tendencies are as follows (ENTSO-E, 2012; Bakken & Graabak, 2012; Farahmand et al., 2013): Firstly, the shift in the European generation mix towards a high share of renewable energy sources implies spatial and temporal imbalances in power generation and consumption, which have to be balanced by increased power exchanges across borders. To allow for increased power flows significant grid reinforcements and expansions will have to be achieved. Secondly, the development of renewable energy generation units and their integration into the power system is the main driver for larger, more volatile power flows over larger distances across Europe and the development of transmission corridors, mostly north to south from Scandinavia to Italy, between mainland Europe and the Iberian Peninsula, Ireland and the UK, or east to south and west on the Balkan Peninsula. Thirdly, the development of an offshore grid in the North Sea is expected to be profitable on the long-term.

Figure 6.2 shows a map of Northern Europe containing all transmission line projects which are planned for the period 2016 to 2022 and are important for increasing the grid transmission capacity across borders (ENTSO-E, 2012). In addition to the existing interconnectors between Norway and Denmark/the Netherlands, cables from South-Norway to Denmark, Sweden, Germany, the UK and the Netherlands are to be built by 2022. Over entire Europe the plans include in total 52,300 km of high voltage routes, whereof 12,600 km are high voltage direct current (HVDC) and 39,400 km high voltage alternate current (HVAC) (ENTSO-E, 2012). 10,500 km of the 12,600 km HVDC lines are subsea or inland cables, while only 1,500 km of the 39,400 km HVAC lines are cables; the rest are overhead power lines. Overall investment costs are estimated to about 104 billion Euros (ENTSO-E, 2012), whereof subsea cables make up 23 billion Euros. The highest investment costs are expected in Germany and the UK (30 billion Euros; 19 billion Euros), followed by France, Italy and Norway (8.8 billion Euros; 7.1 billion Euros; 6.5 billion Euros). According to ENTSO-E (2012), the development of an offshore grid in the North Sea connecting future wind farms with the countries around the North Sea is not expected to be of significance before 2030.

The Twenties study considered the establishment of a North Sea offshore grid (see Figure 6.3) in the simulations for the year 2030, and an installed capacity of 18.2 GW hydro storage and pumped storage hydropower for electricity balancing from Norwegian hydropower (cf. Table 2.2 in Chapter 2). By means of an investment algorithm it was proved that the expansion of transmission capacities of 4 GW along the corridor around the North Sea are profitable, reaching from Sweden to Northern Germany, the Netherlands and Belgium to England and Scotland. The grid model simulations revealed that internal congestions in the Central European power grid prevent transmission of power generated by Norwegian hydropower to Central Europe, even when the required cross-border transmission capacity is available. Additionally, internal congestions in Central Europe do not allow transferring wind power generated in the North Sea region to the load centres located further south. As a consequence, the power is transferred to Norway to be used in pumped storage power plants. The Twenties simulations show that internal reinforcements both in the

Central European grid and the Norwegian grid are necessary to enable larger power flows from Norway to Continental Europe and use the flexibility of Norwegian hydropower.

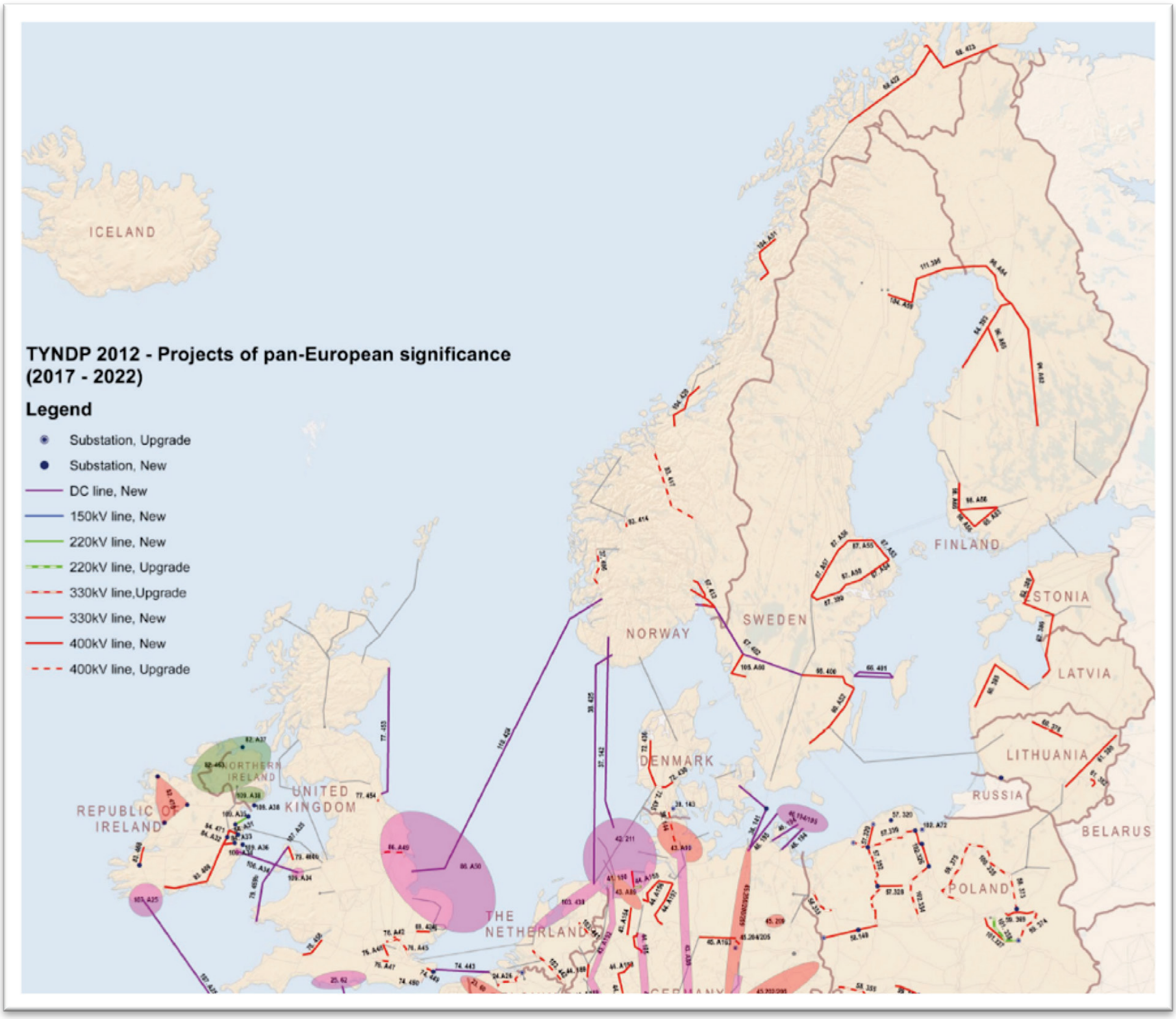


Figure 6.2 **Transmission line projects of pan-European significance planned on the long-term (2017-2022) in Northern Europe. Adopted from ENTSO-E (2012).**

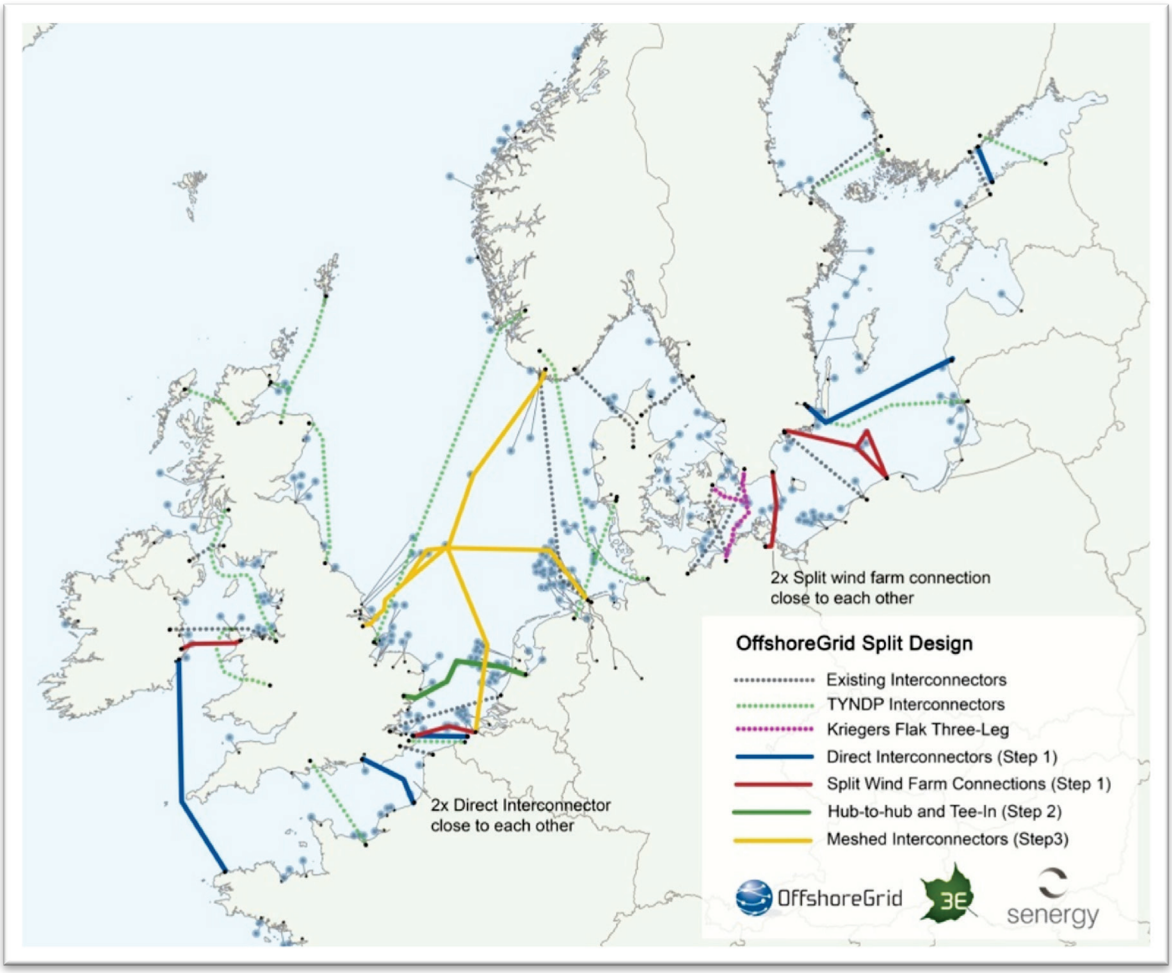


Figure 6.3 Offshore grid in the North Sea in 2030. Adopted from Woyte et al. (2011).

Concerning the long-term perspective up to the year 2050, the SUSPLAN study (Bakken & Graabak, 2012) found that a significant amount of investments into the European transmission grid are required in addition to those ones planned until the year 2030, depending on the type and amount of renewable energy sources, the electricity consumption and the geographical distribution of these factors in particular. High shares of renewable energy sources in the generation mix, especially resources which are located away from the load centres, such as large-scale offshore wind power, require extensive reinforcements and expansion of the transmission grid. Large investments within the period 2030 to 2050 can be expected in the transmission corridors from Southwest Europe (Spain) over France to Central Europe (Germany) and further to Eastern Europe (Poland), mainly due to the location of renewable energy generation units (e.g. wind resources in Southwest and Northwest Europe). The SUSPLAN study found grid expansions between 56 GW and 137 GW to be profitable, depending on the scenario and without taking into account investments necessary to prevent internal grid congestions.

7 Impact on the European power system

7.1 Assumptions

Impacts on the European power system if Norwegian hydropower is used for large-scale balancing purposes are described in (Graabak and Skjelbred 2012). A special focus is on possible reductions of the CO_2 emissions. A scenario methodology is used to explore different future developments of the power systems. This is built upon work done in the EU project SUSPLAN (SUSPLAN, D7.2) and in another CEER, Zero Emission Building (ZEB) (Graabak and Feilberg 2011). Analyses are performed by the EMPS-model (European Multi-area Power Market Simulator) (Wolfgang et. al. 2009).

The analyses are performed on a European power system in 2030 and 2050. They are based on the Blue scenario from the SUSPLAN and the ZEB projects. The Blue scenario has very high volumes of renewable production as shown in Figure 7.1 and the electricity consumption has increased considerably compared to 2010.

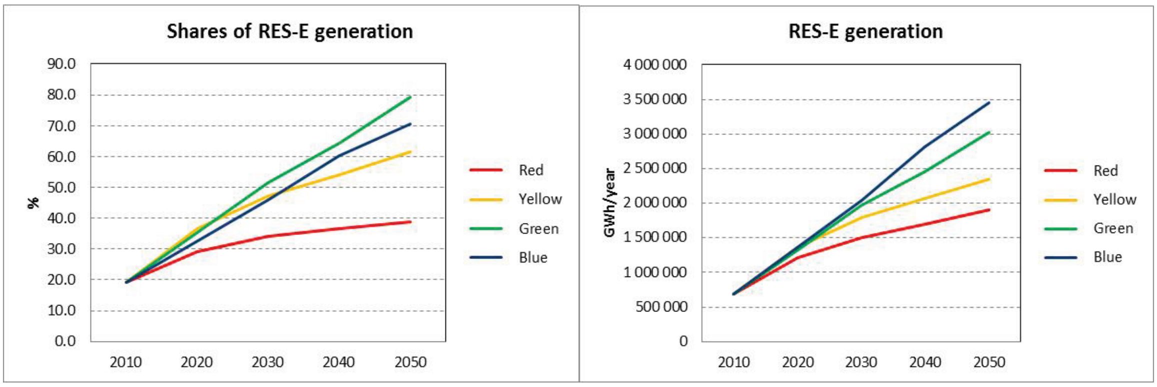


Figure 7.1 Development of RES electricity generation in Europe up to 2050.

Table 7.1 shows the most important transmission capacities between countries relevant for the analysis.

Table 7.1 Assumed transmission capacities [MW].

Country code[1]	Transmission capacity [MW]	
	1,572 MW of pumping capacity in Norway	11,572 MW of pumping capacity in Norway
NO-SE	5,150	5,150
NO-DK	1,650	1,650
NO-NL	700	7,367
NO-DE	1,000	7,667
NO-GB	1,000	7,667
SE-LT	700	700
GB-OW[2] – BE-OW[2]	20,000	20,000
GB-OW[2] – NL-OW[2]	20,000	20,000
GB-OW[2] – DE-OW[2]	20,000	20,000

[1] BE-Belgium, DE-Germany, GB-Great Britain, LT-Lithuania, NL-The Netherlands, NO-Norway, SE-Sweden.

[2] OW are offshore wind farm nodes. The connection between each offshore wind farm and the country to which it belongs, is set large enough to not cause any congestion.

Four different cases have been simulated to investigate the impact of Norwegian balancing power:

- "2030-1,572":
  The analyses are based on the Blue scenario data for 2030 and a pumping capacity in Norway of 1,572 MW. The transmission capacities are shown in Table 7.1.
- "2030-10000":
  The analyses are based on the Blue scenario data for 2030. In addition the capacity of the Norwegian power system is increased with 10,000 MW to a total of about 40 000 MW, but the total production is kept on the same level as for the "2030-1572" case. Further, the pumping capacity is increased with 10,000 MW to a total of 11,572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands are increased with 20 000 MW (Table 7.1).
- "2050-1572":
  The analyses are based on the Blue scenario data for 2050 and a pumping capacity in Norway of 1,572 MW. The transmission capacities are shown in Table 7.1.
- "2050-10000":
  The analyses are based on the Blue scenario data for 2050. In addition the capacity of the Norwegian power system is increased with 10,000 MW to a total of about 40 000 MW, but the total production is kept on the same level as for the "2050-1572" case. Further, the pumping capacity is increased with 10,000 MW to a total of 11,572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands is increased with 20,000 MW (Table 7.1).

7.2 Results stage 2030

The main results from the simulations of stage 2030 are shown in Table 7.2. A few TWh of excess wind energy can be recovered through pumping units. The overall reduction in CO_2 emissions is approximately 10 million tons (Mtons) per year. As a comparison, in 2009 Norway emitted 42.8 Mtons CO_2. The reduction is equal to 1.1 % of the total CO_2 emissions from electricity generation in Europe in the simulated areas.

Table 7.2 Results for case "2030-1572" and case "2030-10000" at European level.

	Unit	"2030-1,572"	"2030-10,000"	"2030-1,572" - "2030-10,000"
CO_2 emissions	Mtons/year	936	925	-10
Curtailment	GWh/year	3,858	3,751	-107
Dumping	GWh/year	8,034	4,696	-3,338
Lignite prod.	GWh/year	76,921	74,944	-1,977
Coal prod.	GWh/year	637,536	634,874	-2,662
Gas prod.	GWh/year	687,994	673,080	-14,914

The simulations of stage 2050 gave an overall reduction in CO_2 emissions of 26 Mtons per year. This is equal to 3.5% of the total CO_2 emissions from electricity generation in 2050 in Europe in the Blue scenario.

As these reductions appear due to less use of fossil fuels, Figure 7.2 shows how this is balanced by other parts of the electricity system in 2030. As shown in the figure only a limited part of the change is reduced transmission losses and dumping. A large share is increased production from bio energy. The bio energy production is increased because prices in among other Sweden increases as a result of increased transmission capacity to Germany through Norway.

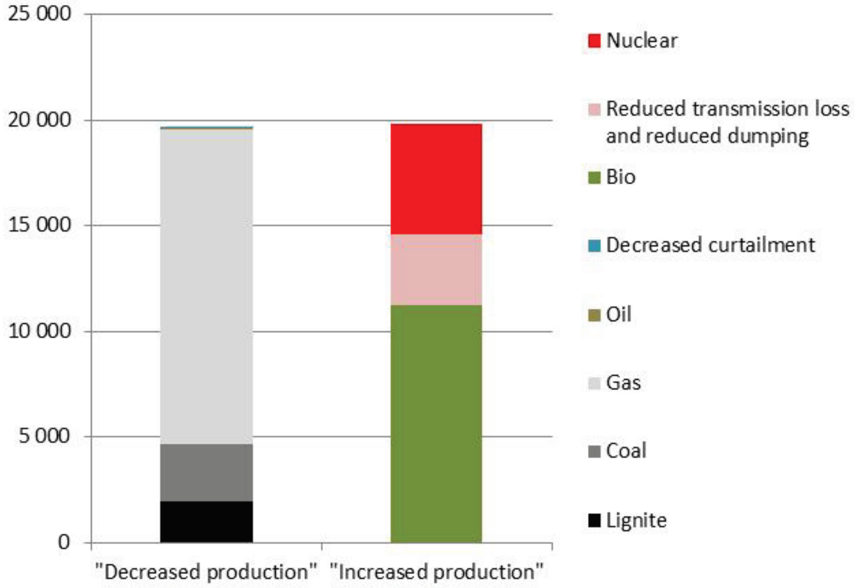


Figure 7.2 Main changes in electricity balance from case "2030-1,572" to "2030-10,000" [GWh/year].

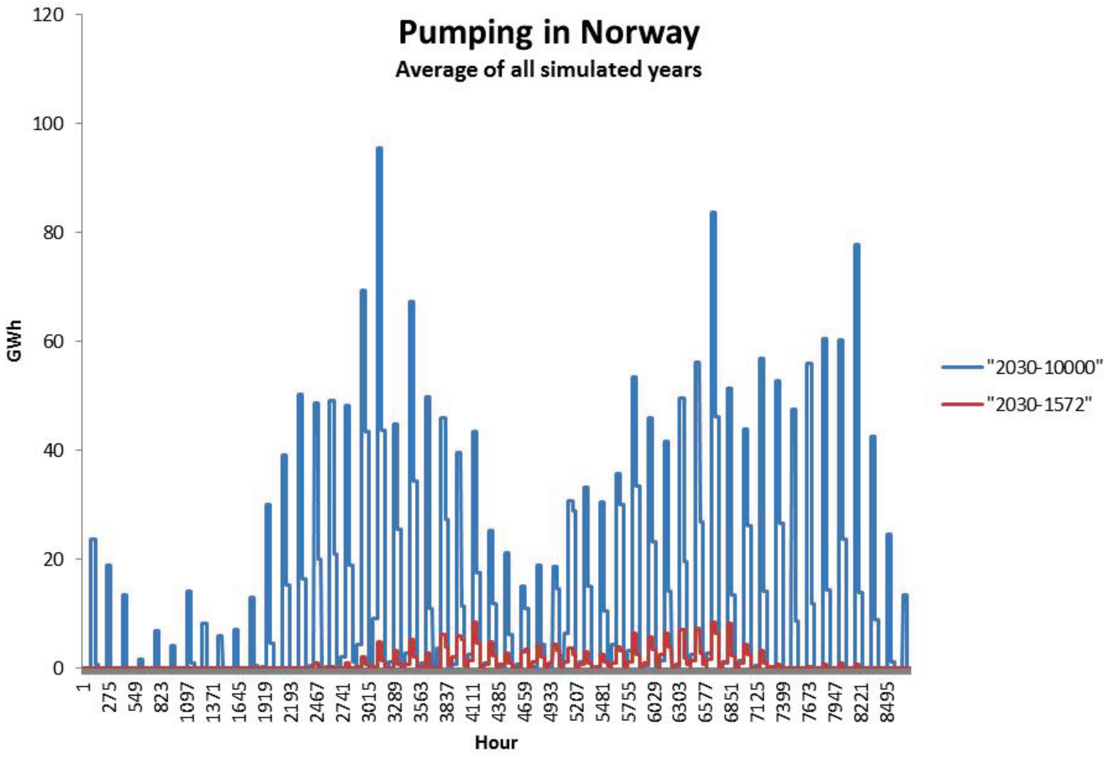


Figure 7.3 Pumping in Norway for case "2030-1,572" and "2030-10000".

As expected, the pumping is increasing when the pump capacity is increased, see Figure 7.3. Further, the pumping is increasing with increasing shares of intermittent production in the system. The simulation of stage 2050 shows that it is pumped much more frequently and with higher volumes (GWh) in 2050 than in

2030. However, with the installed pump capacity of 11,572 MW in the case "2050-10,000" and the high share of intermittent production, the volume of pumping was expected to be higher. More detailed studies shows that only water equivalent to 11.4 TWh of net energy were pumped in the Norwegian system.

Use of Norwegian hydro power for balancing purposes is expected to reduce the surplus in the production system in Europe. Surplus is in this context energy produced from wind turbines or solar systems in a period where it is not sufficient demand to utilise the produced energy. Detailed studies of the results show that in the case "2050-1,572" there is a surplus of offshore wind production in Great Britain of 53.4 TWh per year. In the case "2050-10,000" the surplus is reduced to 45.3 TWh. The surplus is reduced, but still a lot of energy has to be dumped. Germany has a small surplus in "2050-1,572" (1.3 TWh). In "2050-10,000" it is reduced, but not completely.

The CO_2 emissions are reduced with 10 Mtons/year from case "2030-1572" to "2030-10000" (Table 7.2). The reduction is 26 Mtons/year from case "2050-1572" to "2050-10000". The main changes in 2050 are in the Netherlands (9.5 Mtons/y), Germany (6.9 Mtons/y) and in Great Britain (4.1 Mtons/y). However, in 2050 there are still 734 MTons/y CO_2 emissions in Europe.

For both 2030 and 2050, the capacity in the Norwegian power system as well as the pumping capacity is increased from the 1,572 MW case to the 10,000 MW case. In addition the exchange capacity between Norway and Great Britain, Germany and the Netherlands are increased with a total of 20,000 MW. I.e. there are made two major changes at the same time, and the reduction in the surplus, the rationing and the CO_2 emissions are results of both changes.

A considerable part of the observed changes is a result of increased transmission capacity, and has less to do with the increased capacity in the Norwegian hydro power system. The transmission capacity from Great Britain to Germany is increased (going through Norway) and also the transmission capacity from Sweden to Germany. Through the increased capacities, Great Britain and Sweden are exporting cheap renewable energy to Germany, and the effects would have been the same with increased capacities directly from Great Britain to Germany and from Sweden to Germany. In further analysis the 1,572 MW cases should be run with the high level of transmission capacities, and the only change from the 1,572 MW cases to the 10,000 MW cases should be the increase of capacity in the Norwegian production system. Then, it will be possible to calculate more accurately the effects of Norwegian hydro power for balancing purposes.

In these analyses a one-node per country version of the EMPS model is used. This simplification limits the level of pumping. Further, it is not used start/stop costs for thermal production in the simulations. As a result the thermal production will to some degree be used for balancing intermittent renewable production instead of Norwegian hydro power. Use of start/stop costs for thermal production (which is a more realistic approach) would probably have increased the use of Norwegian hydro power.

8 Summary and conclusions

Many European countries are increasing the proportion of wind and solar power generation in their electricity supply. This increases the need for energy storage to compensate for the difference between production and consumption, known as balance power. Hydropower with reservoirs is the only form of renewable energy storage in wide commercial use today.

Existing Norwegian hydropower reservoirs have a large balance power potential. This is illustrated in a preliminary study (Solvang, Harby & Killingtveit 2012) relating to increasing the power output of existing hydroelectric reservoir plants in southern Norway, subject to the constraints of current regulations relating to maximum and minimum regulated water levels (HRWL and LRWL). The main scenario involves twelve new power stations with a combined power output of 11,200 MW. It is envisaged that these power stations would be constructed with new tunnels to an upstream reservoir and to the downstream outflow into a reservoir or to the sea. The power generation outputs in the scenario were chosen mainly so that the water level change in the upper and lower reservoirs does not exceed 13 cm/hour. According to research into the stranding of salmon in rivers, the water level should not sink by more than 13 cm/hour (Harby et al. 2004). Although this is not directly applicable to lakes, this was used as a rule of thumb for acceptable water level reduction in reservoirs.

The output of the 12 power stations in the main scenario can be increased to 18,200 MW without the water level changes in the upper and lower reservoirs exceeding 14 cm/hour. How long the power stations are able to deliver this power output will depend among other things on the current regulations regarding highest and lowest regulated water levels (HRWL and LRWL), as well as what strategies are adopted with regard to pumping in the case of pumped storage power stations. By including more cases in southern Norway in addition to some in northern Norway, it will be possible to increase the output of existing hydroelectric reservoirs by a further 1,800 MW to give a total of 20,000 MW for the whole country.

Drivers for large-scale exploitation of Norwegian hydropower for balancing services for Europe are:

- EU-20-20-20-targets and Roadmap 2050 (European Climate Foundation) – promotion of further development of renewables.
- Balancing services: A way of contributing to a more climate friendly energy system.
- A possibility if biodiversity commitments are taken into account.
- A business and development opportunity is the host municipalities and NGOs are involved at an early stage.
- A possibility if benefits are shared between producers, distributors and host municipalities.

Implications for the operational schemes of the affected reservoirs when balancing wind power from the North Sea area are analysed. Based on time series of stage and live storage volume of the upper and lower reservoirs, balancing power on daily basis was simulated on top of the current operation of three existing power plants. This was assumed to be realised by installing reversible turbines in addition to the existing ones. The objectives were to compare the current patterns of water level fluctuations to the simulated patterns (season, frequency, rate of change) and to analyse which factors determine how much power can actually be balanced compared to how much is required to be balanced (turbine capacity, free reservoir volumes). The characteristics of these patterns may be important when studying environmental consequences of providing balancing power and could serve as parameters related to impacts on the ecosystem.

Two balancing power scenarios were defined; the 7Days-Avg scenario and the Dev-Avg scenario. The 7Days-Avg scenario is based on the 7 day moving average of wind power production assuming that hydropower will compensate short-term fluctuations up to one week. The Dev-Avg scenario assumes that hydropower balances the large fluctuations in wind power production where the number of consecutive days with generation or pumping required, last typically 1 to 2 weeks.

The analysis of the three power plants (reservoir pairs) shows to which extent the current patterns of fluctuations in water volume, water level and surface area in the reservoirs are modified when introducing balancing power operation. In case of the 7Days-Avg scenario these changes affect both the seasonal pattern of the storage volume in the upper and lower reservoirs and introduce short-term fluctuations. The average rates of change in water level are obviously higher than during the current operation, but they are still below the range of critical rates as defined by Halleraker (2003) and Saltveit (2001). The simulation results of the Dev-Avg scenario show the same tendency in terms of water level variations. However, the short-term fluctuations are less frequent and have slightly lower magnitude. The factors limiting the provision of balancing power most are the turbine capacities and the live storage volume of the lower reservoirs.

The analysis shows that water level fluctuations are site-specific. Hence, for the purpose of detailed planning, each case should be studied individually. Water level variations depend on the load, the characteristics of each reservoir pair (live storage volume, steep/gentle bank slope, size of lower reservoir compared to upper one) and the installed capacity. The storage volumes available in the reservoirs are not entirely used for energy storage, since simulation results show that the reservoirs are not often completely filled or emptied in these three cases. Therefore, it would be interesting to analyse scenarios with larger demand for balancing power, i.e. simulate scenarios with more focus on energy storage and balancing than on the current operational regime.

The societal aspects of using Norwegian hydropower reservoirs for large-scale balancing services for Europe are analysed according to how these are expressed by key Norwegian stakeholders. Does this use of Norwegian hydropower have legitimacy, what are the drivers supporting this idea, what are the barriers, and what approaches are necessary to overcome important barriers, are the questions that is addressed.

Interviews with 22 informants, representing four interest groups, as well as the public authorities concerned were carried out. These interests include; energy companies, environmental NGOs, recreational NGOs, as well as the host communities. The interviews performed with the stakeholders focused on the how the idea of Norway as a provider of large-scale balancing services was considered by the different stakeholders in general, and not in relation to concrete projects. In summary, the interviews showed that:

- All stakeholders supported the idea that Norway could play a role in reducing climate change by offering balancing services from hydropower.
- At the same time there is widespread doubt that this is realistic – at least within the timeframe of 2020, because a range of political clarifications and regulatory frameworks that are considered crucial to proceed with planning for balancing services are presently lacking.
- Despite the overall support of considering Norwegian hydropower as balancing services in a European context, stakeholders agree that the likely contribution will be minor, because of limitations set by environmental values, as well as commercial and financial constraints or uncertainty.
- Even if the barriers concerning environmental, economic and social interest in Norway are possible to overcome, all the stakeholders considered the extent of the Norwegian contribution to cover the need for balancing services in Europe as rather limited.
- Among some of the energy companies, there exist uncertainty about the commercial basis for pumped storage as this depend on that energy prices continue to vary significantly. Some companies question if this will last, especially if the European grid is developed further.
- The most concrete barrier within the 2020 timeframe is the existing grid policy. Statnett’s current mandate focuses on national services and currently not on contributing to grids that make it possible for large scale transmission of balancing services to Europe.

- The existing grid policy is also seen as insufficient regarding the distribution of benefits and costs from new cables.
- Representatives from the environmental NGOs stress that Norway must contribute to reduce climate change but at the same time live up to biodiversity commitments.
- Better involvement of stakeholders and local communities is seen as crucial in further planning of balancing services but there are different views on how and who should be responsible for better involvement.
- There is general agreement that host communities must get their share of benefits from production of balancing services, and that the current legislation must be changed to take this into account.
- Balancing services should avoid sites where rivers or smaller downstream reservoirs are affected. Nearby transmission cables is also seen as a prerequisite in choosing suitable projects.

Despite the fact that exploitation of Norwegian hydropower for large-scale balancing services has legitimacy among the stakeholders due to the hope that deliverances of balance power will increase the renewable share of energy production in Europe, this analysis has shown that the barriers identified are several, especially if the timeframe is set within 2020. The main barriers have political, economic, and environmental implications, as for example:

- Lack of political support regarding the future development of hydropower at the national level.
- Perceived risks and uncertainties that such an investment pose, both economically and politically.
- Uncertainty about the commercial basis for pumped storage as this depend on that energy prices continue to vary significantly.
- Uncertainty about further grid development, including the strengthening of the national grid, as well as interconnectors to Europe.
- A barrier if biodiversity commitments are taken into account.
- A barrier if a benefit sharing system is not designed.
- A barrier if early involvement does not take place (host municipalities and NGOs).

The risks the stakeholders identify are not just seen as environmental, economic and social concerns per se. In order to overcome the barriers, the stakeholders in unison call for a national political clarifications regarding the energy policy. Despite their different roles and goals, they all agree that Norway lack an updated and integrated energy policy. It is considered as a national political responsibility to decide whether or not Norway de facto should become a large provider of balance power for Europe, and if so, the regulatory framework needs to be adjusted accordingly. Thus, it is important for the Norwegian political decision makers – government and parliament, to clarify whether and on what premises Norway should contribute to the promotion of renewable electricity development in the EU countries. As part of this, a clarification is called for regarding the grid development towards Europe (Statnett's mandate, on how to finance the cables needed, as well as benefit sharing on revenue generated and so forth), as lack of grid capacity is one of the most concrete and immediate barriers to the idea of Norwegian hydropower as a large provider of balance power for Europe.

This report is showing results of a large pilot study, using relatively simple modeling tools and analysis to assess challenges and opportunities for large-scale balancing and energy storage from Norwegian hydropower. For all the studies conducted, there are more advanced options of modeling and analysis using more comprehensive input data and parameters available. A comprehensive use of models and analysis is not possible in a pilot study, but should be part of a research project. The CEDREN research project "HydroBalance" will focus on many of these aspects and some others, bringing more knowledge and a broader perspective around challenges and opportunities for large-scale balancing and energy storage from Norwegian hydropower.

9 References

Alstom (2012): Hydro Pumped Storage Power Plant, Technical Brochure. Available from www.alstom.com. Viewed October 2012.

Amler, P. (2010): Large Hydro ensuring grid stability with rapidly expanding wind generation - a suppliers perspective. Andritz Hydro. Aberdeen.

Anderson (2006): Analysis of the Potential Water Quality Impacts of LEAPS on Lake Elsinore. Dept. of Environmental Sciences . UC Riverside.

Anderson, M.A. (2010): Influence of pumped-storage hydroelectric plant operation on a shallow polymictic lake: Predictions from 3-D hydrodynamic modeling. Lake Reserv. Manage. 26:1-13.

Angell, S.I.; Brekke, O.A. (2011): Frå kraft versus natur til miljøvenleg energi? Norsk vasskraftpolitikk i eit hunderårsperspektiv. Uni Rokkan Report 2-2011.

Bakken, B.; Graabak, I. (2012): SUSPLAN Final Report, SUSPLAN Deliverable D7.2, available online (accessed 02/04/2013). http://www.susplan.eu/fileadmin/susplan/documents/downloads/WP_7/D7.2_Final_Report.pdf

Bell, E.; Kramer, S.; Zajanc, D.; Aspittle, A. (2008): Salmonid Fry Stranding Mortality Associated with Daily Water Level Fluctuations in Trail Bridge Reservoir, Oregon. North American Journal of Fisheries Management 28: 1515-1528.

Bonalumi, M.; Anselmetti, F.S.; Kägi, R.; Wüest, A. (2011): Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation, Water Resources Research, Vol 47, Iss 9, Sept 2011, doi:10.1029/2010WR010262.

EC COM/2011/0885 (2011): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Energy Roadmap 2050.

ECF (2010): Roadmap 2050 – A practical guide to a prosperous, low-carbon Europe. European Climate Foundation.

ENTSO-E (2001): Procedures for cross-border transmission capacity assessments, available online (accessed 27/02/2013) https://www.entsoe.eu/publications/market-and-rd-reports/

ENTSO-E (2011): NTC Matrices, available online (accessed 01/03/2013) https://www.entsoe.eu/publications/market-and-rd-reports/ntc-values/ntc-matrix/

ENTSO-E (2012): 10-Year Network Development Plan 2012. European Network of Transmission System Operators for Electricity, available online (accessed 04/03/2013) https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012

Eurelectric (2010): Flexible Generation: Backing Up Renewables. Full Report, Eurelectric Renewables Action Plan.

Farahmand, H.; Jaehnert, S.; Huertas-Hernando, D. (2013): Nordic hydro power generation flexibility and transmission capacity expansion to support North European wind power: 2020 and 2030 case studies, Twenties Project EC-GA no. 249812, Deliverable 16.3.

Federal Republic of Germany: National Renewable Energy Action Plan in accordance with Directive 2009/28/EC on the promotion of use of energy form renewable sources.

Fornybar (2012): Pumpekraftverk. Available from: Êhttp://fornybar.no. Viewed September 2012.

Gailiusis, B.; et al. (2003): Modelling the Effect of the Hydroelectric Pumped Storage Plant on Hydrodynamic Regime of the Kaunas Reservoir In Lithuania.Nordic Hydrology, 34 9, 2003, 507-5 18.

Graabak I.; Feilberg N. (2011): CO_2 emissions in different scenarios of electricity generation in Europe, SINTEF Energy Research, TR A7058.

Graabak, I.; Skjelbred, H.I. (2012): Large scale exchange of balancing power between Norway and Europe – analysis of impacts. SINTEF Energy Research, TR A7200.

Griffiths, H. (1990): Nathional Engineering Landmark Plaque Unveiling. Tumut 3 Power Station, Talbingo NSW, Australia.

Grøv, E.; Bruland, A.; Nilsen, B.; Panthi, K. & Lu, M. (2011): Developing future 20 000 MW hydro electric power in Norway. Possible concepts and need of resources. SINTEF report, SBF 2011 A0021.

Halleraker, J.H.; Saltveit, S.J.; Harby, A.; Arnekleiv, J.V.; Fjeldstad, H.; Kohler, B. (2003): Factors influencing stranding of wild juvenile brown trout (Salmo trutta) during rapid and frequent flow decreases in an artificial stream. River Research and Applications 19: 589–603. DOI: 10.1002/rra.752.

Hamnaberg, H. Vattenfall Power Consultant (2011): Pumpekraft i Noreg. Kostnadar og utsikter til potensial. NVE rapport nr. 22.

Harby, A.; Alfredsen, K. Arnekleiv, J.V.; Flodmark, L.E.W.; Halleraker, J.H.; Johansen, S.; Saltveit, S.J. (2004): Raske vannstandsendringer i elver. Virkninger på fisk, bunndyr og begroing [Rapid water level variations. Impact on fish, benthic fauna and aquatic vegetation], SINTEF Energy Research, TR A5932, Trondheim (in Norwegian).

Helland, I.; Finstad, A.G.; Forseth, T.; Hesthagen, T.; Ugedal, O.(2011): Ice-cover effects on competitive interactions between two fish species. J. Anim. Ecol. 80, 539-547.

Huber,C.; Gutschi, C. (2010): Pump-Storage Hydro Power Plants in the European Electricity Market. Institute for Electricity Economics and Energy Innovations Graz University of Technology.

Jonsson, B.; Jonsson, N. (2011): Ecology of Atlantic salmon and brown trout: Habitat as a template for life histories. Fish & Fisheries Series 33, Springer Verlag, 708 s.

Knudsen, J.K.; Ruud, A. (2011): Changing currents in Norwegian hydropower governance? The challenge of reconciling conflicting interests. SINTEF Energy Research, TR A7111.

Lafferty, W.M.; Ruud, A. (2008): Promoting Sustainable Electricity in Europe. Challenging the Path Dependence of Dominant Energy Systems. Cheltenham, UK: Edward Elgar.

Liu, L.X.; Wu, J.C. (1999): Research on ice formation during winter operation for a pumped storage station, ICE IN SURFACE WATERS, VOL 2 Pages: 753-759, published 1999.

Mock, C. (1972): Electrical features of raccoon mountain pumped-storage plant. Tennessee Valley Authority. Tennessee.

Nilsen, Y.; Thue, L. (2006): Statens kraft 1965-2006 : Miljø og marked. Oslo: Universitetsforlaget.

Noack, M.; et al. (2010): Simulation of stranding risk of juvenile fish due to hydropeaking using the habitat model CASiMiR. Renewable Energy Research Conference 2010; Trondheim; 7 - 8 June 2010.

NSCOGI – The North Seas Countries' Offshore Grid Initiative. Memorandum of Understanding (2010).

Nysveen, A.; Molinas, M. (2012): Electric systems for Pumped Storage Plants. Technology evaluation. SINTEF Energy Research, TR A7262.

Øygard, K. (2008): Pumpekraftverk for effektproduksjon. Masteroppgave i energi og miljø. NTNU, Trondheim.

Potter, D.U.; Stevens, M.P.; Meyer, J.L. (1982): Changes in Physical and chemical variables in a new reservoir due to pumped storage operations, Journal of the American Water Resources Association, 18: 627–633. doi: 10.1111/j.1752-1688.1982.tb00045.x

Puffer, M.; Berg, O. (2010): Review on impacts of artificial rapid and frequent flow changes on salmonids in fast flowing waters. 8th International Symposium on Ecohydraulics 2010; Seoul, Korea, 12-16 September 2010.

Røed, H.; Skaaland, Å.; Imenes, A.G.; Knudsen, J.P. (2011): Lister – Europas "grønne batteri". Trusler og muligheter for regionen. Prosjektrapport nr. 5/2011. Agderforskning.

Ruud, A.; Knudsen, J. (2009): Renewable energy policy making in the EU: What has been the role of Norwegian stakeholders. SINTEF Energy Research, TR A6860.

Ruud, A.; Knudsen, J.; Jacobsen, G.B. (2011): Energy for Climate in Europe. An assessment of energy policies with climate-relevance. SINTEF Energy Research, TR A7066.

Ruud, A.; Kielland, J.J.H.; Lafferty, W.M. (2011): ”Case Hardanger”. En analyse av den formelle konsesjonsprosessen og mediedekningen knyttet til den omsøkte luftledningen Sima-Samnanger. CEDREN/SINTEF, A20905.

Sætre, A.L. (2012) Use of Pumped Storage to Balance the Varying Output From Large-Scale Wind Power Installation in the North Sea. Specialization Project 2012, NTNU

Saltveit, S.J.; Halleraker, J.H.; Arnekleiv, J.V.; Harby, A. (2001): Field experiments on stranding in juvenile Atlantic salmon (Salmo salar) and brown trout (Salmo trutta) during rapid flow decreases caused by hydropeaking. Regulated Rivers: Research and Management 17: 609–622. DOI: 10.1002/rrr.652.

Sauterleute, J. (2013): Overview of the existing grid and possible future development of connections between countries in Europe. EERA Joint Programme on Energy Storage - Sub-Programme on Mechanical Storage.

Solvang, E.; Harby, A.; Killingtveit, Å. (2012): Increasing balance power capacity in Norwegian hydroelectric power stations. A preliminary study of specific cases in southern Norway. SINTEF Energy Research, TR A7126.

Stanford, J.A.; Hauer, F.R. (1992): Mitigating the impacts of stream and lake regulation in the flathead river catchment, Montana, USA – An ecosystem perspective, Aquat. Cons: Marine and Freshwater Ecosystems, 2(1): 35-63.

Stockner, J.G.; Macisaac, E.A. (1996): British Columbia lake enrichment programme: two decades of habitat enhancement for Sockeye salmon. Regulated Rivers: Research and Management 12, 547–561.

Suul, J.; Uhlen, K.; Undeland, T. (2008): Variable speed pumped storage hydropower for integration of wind energy in isolated grids - case description and control strategies. Nordic Workshop on Power and Industrial Electronics, NORPIE 2008, IEEE.

Tande, J.O.G.; Korpås, M.; Warland, L.; Uhlen, K.; Van Hulle, F. (2008): Impact of TradeWind offshore wind power capacity scenarios on power flows in the European HV network. 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, Madrid, Spain, 26-27 May, 2008.

Thue, L. (2003): For egen kraft. Kraftkommunene og det norske kraftregimet 1887-2003. Abstrakt forlag.

UCTE (2007): Final Report System Disturbance on 4 November 2006.

Wolfgang, O.; et.al. (2009): Hydro reservoir handling in Norway before and after deregulation. Energy 34 (2009) 1642–1651.

Woyte, A.; et al. (2011): Offshore Electricity Grid Infrastructure in Europe.

Zakowski, T.; et al. (2010): The Effects of Rapid Flow Variation on Benthic Macroinvertebrates in Norwegian Rivers. 8th International Symposium on Ecohydraulics 2010; Seoul, Korea; 12 - 16 September 2010.

Zohary T.; Ostrovsky, I. (2011): Ecological impacts of excessive water level fluctuations in stratified freshwater lakes, Inland Waters (2011) 1, pp. 47-59.

Internet resources

- Bellona: http://www.bellona.org/subjects/1140449074.91/aboutussection_view
- EREC – European Renewable Energy Council: http://www.erec.org/projects/other-projects/reshare.html
- European Commission Climate Action: http://ec.europa.eu/clima/policies/package/index_en.htm
- The Lister Council: http://www.lister.no/listerradet
- National Renewable Energy Action Plans: http://ec.europa.eu/energy/renewables/transparency_platform/action_plan_en.htm
- Natur & ungdom: http://www.nu.no/english/
- Naturvernforbundet: http://naturvernforbundet.no/about/
- NTB (20.01.2011)"Vil gjøre Norge til Europas grønne batteri": http://www.abcnyheter.no/nyheter/politikk/110120/vil-gjore-norge-til-europas-gronne-batteri
- Roadmap 2050: http://www.roadmap2050.eu/who-are-we
- WWF Norway: http://www.wwf.no/om_wwf/hvem_er_vi/
- Avellan, F. (2011): Storage Pumps & Reversible Pump Turbines. Laboratory for Hydraulic Machines (LMH). Available from: http://www.renewables-grid.eu/fileadmin/user_upload/Files_RGI/RGIStorageWS-27Jan2011-Avellan_EPFL.pdf. Viewed November 2012.
- Chemistry Daily (2012): Pumped-storage hydroelectricity. The chemistry encyclopedia. Available from: http://www.chemistrydaily.com/chemistry/Hydroelectric_energy_storage. Viewed November 2012.
- CLP (2012): Guangzhou Pumped Storage Power Station. Available from: https://www.clp.com.hk/ouroperations/power/guangzhoupumpedstoragepowerstation/Pages/guangzhoupumpedstoragepowerstation.aspx . Viewed November 2012.
- Dominion (2012): Bath County Pumped Storage Station. Dominion. Available from: https://www.dom.com/about/stations/hydro/bath-county-pumped-storage-station.jsp Viewed November 2012.
- DTE Energy: Ludington Pumped Storage Plant. DTE Energy. Available from: http://www.consumersenergy.com/uploadedfiles/ceweb/shared/ludingtonpumpedstorage.pdf Viewed November 2012.
- Goulds Pumps (2012): Goulds VIT Vertical Industrial Turbine Pumps. Available from: http://www.gouldspumps.com/Products/VIT/ . Viewed November 2012.
- Hydro Equipment Association (2012): Pumped storage power plants. Available from: http://www.thehea.org/hydropower/special-focus/ . Viewed October 2012.
- Ikeda, K.; Inagaki, M.; Niikura, K.; Oshima, K. (2000): 700-m 400-MW Class Ultrahigh-head Pump Turbine. Hitachi Review Vol.49. No.2. Available from: http://www.hitachi.com/rev/field/powersystems/__icsFiles/afieldfile/2004/06/01/r2000_02_107.pdf Viewed November 2012.

- IEA Hydropower (2006): Mingtan Pumped Storage Power Plant. New Energy Foundation. Taiwan. Available from: http://www.ieahydro.org/reports/Annex_VIII_CaseStudy0506_Mingtan_Taiwan.pdf Viewed November 2012.
- Vattenfall (2012): Markersbach. Available from: http://powerplants.vattenfall.com Viewed December 2012.
- Voith (2012): Available from: http://www.voith.com/en/index.html. Viewed October 2012.
- Wikipedia (2012): Pumped-storage hydroelectricity. Available from: http://en.wikipedia.org/wiki/List_of_pumped-storage_hydroelectric_power_stations Viewed November 2012.

APPENDIX

A Interview guides

A.1 The companies

Intervjuguide for prosjektet HydroBalance, delprosjekt om verdiskaping og samfunnsaksept

1) Hvordan ser du på mulighetene for norsk vannkraft som balansekraft for å regulere uregulerbar kraftproduksjon i Europa ut i fra selskapet sitt ståsted?

2) Hva er årsakene til selskapets interesse for balansekraft? Hvilke argumenter bruker dere for å begrunne interesse?

3) Hvor langt er selskapet kommet i vurderingen av balansekraft?

4) Hva tenker du en økt satsning på effektkjøring og pumpekraftverk kan føre til på de følgende områder:

   a. Fordeler for selskapet (i anleggsperioden og i driftsfasen)
      i. Miljømessig
      ii. Landskap
      iii. Økonomisk
      iv. Sosialt

   b. Fordeler for lokalsamfunnet (i anleggsperioden og i driftsfasen)
      v. Miljømessig
      vi. Landskap
      vii. Økonomisk
      viii. Sosialt

   c. Ulemper for selskapet (i anleggsperioden og i driftsfasen)
      ix. Miljømessig
      x. Landskap
      xi. Økonomisk
      xii. Sosialt

   d. Ulemper for lokalsamfunnet (i anleggsperioden og i driftsfasen)
      xiii. Miljømessig
      xiv. Landskap
      xv. Økonomisk
      xvi. Sosialt

5) Hvordan kan eventuelle ulemper kompenseres? Og hva tror du kan øke samfunnsaksepten for slike prosjekter?

6) Kommunikasjon og involvering. Dersom ditt selskap ønsker å satse på slike prosjekter i framtiden, har dere tenkt over på hvilke måter dere vil involvere berørte aktører?
    a. Involvering: Hvem, når og i hvilken form?
    b. Hva slags prosesser og informasjon tenker du at det vil være viktig å legge opp til for å gi prosjektene legitimitet?

7) Avbøtende tiltak – hva slags tiltak kan bli aktuelle?

8) Hva skal til for å realisere Norge som et grønt batteri for Europa fra ditt selskap sitt ståsted?

A.2 Other stakeholders:

Intervjuguide for prosjektet HydroBalance, delprosjekt om verdiskaping og samfunnsaksept

HydroBalance er et forskningsprosjekt innenfor CEDREN (Centre for Environmental Design of Renewable Energy) hvor vi forsker på tekniske og samfunnsmessige utfordringer knyttet til hvordan vi kan fremme et godt miljødesign for kraftproduksjon i fremtiden. I dette prosjektet ønsker vi å belyse utfordringer og muligheter, herunder hvilke virkninger av økt effektkjøring og pumpekraftverk som er akseptable, og hvordan ulemper kan kompenseres. I informasjonsbrevet finner du en kort forklaring på hva som menes med begrepene effektkjøring, pumpekraftverk og balansekraft.

2) Hvordan ser du på mulighetene for norsk vannkraft som balansekraft for å regulere uregulerbar (f.eks. vindkraft eller solenergi) kraftproduksjon i Europa?
    a. Generelt:
    b. Fordeler?
        i. Hva skal til for at fordelene skal realiseres?
    c. Ulemper?
        i. Hva må gjøres for at ulempene unngås/evt. minskes?

3) Har du noen tanker om hva en økt satsning økt effektkjøring og pumpekraftverk kan føre til på de følgende områder:
    a. Fordeler (i anleggsperioden og i driftsfasen)
        i. Miljømessig
        ii. Landskap
        iii. Økonomisk
        iv. Sosialt
    b. Ulemper (i anleggsperioden og i driftsfasen)
        i. Miljømessig
        ii. Landskap
        iii. Økonomisk
        iv. Sosialt

4) Hvordan kan ulempene kompenseres? Og hva kan gjøre en økt effektkjøring og etablering av pumpekraftverk akseptabelt?

5) Kommunikasjon og involvering. Dersom slike prosjekter vil komme i fremtiden hva er viktig for deg/deres organisasjon å få kunnskap om? Og hvordan bør en god dialog være?
    a. Involvering: Når og i hvilken form?
    b. Hva slags informasjon er viktig?
    c. Formålet med prosjektet?
    d. Avbøtende tiltak?

6) Bør Norge satse på å være et grønt batteri for Europa?
    a. Hvorfor?
    b. Hvorfor ikke?

SINTEF

Technology for a better society

www.sintef.no