HydroBalance

Roadmap for large-scale balancing and energy storage from Norwegian hydropower

Opportunities, challenges and needs until 2050

Julie Charmasson, Michael Belsnes, Oddgeir Andersen, Antti Eloranta, Ingeborg Graabak, Magnus Korpås, Ingeborg Palm Helland, Håkon Sundt, Ove Wolfgang

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Centre for Environmental Design of Renewable Energy

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Coverphotos: Antti Eloranta

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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 of the scheme 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.

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SINTEF [1], NINA [2], NTNU [3]

Content

Preface

In the span of the CEDREN HydroBalance project (2013-2017) we have witnessed large changes in the power sector. The cost of solar panels and wind turbines have decreased and are putting pressure on the cost effectiveness of hydropower. On the other side the increase in intermittent electricity production from wind and solar power has shown that the power system will have a growing demand for flexibility and energy storage. Our calculations show that by 2050, the need for storage in West-Central Europe will reach about 23 TWh in the month with lowest wind and solar power production, and the hourly balancing need will be up to 300 GW. Norway already has a storage capacity today (85 TWh), accounting for 50% of the total European storage capacity, while installed hydro capacity is about 30 GW.

If Europe were to buy batteries (like Tesla Power Wall) to reach a household energy storage comparable to the energy content of Norway's largest reservoir Blåsjø (7.8 TWh), Europe would have to invest 40-50 trillion NOK or 5-6 times the current value of the Norwegian Pension Fund. In this setting the CEDREN project HydroBalance investigated the feasibility of using Norwegian hydropower for supporting integration of intermittent renewable electricity generation in Europe. The project combines technological, environmental and social aspects in the questions: Is it economically sound to do so? Can it be done respecting nature? Is it acceptable for people in Norway?

My conclusion is, yes, it makes sense to use the flexibility from hydropower to deliver energy security to Europe. The expansion must necessarily take place in a sustainable way respecting nature and following a long-term plan for flexibility from Norwegian hydropower. It will be possible for Norway to pursue and harvest the value creation that could come from redevelopment of the Norwegian hydropower system with the aim to deliver balancing services. Norway should also aim to benefit from a parallel development of the Norwegian service and manufacturing industry for hydropower technology.

CEDREN HydroBalance was a Knowledge Building Project for Industry (KPN) with a budget of about 25 MNOK. The project received 70% funding from the the Research Council of Norway and 30% from 11 funding industry partners. In total 11 research partners collaborated in the project, and the main partners were SINTEF Energy, NTNU and NINA.

Michael Belsnes,
Project Leader for HydroBalance,
SINTEF Energy Research

1. Purpose, process and structure

1.1. Purpose

This roadmap is a deliverable from the HydroBalance project (2013–2017) carried out under the umbrella of the Centre of Environmental Design of Renewable Energy (CEDREN). Funding was provided by the Research Council of Norway (grant no. 228714). CEDREN partners from private sector and public authorities, such as power companies, together contributed about one third of the total funding.

The HydroBalance roadmap aims at:

- Pointing out main elements in the process of deploying the flexibility of Norwegian hydropower with expansion of existing hydropower capacity and construction of new pumped-storage plants by 2050.
- Reviewing challenges and needs that the society will face for such use of hydropower.
- Integrating economic, technological, environmental and societal aspects for a trans-disciplinary approach of hydropower's role in an energy system with a higher share of intermittent[1] energy.

HydroBalance investigated the feasibility of large-scale balancing and energy storage from Norwegian hydropower in the future European energy system, with respect to the power system, economic viability, environmental aspects, social acceptance and regulatory framework.

While Norway has a large potential for improving and expanding the hydropower capabilities, for fast and slow reserves and energy storage and for balancing services, a coherent strategy for assessment of the consequences and eventually realization of this potential is currently not established.

The roadmap was elaborated by researchers from SINTEF Energy, NTNU and NINA involved in the HydroBalance project, with the support of user partners, namely Norwegian hydropower companies, Norwegian authorities, the Norwegian Transmission System Operator (TSO), and international universities and institutes. Several meetings were organised during the project, where user partners contributed to elaboration and improvement of the roadmap. However, the Key actions are suggested by the main research partners, and do not necessarily represent the view of all project partners.

[1] *Intermittent energy is energy that is not continuously available due to external factors that cannot be controlled. Sources of intermittent energy include solar power, wind power, tidal power, and wave power.*

1.2. Target groups and stakeholders

The primary target groups of the HydroBalance roadmap are Norwegian politicians, national authorities and agencies, namely Statnett (Norwegian Transmission System Operator), the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Environment Agency (Miljødirektoratet), and Energy Norway (organisation for the electricity industry in Norway).

Because the roadmap demonstrates the possible value creation from Norwegian hydropower, hydropower production companies are also considered a target group.

The roadmap is also directed at research funding organizations because it proposes avenues for future research projects.

1.3. Process

This roadmap is the final deliverable of the HydroBalance project studying the feasibility of large-scale balancing services from Norway to Europe. Early in the project, the researchers and user partners developed several scenarios for using the flexibility and storage potential from Norwegian hydro towards 2050 (Sauterleute et al. 2015). Each scenario was a combination of uncertain futures and strategies taken by Norwegian stakeholders. Strategies were a result of identified trends and influencing factors.

For the elaboration of this roadmap, we focused specifically on scenarios with ambitious development of the utilisation of the Norwegian hydro and pumped storage to provide balancing and storage to the future electricity market in 2050.

In these specific projections, the share of renewables in the European energy system is considered as medium to high, and conditions are in favour of large volumes of balancing between Norway and neighbouring countries. The scenarios encompass significant market integration allowing use of hydropower for balancing over various time horizons (e.g. in day-ahead, intraday and balancing energy). In addition, the scenarios assume expansion of the Norwegian hydropower capacity by 20 to 30 GW (including pumped storage) and a corresponding increase in grid transmission capacity between Norway and other Northern European countries.

All assumptions made to develop the projections of the potential future role of Norwegian hydropower by 2050 are based on trends and influencing factors identified at the time of the elaboration of the scenarios. Unpredictable events such as Fukushima or the Brexit cannot be incorporated in the vision of the future, while they would have a significant impact. Therefore, the scenarios which build the basis for the elaboration of the roadmap cannot be considered as predictions of the future European energy system. They draw a picture of how this future could be, and therefore they must be used as a tool for assisting policy makers and authorities in shaping the choices they make.

The strength of the research in HydroBalance is that we have not identified a single path for future hydropower development. Instead, we have developed methodology for a comprehensive analysis, progressing step-by-step from a qualitative scenario for the future energy system in Europe, to corresponding optimisation of hydropower generation, to profitability of specific hydropower investments, and finally, to evaluation of environmental impacts in specific hydropower reservoirs in Norway.

The HydroBalance roadmap focuses particularly on:

- The need for flexibility and storage
- Impacts on the European power system from connecting it with the flexible Norwegian hydropower
- Energy storage technologies competing with hydropower and comparison of costs for different flexibility options
- Economic benefits gained from connecting and operating common energy markets and calculation of revenues for hydropower producers utilising the flexibility of hydropower in several parallel markets
- Environmental consequences of current and future operational regimes in hydropower reservoirs
- Societal and regulatory challenges related to increased use of hydropower reservoirs at the local, regional and national levels

1.4. Structure of the roadmap

The roadmap is organised in 6 main sections. It starts with an introduction of the context of deployment of renewables and the role of hydropower as a facilitator for the integration of intermittent renewables.

It then describes the key findings based on research results, and continues with the list of key actions for stakeholders, followed by a list of prioritised research needs.

The last four sections are a review of results from research conducted in the different fields of the project, namely balancing needs, market and hydropower operation, environmental impact, and social and regulatory aspects.

2. Introduction

2.1. Background

The last report from the Intergovernmental Panel on Climate Change (IPCC) concluded that collective and significant global actions are required to meet climate targets and that full decarbonisation of the energy system is a prerequisite to cut greenhouse gas (GHG) emissions (IPCC, 2014). Europe has set ambitious targets to tackle climate change and to establish a new framework to guide the European society through the transition towards a low-carbon economy. Europe has set a target to cut emissions by at least 40% below 1990 levels by 2030 (European Council, 2014) and to boost the share of renewables to 27% of EU energy consumption by 2030. EU's long-term objective is to cut GHG emissions by 80–95% by 2050 (European Council, 2011). To achieve these ambitious targets, the complete elimination of GHG emissions from electricity generation by 2050 is a critical step.

In the meantime, electrification is a persisting trend and all sectors are involved: electrification of transport, shift towards electricity for heating and cooling, and increase of electric appliances in the residential and industrial sector. Improved energy efficiency slows slightly the growth of total energy consumption. Both core scenarios from the International Energy Agency (IEA) for electricity demand (New Policy Scenario and 450 scenario) show a significant rise by two-thirds of global electricity generation in 2040 relative to today to satisfy increasing demand (**Figure 1**).

The combination of EU's GHG targets and increase in electricity demand shall result in a higher share of electricity generation from intermittent sources such as solar and wind power. IEA's forecast indicates that the share of variable renewable energy (VRE) in electricity generation will reach 25% by 2022 in Ireland, Germany and the UK, while Denmark is expected to become the world leader with a 70% share of VRE (**Figure 2**). As intermittent sources can only generate electricity depending on weather conditions and not as a function of the electricity demand, the power system will have to balance higher generation from intermittent sources with electricity production from other sources. Hence, the rise of the share of intermittent sources in the electricity production requires more flexibility from the power system.

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Consequently, the power system needs to be re-organised and operated differently in the future to insure energy supply and reliability. The Clean Energy Package (also called Winter Package)

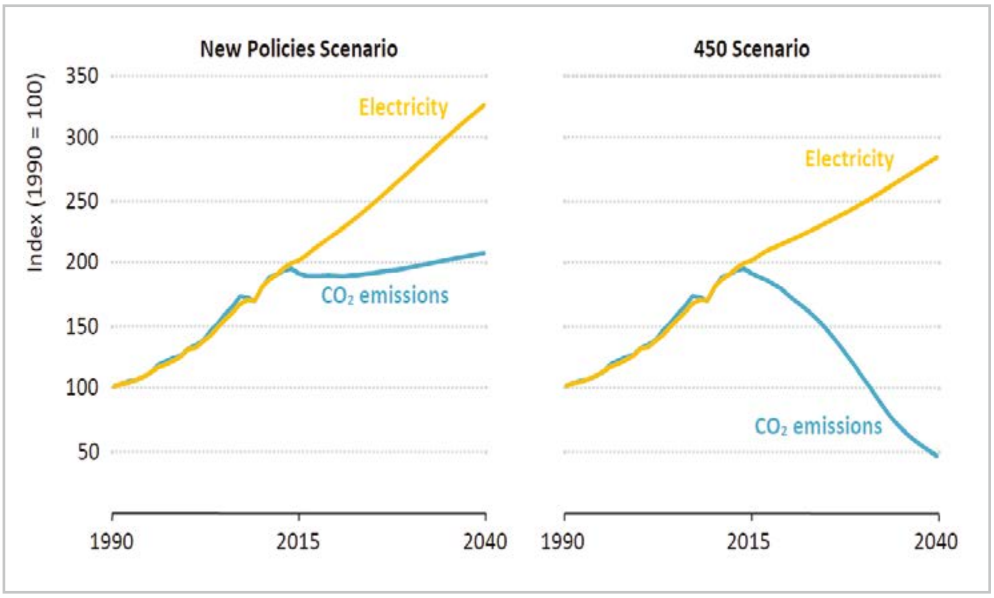

Figure 1. Expected growth in global electricity generation and related CO_2 emissions in two IEA scenarios. Figure is extracted from IEA (2016).

With its large number of hydropower reservoirs and an installed hydropower capacity of about 30 GW, Norway has the largest storage capacity in Europe. Photo: Statkraft

presented by the European Commission in November 2016 includes measures with regards to energy efficiency, renewables, energy access, and electricity market (European Commission, 2016a). Here, the EU Commission pointed out several actions to meet the demand of flexibility.

One major strategy to increase system flexibility is to increase the cross-border transmission capacity. In 2014, the European Council EU required all member states to achieve interconnection of at least 10% of their installed capacity by 2020, possibly 15% by 2030 (European Commission , 2015a). The interconnection of national electricity grids of EU countries allows electricity trade across borders and thus export from surplus energy areas to deficit energy areas. As a result, occurrence of black-outs decreases at national level, isolated areas and countries can rely on neighbouring electricity systems for security supply, and integration of high levels of intermittent renewables is facilitated. In addition, interconnection is the key factor to achieve an integrated EU energy market as defined in the Energy Union. For Norway, the interconnection wil be insured via construction of additional interconnectors to Northern Europe.

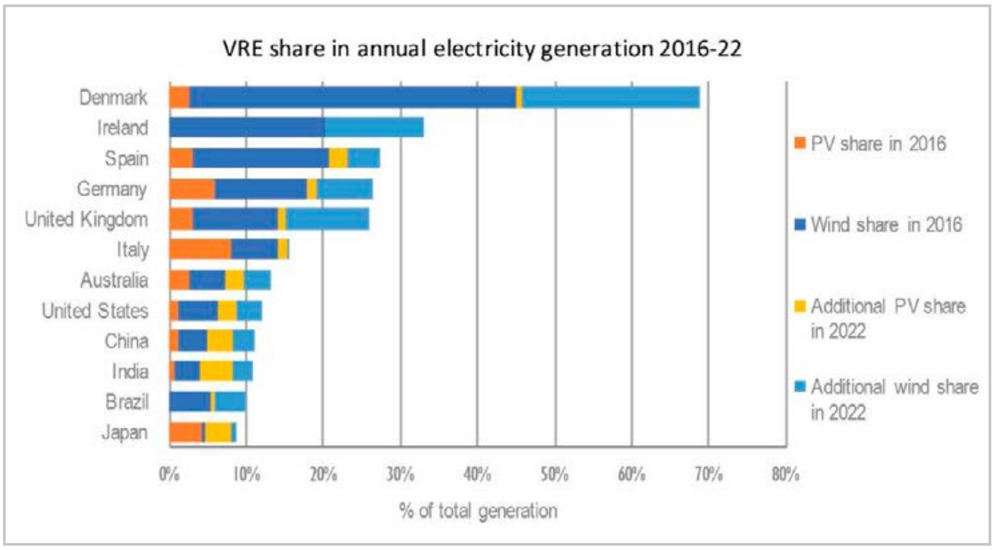

Figure 2. Variable renewable energy (VRE) share in electricity generation 2016-2022. Figure is extracted from IEA (2017).

Norwegian hydro reservoirs have 90 TWh of storage capacity and can use parts of this for balancing European renewable energy.
Photo: Atle Harby, SINTEF

In addition to more interconnected power systems, new market design, new national and European policies and incentives, as well an updated regulatory framework for new forms of energy production will play a key role for increase of system flexibility by ensuring the integration of variable renewables in a secure and cost-effective way. The new market should encourage both consumers and generators to increase their flexibility; the former should adjust their electricity consumption to real time prices, whereas the latter should make their production as predictable as possible (European Commission, 2015b).

Increased cross-border transmission capacity will facilitate the integration of intermittent renewables.

Increase of cross-border transmission capacity and re-design of new electricity markets and policies must be accompanied by deployment of energy storage. Storage offers the possibility to store electricity when there is a surplus of production and electricity prices are low and release it later when demand and prices are high. Therefore, electricity storage is a major component of balancing services as it provides flexibility indispensable to balance generation from solar and wind. Storage is expected to play a major role in integration of renewables in the European energy system and has been on the political agenda in many European countries.

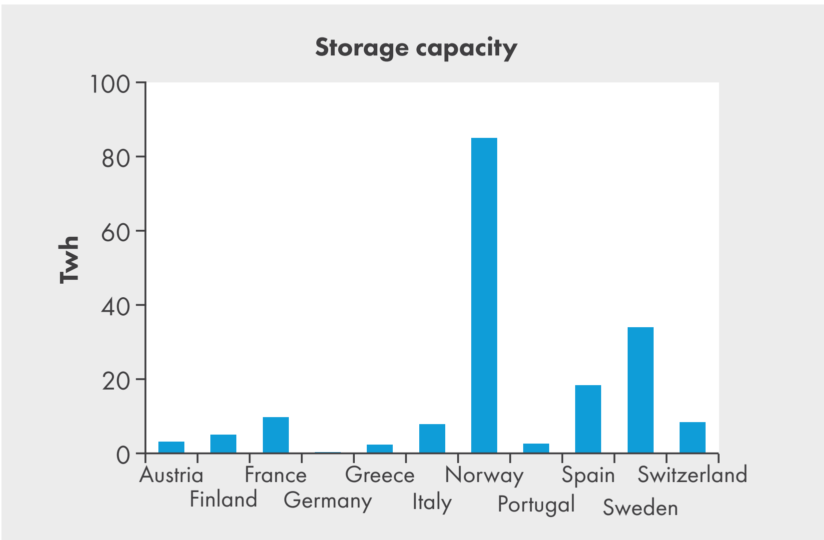

Figure 3. Maximum storage capacity in Europe. Data source Lehner et al. (2005).

In 2010, Germany passed the Energy transition policy (Energiewende) for an integrated approach of climate and energy policy. It was the first document defining storage as a pillar of integration of variable renewable energy. The considerable and cost-effective Norwegian pumped-storage potential is considered as a major option for balancing variable renewable energy production in Northern Europe (German Advisory Council on Environment, 2011). At both European and global scale, hydro storage is the most mature technology, and it represents 99% of the energy storage capacity. In Europe, Norwegian hydropower reservoirs account for 50% of this capacity (Lehner et al. 2005).

The Norwegian hydropower system remains a major option for balancing variable renewable energy production in Northern Europe according to German Advisory Council on Environment (2011).

In Norway, in the last decades the Research Council of Norway (RCN) has established dedicated research programs to investigate the feasibility and consequences of balancing the European energy system with Norwegian hydropower, both from the technological and economic point of view. Energi21 is the Norwegian national strategy for research, development, demonstration and commercialisation of new energy technology. The recent update of this strategy highlights the role of integrated energy systems, including interconnectors with EU (Energi21, 2018). The Large-Scale Power Exchange project is one of the first projects, which also focused on hydropower capabilities for flexibility from existing Norwegian hydropower (Holen, 1997, Belsnes, 1999). In 2012, SINTEF investigated the potential for large-scale balancing and energy storage for Europe (HydroBalance I, Funding was provided by the Research Council of Norway). This project concluded that Norway's hydropower capacity could be increased by 20 GW via upgrading existing hydropower plants and construction of new pumped-storage plants between existing reservoirs, following current regulation and concession requirements (Killingtveit 2017, Harby et al 2013, Killingtveit 2012, Solvang et al. 2012). However, the previous research projects did not include aspects like the political feasibility or environmental and societal consequences.

While water resources are important to produce climate-neutral energy, catchments also provide other essential ecosystem services such as irrigation, drinking water, biodiversity and recreation. Hence, even if Norwegian hydropower potentially may contribute to reduced CO_2 emissions in Europe, this must be balanced with the potential negative impacts on local environment, local communities and other business sectors. Loss of habitat and habitat degradation are regarded as major threats to biodiversity worldwide, and the recent report from IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) state that loss of biodiversity is as large a threat to humanity as climate change (IPBES, 2018). All energy production, including renewable energy, have some impact on nature. Consequently, using the Norwegian hydropower system for balancing the electricity demand involves trade-offs between the need for climate-neutral energy and the need to preserve landscapes and biodiversity.

Implementation of the European Water Framework Directive (WFD), the Norwegian Nature Diversity Act and other new regulatory requirements exert pressure on the Norwegian hydropower industry by establishing targets for environmental conditions in regulated watersheds, potentially at the cost of power production. For an example, it has been roughly estimated that revisions of hydropower licenses in Norway alone can cause an annual loss of 2–4 TWh hydropower production, to fulfil today's environmental objectives (sørensen et al. 2013). The main purpose of the revisions is to improve the environmental conditions in regulated waterbodies. Before 2020, up to 430 hydropower licences can be opened for such revisions. Simultaneously, the question of how to reach the environmental targets in waterbodies affected by hydropower is given much attention in the process of implementing the European WFD in Norway (Ruud and Aas 2017). The present river basin management plans (for the period 2016–2021) was approved by The Ministries in Norway in 2016 and contain several waterbodies with environmental targets that are expected to cause reduction in the hydropower production.

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If the challenges and uncertainties of the future hydropower production, such as new market possibilities and need for upgrades and expansions, are not evaluated against environmental concerns, the ongoing environmental processes like implementation of WFD and revisions of licenses may give undesired restrictions on the future hydropower production in Norway. It is likely that large scale balancing will result in more frequent fluctuations of water in regulated lakes (Killingtveit 2017, Solvang et al. 2014, Harby et al 2013). Today, most Norwegian hydropower producers do not have restrictions on how rapidly water discharge can be changed in rivers, or regulations that consider frequency and rate of change of water level fluctuations in reservoirs. Hence, present day environmental regulations of hydropower operations are not suited for balancing services. Ideally, the ongoing period of implementation of new environmental regulations should be considered as a window of opportunity, which can enhance environmental conditions in waterbodies and simultaneously prepare the hydropower industry for the future markets through cross-sectoral corporation and the use of environmental design methodology.

Through development of environmental design of hydropower Norway has illustrated that it is possible to find knowledge-based solutions that optimise the trade-offs between hydropower production and other socio-economic benefits.

Through development of environmental design of hydropower (Forseth and Harby 2014), Norway has illustrated that it is possible to find knowledge-based solutions that optimise the trade-offs between hydropower production and other socio-economic benefits. By continuing to balance environmental, technological, economic and societal needs, one can increase the potential for Norwegian hydropower industry to meet tomorrow's national and international market potentials and environmental legislations.

2.2 Norway as a provider of large-scale balancing power: What does it mean?

The overall idea of "balancing" is that there must always be a balance between production and consumption, and thus the power system needs some flexible, controllable options such as hydropower to deal with e.g. wind and solar power variability. Water in a reservoir represents a storage of potential energy[2] that can be converted to electric energy with very high efficiency. Thus, when the wind and photovoltaic (PV) plants do not produce sufficiently to cover the power consumption (also called load), hydropower plants can increase their production to balance the load. When wind and solar[3] power plants produce more than the load, the hydropower plants can decrease their production to obtain balance. If pumped storage is installed and pumping capacity is available, the surplus from wind and solar power plants can be used to pump water to reservoirs at higher altitudes. This extra water can then be used to produce extra power in periods with low wind and solar power production.

With its large potential for electricity storage from hydropower reservoirs, Norway can act as a battery for the European power system, also called "Green Battery". It requires a different operation of the reservoirs to respond to changes in electricity generation from wind and solar and thus being able to balance electricity demand in the European market. Nevertheless, offering balancing power services to Europe demands expansion and reinforcement of the transmission grid via construction of additional interconnectors to Northern Europe as mentioned in the previous section (Statnett 2014).

Timescale aspects

Balancing wind and solar power generation requires that power units can respond to changes in electricity production ranging from short- (seconds) to long-term variations (weeks). Alternative technologies like electrochemical batteries, flywheels, or compressed air, can handle short-term fluctuations of the power system by delivering high power rating (1–1000 MW) during short and medium periods (from minutes to days). While hydropower can balance short-term fluctuations too, it also has the advantage of being able to store large amounts of water and generate electricity over medium and long periods (from days to weeks). These characteristics allow hydropower to balance long-term fluctuations of wind

[2] *Potential energy: energy of a body or a system with respect to its position*

[3] *In the Roadmap, solar power plants refer to photovoltaic power plants (PV plants), and not concentrating solar power (CSP) plants*

Wind and solar energy production vary with the weather conditions. Alternative production and storage must supply the load in periods with low production from the renewable resources.
Photo: Emelysjosasen: CC-BY-SA-4.0

and solar power by generating electricity during cloudy and windless periods. With its large number of hydropower reservoirs and an installed hydropower capacity of about 30 GW, Norway has the largest storage capacity in Europe. In total 85 TWh can be stored in Norwegian reservoirs, accounting for approximately 50% of the total European storage capacity (Table 1). Norway has the potential to provide significant parts of the flexibility in a timescale from hours to months (Killingtveit 2017, Killingtveit 2012, Solvang et al. 2012), which is a prerequisite for the integration of variable renewable energy in Europe.

Table 1. Main characteristics of the Norwegian hydropower system per 2010.

Installed capacity	30 GW
Average annual generation	123.5 TWh
Share of total electricity generation	99.4 %
Storage capacity	85 TWh
Number of hydropower plants > 50 MW	143
Average annual generation from hydropower plants > 50 MW	95 TWh

Market aspects

In electricity market terminology, "balancing power" is a narrow concept referring to real-time markets for maintaining the electricity balance. However, as described later in this roadmap (Chapter 6.2), the utilisation of Norwegian hydropower for large-scale balancing of the power system is not limited to balancing markets only, but it includes balancing and energy storage at all time scales.

Environmental aspects

Large-scale balancing and storage from Norwegian hydropower in the European power system might have different environmental consequences than what we see from today's hydropower production. The reservoirs will likely experience more frequent emptying and filling, which may lead to both short- and long-term impacts on ecosystems in affected reservoirs, as well as in downstream rivers (Killingtveit 2017, Solvang et al. 2014, Harby et al. 2013). If pumps are installed to move water from downstream to upstream reservoirs, this mixing of water may cause large modifications to upstream reservoirs. Furthermore, upgrading the Norwegian hydropower system for exchange of large-scale balancing might not only modify watercourses, but also involve installations of new tunnels, roads, off-shore cables, power lines etc., which will affect biodiversity and ecosystem services delivered by landscapes.

3. Main key findings

This chapter summarises the research results from HydroBalance. The key findings constitute the background for the key actions described in the following chapter. Further details on key findings can be found in the corresponding subsections of chapter 6.

Energy balancing and storage needs

- The future power production in Northern Europe, with large shares of intermittent production from wind and solar power, will result in periods with very low production when there is hardly any wind or sun. Our simulations show that there will be periods where only 2% of the total installed wind and PV power plants are producing. Furthermore, we identified winter periods of 90 to 120 consecutive hours with very low wind and solar power production. In such periods, it will be challenging to supply the demand without increasing storage capacity in the system, since most of the thermal power plants are expected to be decommissioned due to low average power prices and high CO_2 emission prices in the future.
- By 2050, the need for storage in West-Central Europe will be up to 23 TWh/month and the hourly balancing need about 200-300 GW, according to our calculations.
- Extended and reinforced transmission grids in the EU will smooth out some of the variability from wind and solar power production by allowing transfer of power from areas with surplus of production to areas with deficit of production. However, it will not solve the main variability challenges, such as periods with very low wind and solar power production.
- Small scale batteries currently available, like home batteries, smooth out power variability for only a few hours due to limited storage capacity (Tesla home battery is 10 kWh).
- Simulations of the future European power system indicate that an increase in the Norwegian hydropower capacity by 11–19 GW may significantly decrease peak and average prices in neighbouring countries like the Netherlands, Germany and the UK. The average price reductions in these neighbouring countries were at least 8% in our simulated scenarios.
- We simulated the future European power system with large shares of production from wind and solar plants and increased the capacity of existing Norwegian hydropower plants from about 30 GW in the present system to 41 and 49 GW in alternative scenarios. We found that capacity upgrading of Norwegian hydropower plants for large-scale balancing and energy storage should be realised only for carefully identified plants, since only some of them are able to fully utilise their increased capacity. This is mainly due to local limitations in the watercourse, such as the size of the regulated water volume in reservoirs.

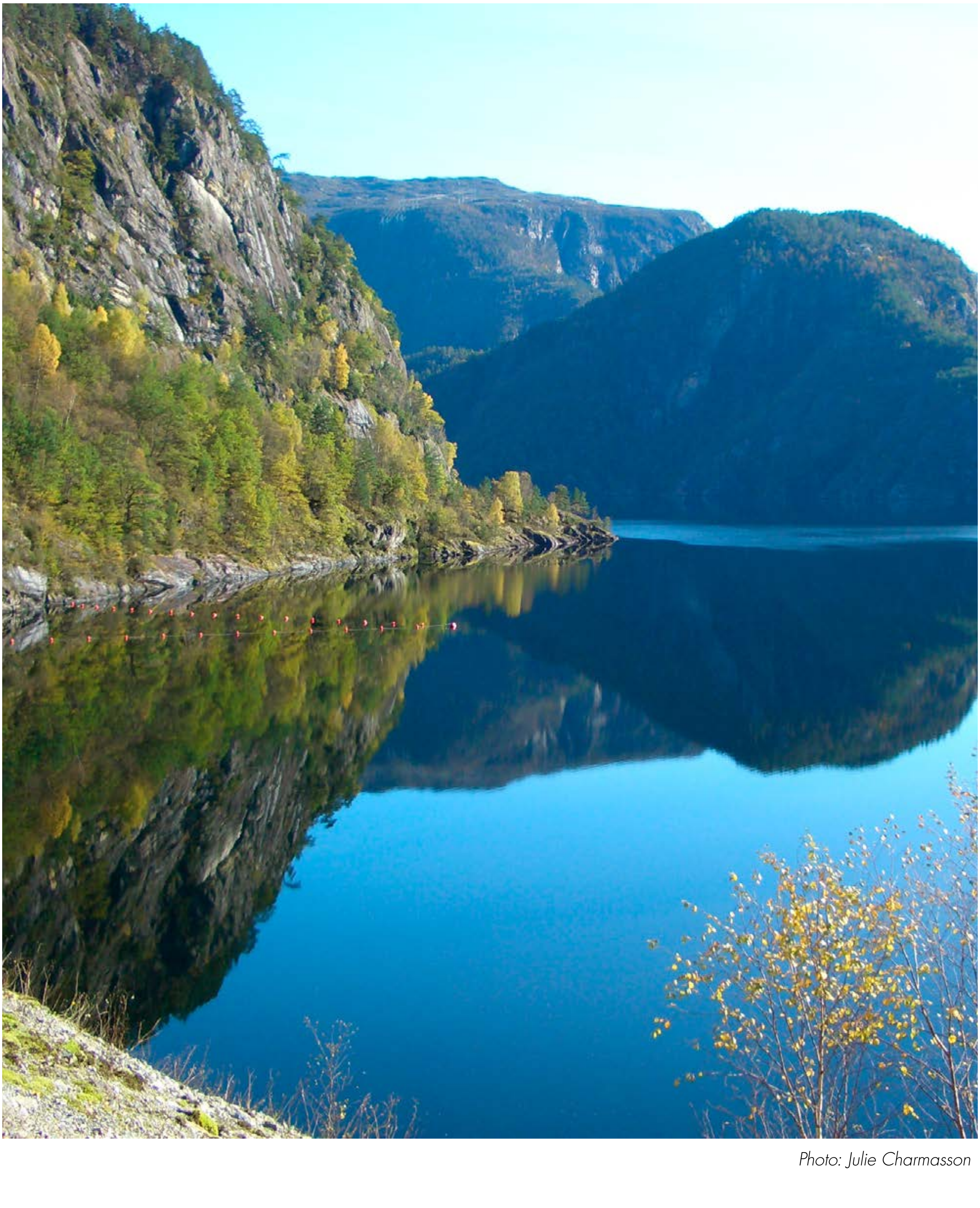


Photo: Julie Charmasson

Hydropower operation in the future European market

- If additional interconnectors (cables) are installed between Norway and other European countries, hydropower producers can achieve a considerable extra income by supplying within-day markets and real-time balancing markets i*n addition to the day-ahead market*. In a case study of a real Norwegian river system with a potential pumped-storage plant, the total income was increased by 22% if the producer participates in all market types. The profitability of a pumped-storage investment increases by a factor of 6 if the producer participates in all market types.
- Investments in extra capacity for Norwegian hydropower (including pumped storage) and corresponding transmission capacity would be cost-effective for the European power system, and there are several types of benefits. Additional hydropower capacity would also make it possible to reduce the amount of expensive peak thermal generation and allow cost reduction due to fewer start-stops in thermal power generation.
- Norwegian pumped storage is more cost-effective than gas power plants located in Europe when it comes to provisioning flexible capacity (i.e. capacity when it is needed due to low wind and solar power generation. This is also when considering the installation costs of new transmission cables between Northern Europe and Norway to increase transmission capacity.
- There will be more frequent and more rapid water level fluctuations in reservoirs than today if extra generation capacity and corresponding pumps are installed and hydropower is optimised towards future European power prices that are more volatile than historical prices in Norway (NB: water level fluctuations in rivers have not been studied under the research carried out in HydroBalance).
- Traditionally, the market rules and definitions of specific products for the provision of ancillary services have differed between European countries. Currently, the EU aims at harmonising all electricity market types, leading to an increase of cross-border trade and cost-effectiveness of the total European power system. ACER (the EU's regulators, such as NVE) and ENTSO-E (the EU's system operators, such as Statnett) which were established through the EU's third energy package, are important for developing a corresponding EU regulation for electricity markets. Regulation includes directives within the European Economic Area (EEA) relevant for different market types, including day-ahead market and intraday, as well as cooperation between system operations and balancing market products. From a formal point of view, most countries in Europe are already included in a common day-ahead market. Prices are still different at different locations due to transmission capacity limitations.

Environmental impacts of new operational regimes in reservoirs

- Combining models of market optimisation and models of hydrological changes in reservoirs is a necessary step to predict environmental effects of future hydropower operations (i.e. water level regulation patterns).
- The mechanisms behind how hydropower operations influence reservoir ecosystems are much less understood than the effects on river ecosystems.
- Environmental impacts of hydropower operations are complex and case-specific, depending e.g. on the reservoir morphometry and fish community composition.
- When evaluating the impacts of hydropower on reservoir fish, the responses at individual and population levels may differ. For example, while the fish population density may increase with increasing frequency of water level fluctuations, the condition of individuals may decrease.
- Potential development of a more flexible hydropower system should target reservoirs that are resistant to rapid water level fluctuations and have low social value, leading to limited ecological and social impacts.

Societal acceptance and regulatory framework

- Infrastructure development and the EU Commission's proposal for a broader interconnector strategy support national opportunities for cross-border transmission.
- A major barrier is currently the need for comprehensive political strategies and necessary governance measures to realise increased large-scale balancing and storage from Norwegian hydropower. Local authorities are primarily concerned about local benefits and environmental impacts, more than hydropower's role in the context of transition towards a low-carbon society. Existing regulations and tax systems do not take into account the possibility of prioritising balancing services.
- It is important to initiate a broad dialogue-process between authorities, companies and stakeholders at the local level, with the aim of formulating political commitments to hydropower development accounting for all main societal interests.
- Local communities should be better involved in new governance approaches that to a greater extent share the costs and benefits of increased balancing and energy storage from Norwegian hydropower between international, national and local communities.
- To secure public support and legitimacy, local community benefits should be specified beyond financial compensation, and national benefits should be clearly identified and emphasised.
- Early and sufficient involvement of local stakeholders during the planning and licensing processes of hydropower projects is a prerequisite for improved social acceptance.

4. Main key actions before 2050

Key findings are scientific results from HydroBalance. **Key actions are our recommendations for *how* Norway can become a large-scale supplier of balancing services, based both on our research results and expert knowledge. Hence, we do not evaluate if or to which degree Norway *should* deliver such services.**

The following key actions are targeted for specific stakeholders.

National policy makers should:

- Establish an expert board covering technological, economic, environmental and social sciences, with the mission to give holistic and science-based advice to the policy makers on how to best develop Norwegian hydropower, including national and international transmission lines and interconnectors.
- Develop plans and strategies for Norwegian hydropower in the common integrated European electricity market addressing political, economic, environmental, societal and technological aspects.
- Develop a benefit sharing scheme between industry, consumers, producers, host communities, DSOs[4] and TSO[5] for income from Norwegian flexibility and balancing services to other countries.
- Make it possible for services from Norwegian hydropower to take part in foreign capacity markets through bilateral negotiations at EU level.
- Specify policy efforts that must be made to realize new interconnectors from Norway.
- Implement a new regulatory framework for hydropower production with updated restrictions (environmental, economic, and operational) that are adapted to flexible services in future markets.
- Design markets, tax rules, and other regulations in such a way that the value of providing flexibility in all parts of the power system gives a corresponding incentive for investors.

Statnett (Norwegian TSO) should:

- Make and periodically update a concrete rolling plan for how the next cables from Norway shall be realized.
- Coordinate plans with neighbouring countries to make sure that their national grid capacity for the exchange of Norwegian balancing power is sufficient before new interconnectors are built.
- Agree with neighbouring countries about sharing of investments, profits, and risks of new interconnectors.
- Ensure that new domestic and international transmission cables are constructed with minimal impact on landscape and biodiversity, i.e. utilise state of the art knowledge on optimal design and routing of power lines.

[4] *Distribution System Operator*
[5] *Transmission System Operator*

National authorities (OED and NVE[6]) should:

- Develop a coherent and comprehensive planning framework concerning the potential for balancing services related to grid development. Such a framework is currently not in place, but it could make balancing services more feasible.
- Create an overall plan for how to identify which hydropower plants that are the most suitable targets for balancing services, and which that are unsuitable due to hydro-physical characteristics and environmental and/or socio-economic considerations. This plan should not be limited to hydropower and waterways, but also consider landscape effects from construction of new tunnels, roads, off-shore cables, power lines etc.
- Integrate the concept of environmental design of hydropower in the ongoing processes of licence revisions and implementation of the water framework directive to find win-win solutions for stakeholders. Environmental design methodology can reduce social conflicts and avoid that environmental concerns prevent the expected future growth of the Norwegian hydropower industry.
- Develop environmental regulations of hydropower operations that are adapted to future markets with balancing services, such as restrictions on how rapidly water levels may fluctuate in rivers and reservoirs. Since the actual market value of flexible hydropower production will depend on future restrictions, it will not be possible to realise the ambitions of increased flexibility without modernising the environmental restrictions in parallel to the modernisation of the hydropower system.
- Specify how to balance national trade-offs between the value of increased exchange of balancing power from hydropower and other socio-economic considerations, such as protection of local biodiversity and landscapes.
- Initiate a broad dialogue process, including politicians, authorities, and public and private stakeholders, with the aim of formulating common goals that encompass and balance different societal interests and concerns related to further hydropower development or new operating regimes.

Hydropower producers should:

- Make a strategy to increase the ability to provide balancing services.
- Replace fish stockings with habitat improvements and water level regulation patterns that facilitate natural recruitment and improved ecological status of the reservoirs, following the idea of environmental design for hydropower.
- Create bathymetric maps and record spatial and temporal water temperature variations in a variety of reservoirs, to facilitate predictions of water level regulation impacts under future operational regimes.
- During the planning process, specify how community benefits and costs are allocated. Community acceptance may increase if local groups are given the opportunity to provide direct input during the planning and construction phase.

[6] *OED Ministry of Petroleum and Energy. NVE The Norwegian Water Resources and Energy Directorate*

5. Research needs

Research needs have been identified through the work conducted in the project. They are classified by topic.

Balancing needs and hydropower operation

There is a need to:

- Develop power system models for advanced hydropower optimisation that can handle changes in power markets such as increasing importance of markets for flexibility, change of consumer's role, integration of variable renewable production, etc. More specifically, power system optimisation models must include other types of storages than hydropower reservoirs, modelling of several interconnected subsequent markets (day-ahead, intraday, and balancing services), improved modelling of flexibility demand, and new methods for water and capacity value calculation considering short-term variation. There is also a need to improve the modelling of variable residual load in the future European system by extending the weather prediction model COSMO EU to a longer time horizon and a larger geographical area, and to include electrification of transport and heating into variable residual load models.
- Evaluate the needs for expansion and reinforcement of cross-border transmission considering the power prices in different markets such as; day-ahead, intraday, procurement and activation of reserves. It is furthermore necessary to evaluate the needs for internal grid capacity serving cross-border lines and internal market access. Studies should include socio-economic benefits and distribution of costs, benefits and risks between stakeholders (nations, producers, consumers, TSOs).
- Carry out investment profitability analysis for a large range of case studies to evaluate the costs and benefits of expanding Norwegian hydropower generation capacity, including pumped storage. The studies should be linked to analyses of environmental impacts.

Environmental impacts

There is a need to:

- Expand the concept of "Environmental design in regulated rivers" to hydropower reservoirs. A first goal should be to develop a handbook for "Environmental design for brown trout in hydropower reservoirs", as several ecological bottlenecks, such as lack of access to spawning habitats, are already known for this species. However, neither the diagnostic tools nor the design solutions are yet developed for brown trout in reservoirs.
- Develop metrics that incorporate relevant patterns of the water level fluctuations (i.e. amplitude, timing, frequency and rate of water level change) and reflect the environmental impacts on reservoir ecosystems.
- Expand the developed method of linking market optimisation of the hydropower operation to hydrological changes to additional case studies in order to evaluate future environmental effects in a variety of reservoirs.

Photo: Atle Harby

Social acceptance and regulatory framework

There is a need to:

- Develop a systematic approach for conflict management that integrate mitigation measures to improve current practices. The Potential for Conflict Index is a suitable tool to map social acceptance in two hydropower development cases, one with and the other without early involvement of stakeholders.
- Study how to better implement the main concerns from local communities into national and international policy.

6. Project results

The present section presents results from research carried out in the project. Results developed here constitute the basis for Key Findings and Key Actions.

The section is organised in four sub-sections corresponding to the different fields of the project, namely (1) balancing needs, (2) market and hydropower operation, (3) environmental aspects, and (4) social and regulatory aspects.

6.1. Balancing of wind and solar power

6.1.1. The need for balancing and storage

The future European power system will probably include large shares of power production from wind and solar resources. In 2050, wind and solar resources may supply the main share of the annual European demand. Wind and solar resources are variable. In winter, there is limited solar radiation (particularly in Northern and Central Europe), and periods with very little wind. In the present power system, thermal production supplies the load in periods with low wind and solar power production. In 2050, it is likely that most thermal production is decommissioned since its profitability is expected to decrease due to low average power prices and high CO_2 emission prices in the future. Consequently, it may be challenging to supply the load during long periods with low production from wind and solar plants.

HydroBalance studied the variability of wind and solar power production in West-Central Europe in 2050, based on assumptions on installed wind and solar power capacities from the EU 7th Framework project eHighway2050 (www.e-highway2050.eu). Analysed countries are the United Kingdom, Ireland, France, the Benelux countries, Western Denmark, Germany, Switzerland, Austria, the Czech Republic and Slovenia. The wind and solar generation are simulated from the weather prediction model COSMO-EU (**Figure 4**). This model has a spatial resolution of 7 x 7 km for Europe and a temporal resolution of one hour. We studied the hourly variability of the wind and solar power production based on wind speed and radiation for the years 2011-2015 (Graabak et al. 2016a, 2016b). In the analyses, we assumed there were no transmission limitations nationally or between the countries. The installed wind capacity is 494 GW, and the PV capacity is 358 GW, being in total 852 GW.

The calculations of wind and solar power production showed a very volatile production with a high hourly variability for the studied period. During the hours with lowest production from the wind and solar plants, only about 2% (17 of 852 GW) of the installed capacity was producing. During the hours with the highest production, about 65% of the installed capacity was producing. In the winter, there were consecutive periods of up to 125 hours with low production from the wind and solar plants, where most of the load had to be supplied by other types of production or storage.

To estimate the future need for storage, we calculated the hourly net load in 2050. The net load is equal to the total load minus the wind and solar power production. We assumed that the calculated mean net load for each month is supplied by baseload production, e.g. nuclear. Finally, we assumed that every hour large-scale storage (e.g. pumped storage) supplies the deviation between the mean net load and the net load. The calculations showed a need for storage in West-Central Europe of about 23 TWh/month and an hourly balancing need of about 200-300 GW by 2050 (Graabak et al. 2017). Norway has hydropower reservoirs that can store 85 TWh of energy. The Norwegian storage possibilities could be sufficient for balancing the future West-Central European power production dominated by wind and solar resources.

The calculations showed a need for storage in West-Central Europe of about 23 TWh/month and an hourly balancing need of about 200-300 GW by 2050.

Photo: Julie Charmasson

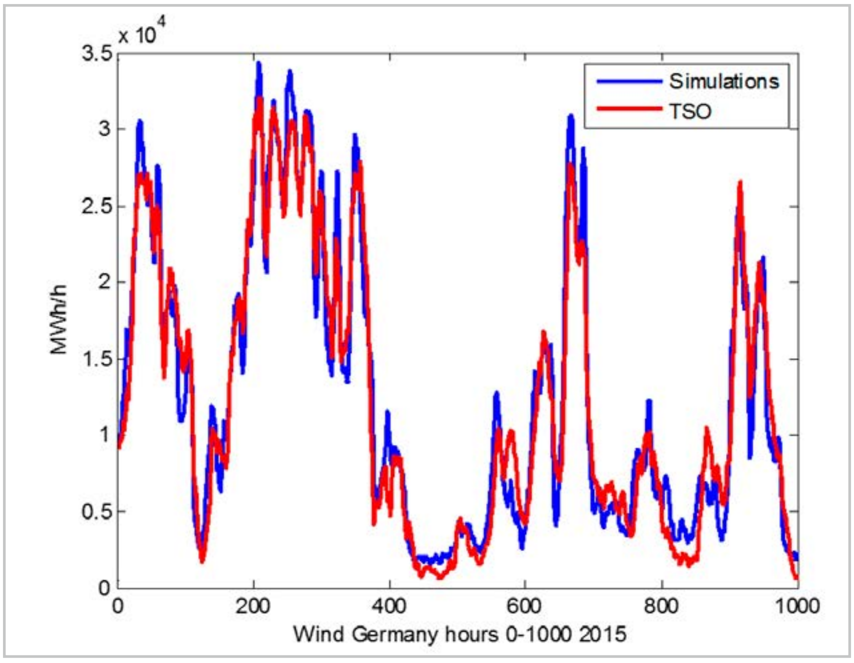


Figure 4. Figure shows validation for the German wind power production in 2015. The blue curve is our simulations of the wind power production based on the wind resources from the COSMO-EU model and information about installed wind power production capacities and their geographical locations from the wind power database (the.windpower. net). The red curve is the real wind power production quantified by the Transmission System Operators (TSO) in Germany.

6.1.2. Simulating how to balance future European wind and solar production

This section presents simulation results of a 2050 case where balancing of variable wind and solar power production in Europe is done with Norwegian hydropower. Assumptions about the future European power system are taken from the eHighway2050 project. We used a 100% Renewable Energy Sources (RES) scenario assuming high shares of generation from wind, solar, biomass and hydro, high CO_2 prices and a large increase in transmission capacities. As simulations showed that the 100% RES scenario was unstable and presented many periods where the load was not supplied (rationing of demand), we added nuclear power (based on another eHighway2050 scenario) to the power system to make it more stable and realistic.

Previous work has pointed out the possibility of expanding the current Norwegian hydropower capacity (by 30 GW in total) by upgrading current installations and installing new pumped storage by 11 GW and 8 GW, respectively (Killingtveit 2017, Harby et al. 2013, Killingtveit 2012, Solvang et al. 2012). We used this study as a framework for our analysis and simulated the Norwegian hydropower system with respectively 30, 41 and 49 GW capacity. Historical inflow data from the previous 75 years were used as input to the hydropower system. Wind and solar data were extracted from the NCEP/NCAR Reanalysis weather data from the NOAA Earth System Research Laboratory (Kalnay E. et al. 1996). Reanalysis data were available for the whole of Europe from 1958. Simulations were carried out with two different power optimisations and simulation dispatch models, namely the EMPS model and the SOVN model, and then results were compared. The models use different approaches for optimising the balance between production and consumption in power markets. The EMPS is a model used for decades in long-term analyses of the Nordic power market. SOVN is a new model developed to account for hydropower constraints, e.g unpredictable fluctuations in unregulated generation. Both models used the same input data with high spatial resolution for the Nordic countries, UK and Germany, and aggregated representation for other European countries. We simulated different cases of the 100% RES scenario and set up different case-studies: with and without flexibility in demand, different levels of demand in Norway, different prices for "demand-not-supplied" (curtailment of demand), and additional capacity in terms of non-flexible nuclear or flexible gas.

Firstly, our simulations indicate that an increase in the hydropower capacity in South-Western Norway may significantly reduce power prices in adjacent regions like the Netherlands, UK and Germany

Firstly, our simulations indicate that an increase in the hydropower capacity in South-Western Norway may significantly reduce power prices in adjacent regions like the Netherlands, UK and Germany (Figure 5). All simulations show a decrease in power prices, but the range of the price reduction depends on the case study. Among all simulations, the smallest price reduction corresponded to a 8% decrease for future power prices. The input assumptions (defining the different case-studies) strongly influence simulation results and hence influence simulated power prices. The rationing of power demand (characterised by very high power prices in the model to represent the costs for not supplying the demand) is identified as an important driver for power price results. In our simulations, rationing power prices were set to 10 000 Euro/MWh (assumption from eHighway2050 project). Results show that in the beginning of the year (winter), there are periods with rationing of demand due to low wind and solar power production and consequently high average prices. In the simulations, the Netherlands were connected to South-Western Norway with high transmission capacities. Due to the large transmission capacities, periods with rationing of demand in one region will result in rationing prices in many regions during that period.

Secondly, the simulations show that the hydropower production pattern changes significantly with increasing capacity (Figure 6). The larger the extra-capacity gets, the higher the power production will be. In average, power production is increasing all year around, while being slightly lower in winter. Our simulations of hourly data (averaged across 75 years) indicate that hydropower production generally increases when power prices are high (Figure 5 versus **Figure 6**). Pumping results are in average more intense in spring and mid-summer when prices are low due to snow melt or high power production from wind and solar.

Finally, in-depth studies show that increased hydropower capacities are only partly utilised during the year. While hydropower plants connected to large reservoirs upstream and downstream often will be able to utilise the new installed capacity, river systems with small reservoirs and lower flexibility will not benefit from extra capacity to the same extent. Here hydropower capacity was expanded as suggested in (Solvang et al. 2012) , a study that did not fully include hydropower constraints.

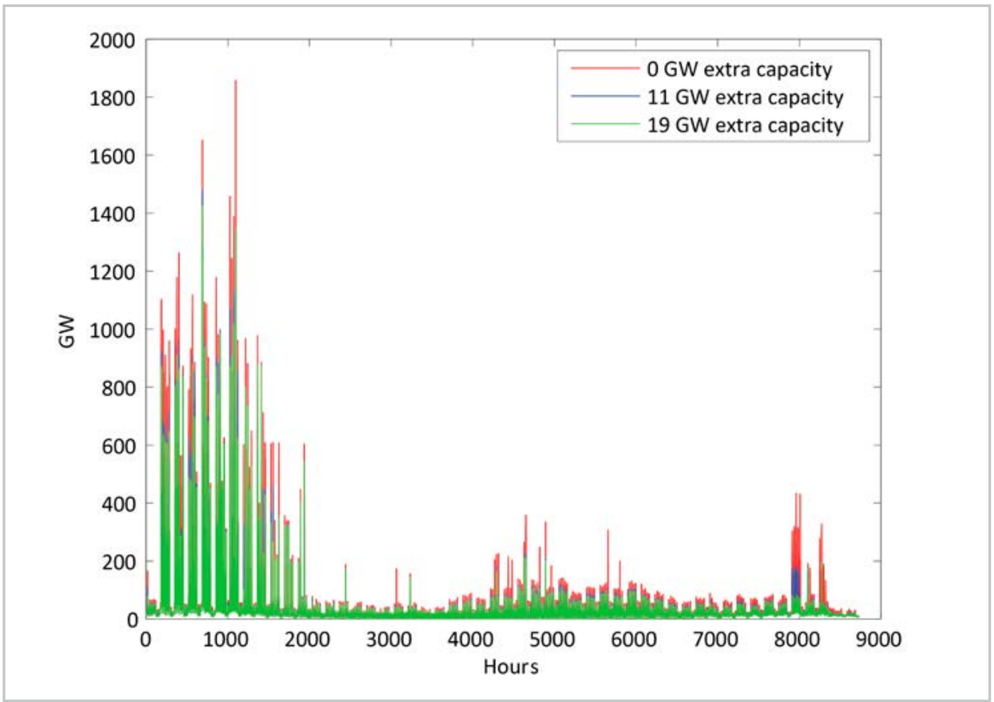


Figure 5. Simulated power prices in Southern Norway for the present Norwegian hydropower capacity (red), for 11 GW additional hydropower capacity (blue), and for 19 GW additional hydropower capacity (green) in the 100% RES eHighway2050 scenario. Simulations are carried out with the optimisation model SOVN with an hourly time interval and results are averaged over 75 years.

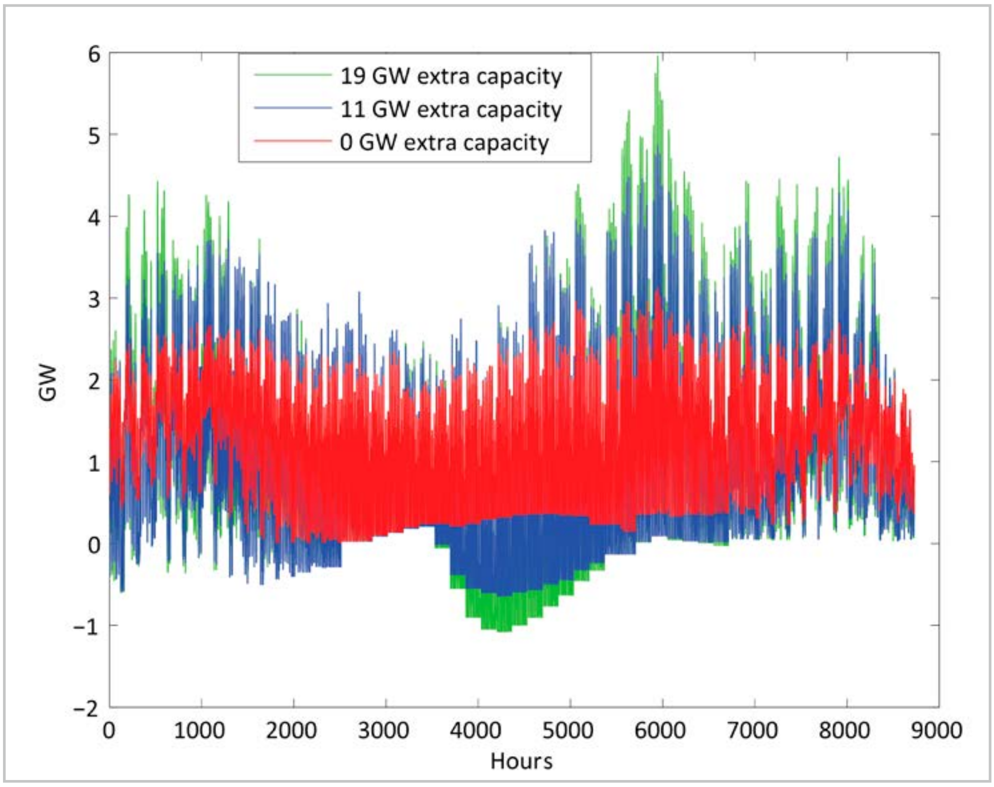


Figure 6. Simulated power production over one year in Southern Norway for the present Norwegian hydropower capacity (red), for 11 GW additional hydropower capacity (blue), and for 19 GW additional hydropower capacity (green) in the 100% eHighway2050 scenario. Simulations are carried out with the optimisation model SOVN with an hourly time interval and results are averaged over 75 years.

Photo: Espen Lie Dahl

For most of the involved areas, the volume of water stored in reservoirs (and thus the amount of energy storage) increases with hydropower capacity (**Figure 7**). One reason is that it is possible to produce more during the high price periods. Thus, it is valuable to have more water available in the reservoirs.

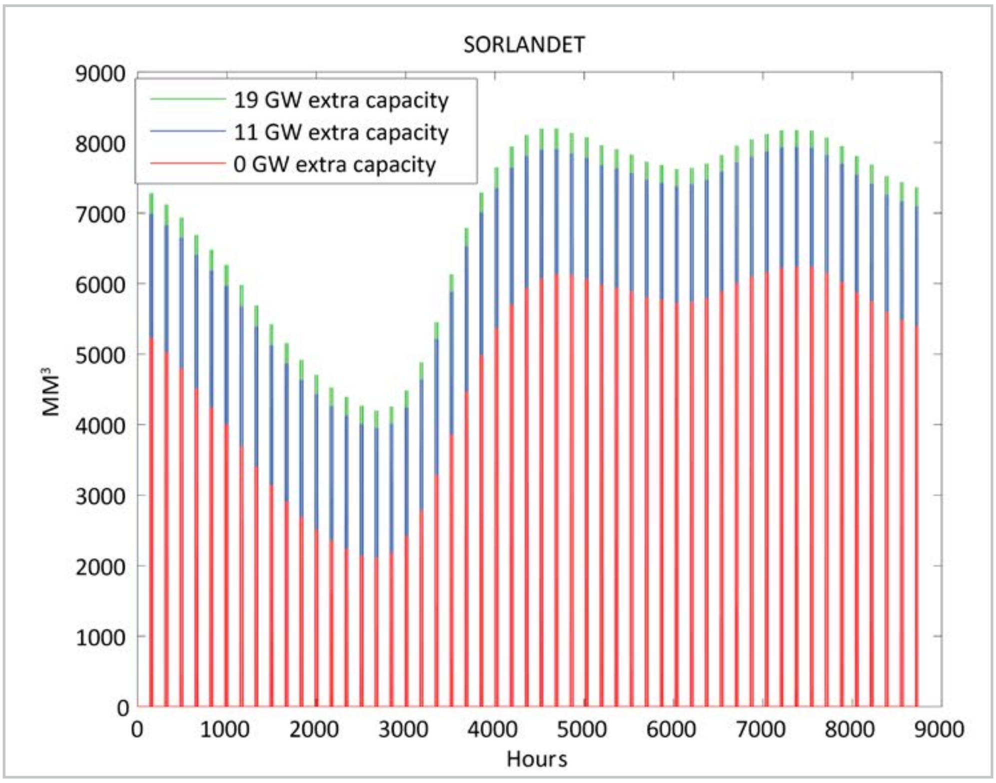


Figure 7. Simulated weekly energy stored in reservoirs in Southern Norway for the present Norwegian hydropower system capacity (red), for an additional 11 GW (blue), and for an additional 19 GW (green) in the 100% RES eHighway2050 scenario. Simulations are carried out with the EMPS model and results are averaged over 75 years. For the Southern Norway region, the corresponding hydropower capacity is 4.1 GW at present, and expanded by 7.6 GW and 8.3 GW for the scenarios with expansion at national level.

6.2. Future operation and profitability

6.2.1. Hydropower optimisation and pumped-storage profitability

Future hydropower operation in Norway is highly driven by Norwegian power prices, which determine the profitability of conventional hydropower and pumped storage.

Norwegian prices in a Nordic and European system

Norwegian power prices are affected by many factors, including production facilities and climatic conditions in Norway, prices in the Nordic power system (Sweden, Finland, Denmark, Norway), access to European markets (formally and physically through interconnectors), and European prices. This is illustrated in Figure 8.

The Nordic power system is connected to Europe through several direct transmission connections, and Nordic prices are thus affected considerably by prices in other European countries.

European power prices

Europe is in the first phase of the planned shift from fossils to renewables in the European electricity mix. As renewable generation is variable, the traditional price pattern (high day prices, low night prices) is already changing. Power prices will become more volatile, reflecting the availability of renewables. Furthermore, markets that are set up to deal with forecast errors for bids in the traditional day-ahead market will become more important. Those markets include intraday, ancillary services (such as balancing energy and power reserves), and capacity markets.

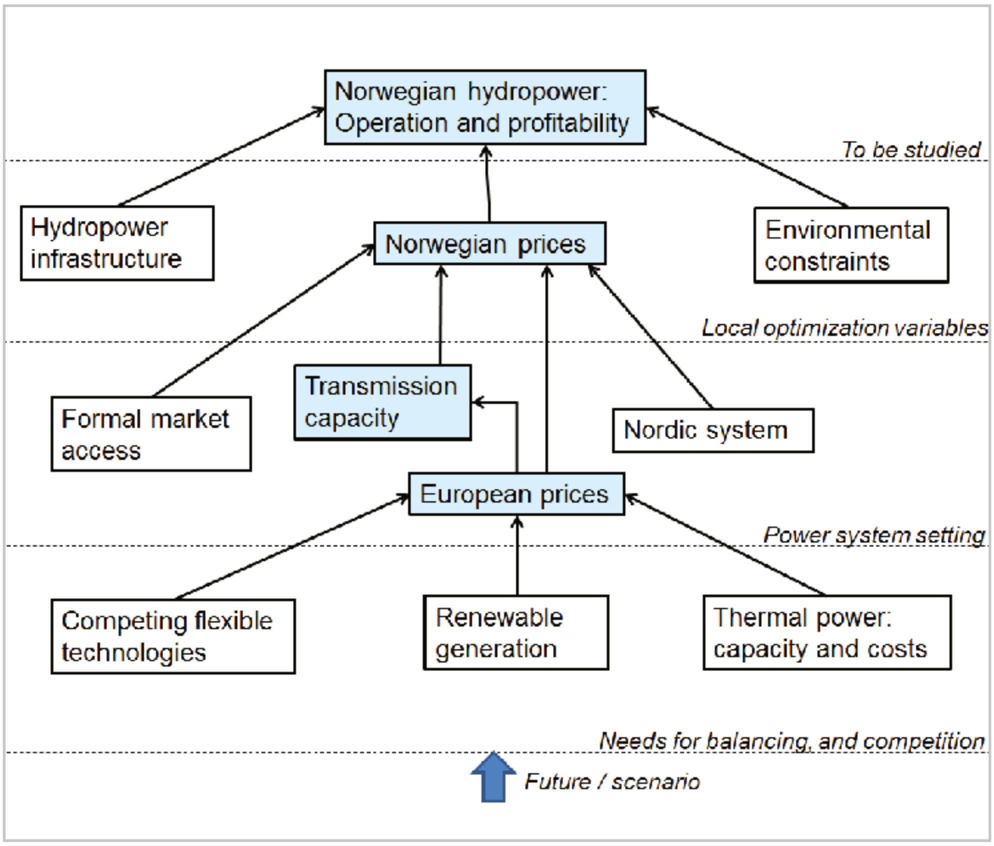


Figure 8. Important factors affecting the profitability of Norwegian hydropower (not exhaustive).

European Commission is working towards a common European electricity markets with considerable cross-border trade.

To reduce the cost of the transition towards renewables for the consumers, the European Commission is working towards a common European electricity markets with considerable cross-border trade. The 3rd Energy Package with the establishment of the Agency for the Cooperation of Energy Regulators (ACER) was an important step in that process as they are currently important for the development of an EU regulation for electricity markets. ACER members are EU regulators (such as NVE) and ENTSO-E members (such as Statnett).

In the following, we will show how future European prices can affect the income for Norwegian hydropower producers, and the profitability for pumped-storage investments in Norway.

Profitability for investments in pumped storage

In the HydroBalance project, it was a premise that we should consider pumped storage, and as a part of this we carried out an economic assessment for a specific pumped-storage project in Norway. The method consisted of the following steps:

- Step 1: Calculation of future prices
- Step 2: Making a multi-market model for hydropower optimisation
- Step 3: Carrying out a case study for a real river system and a relevant investment project

Each step is described briefly below.

Step 1: The Institute of Power Systems and Power Economics (IAEW) at University of Aachen calculated day-ahead prices for different European countries for HydroBalance scenarios in 2050, plus German prices for different market types (Moser et al. 2015).

The HydroBalance project was a study of the feasibility of large-scale balancing supplied from Norwegian hydropower. The quantification of this included up to 60 GW capacity in Norwegian hydropower (about the double of today's capacity) and a corresponding 30 GW capacity of cables in the North Sea. Since such transmission capacity would tend to even out prices between areas, the calculated German prices for different electricity market types were used as an estimate for Norwegian prices.

Figure 9 gives an illustration of the corresponding prices in some of the studied markets, compared to historical prices in Norway. Future prices are higher due to higher prices for CO_2 permits and natural gas, whereas price fluctuations are higher due to a higher share of renewable generation.

This is the first detailed model for hydropower able to include several markets (day-ahead, intraday, balancing energy and reserve power).

Step 2: In the HydroBalance project, we developed a new methodology (Wolfang et al. 2015) to analyse hydropower's supply to and income from several market types, including day-ahead, intraday, and balancing energy and reserve power. The modelling is based on ProdRisk, a model used by Nordic hydropower producers for optimisation and planning of power production (Gjelsvik et al. 2010). As far as we know, this is the first detailed model for hydropower able to include all those markets (CEDREN , 2017).

Step 3: Otravassdraget is a watercourse located in Southern Norway where Agder Energy applies ProdRisk. In that watercourse, there is also several potential pumped-storage projects. We used the dataset from Agder Energy, as well as prices from Step 1, and methodology from Step 2 to calculate the income from different markets (Figure 10).

The results show that the total income increases if the producer participates in all additional markets. The extra net income is 22.4% higher if the producer participates in all markets instead of only participating in the traditional day-ahead market (see the difference between "DA" and "ALL" in Figure 9). The extra income is in general a consequence of the hydropower producer's ability to react on new prices, also including reduced production at a very low cost for the hydropower

Photo: Antti Eloranta

producer when prices for balancing energy is low due to higher wind and solar power production than expected (see power prices for activation of reserves in **Figure 9** and negative revenues in **Figure 10**). The saved water can then be used for additional production later.

In our study, the inter-market optimisation for the capacity is illustrated by "RR" versus "RR_opt" in **Figure 9**. In the latter, the capacity made available for day-ahead and intraday is optimised under uncertainty with respect to power prices in subsequent markets. As shown in **Figure 10**, there is an additional 3.7% increase in income from the intra-market optimisation. This is an important finding since previous analyses have not shown any major gain of inter-market optimisation for the available capacity (Klæbu et al. 2013). See Wolfang et al., (2015) for additional description of results.

Additional 3.7% increase in income from the intra-market optimisation. This is an important finding since previous analyses have not shown any major gain of inter-market optimisation for the available capacity.

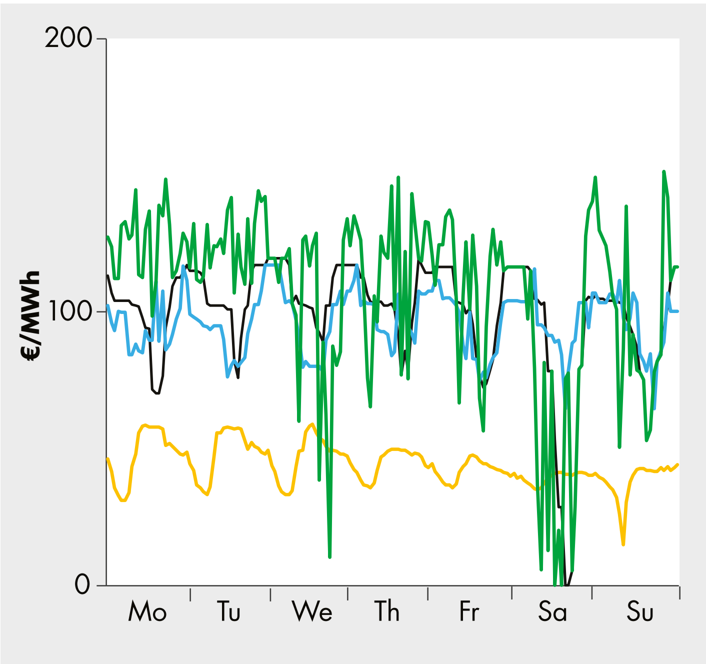


Figure 9. Historical (2008) day-ahead power prices in Norway (yellow), simulated day-ahead prices for 2050 (black), and simulated prices for activation of reserves (green) over one typical week.

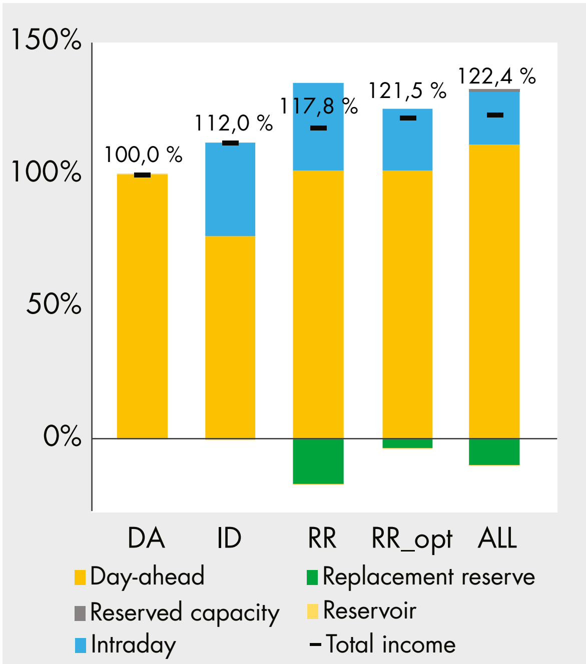


Figure 10. Income for hydropower from different markets, and for different strategies regarding market-participation.

The profitability for pumped-storage investment is exemplified in Figure 11. As shown, the investment would be profitable at calculated 2050 prices even if the producer would participate only in the day-ahead market (income "DA" exceeds investment costs). However, the additional income coming from the pumped-storage investment is increased by almost a factor of 6 if the producer participates in all electricity markets.

Why is the extra income from the pumped-storage investment more sensitive (factor 6) for market participation than the total income (22%)? The reason for this is that the total income is mostly determined by the general price level. The extra income from participation in additional markets gives some adjustments. For pumped storage, however, the whole benefit comes from power price volatility, i.e. the difference between price during pumping and price during generation. Since the volatility in calculated prices are far higher e.g. for balancing energy than in the day-ahead market (cf. Figure 9), the profitability of the investment will be heavily impacted by the participation of hydropower in that market.

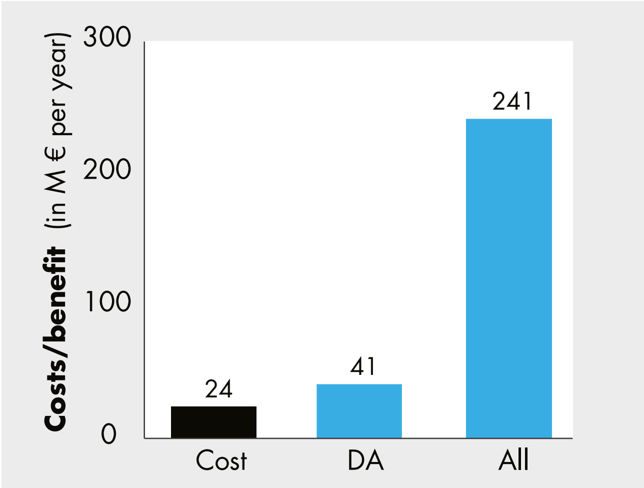


Figure 11. Profitability for the pumped-storage investment, for different strategies regarding market-participation.

6.2.2. Cost-effectiveness of pumped storage

Norwegian investments in additional hydropower capacity and pumped storage have also been studied in terms of cost-effectiveness from a European system perspective, using two different methods that are described below.

Cost-benefit analysis of extra capacity

A cost-benefit analysis of a total 60 GW hydropower capacity in Norway (of which 13.7 GW pumped-storage) and a corresponding transmission capacity to Europe was carried out in HydroBalance (Maaz et al. 2016). The calculated benefit in terms of reduced total costs in the European power system was 130 €/kW per year, which is 48% higher than corresponding investment costs.

The benefit mainly comes from:

- Smoothening of the production from fossil fuel power plants and thus decreased generation costs because of fewer start-stops and higher average efficiency.
- Less unused wind and solar power due to utilisation of pumps at times of excess electricity supply from renewable sources.

The study calculated the average benefit for the total capacity. The marginal benefit from one extra MW of extra capacity will decrease with additional new capacity. The study could therefore in principle give the same benefit with lower transmission capacity.

Levelized cost of peak generation

Another study in the HydroBalance project (Korpås et al. 2015) showed comparable results by comparing the cost-efficiency of pumped storage in Norway versus Combined Cycle Gas Turbine (CCGT) and Open Cycle Gas Turbine (OCGT) in Europe. In the short term, existing gas power capacity has an advantage since the investment has already been made. However, in the long term, existing capacity will be decommissioned. The study therefore focuses on new pumped-storage versus new gas power plants.

Building on the well-established metric "Levelized Cost of Electricity" (LCOE), the new concept "Levelized Cost of Peak Generation" (LCPG) was invented. Whereas LCOE represents the per-kilowatt-hour cost of building and operating a power generating plant over its lifetime and duty cycle, LCPG represents the cost of providing electricity when fluctuating renewables and inflexible thermal generation cannot meet the demand. Results from this case study give clear ndications that building new reversible pumped-storage facilities between existing reservoirs in the Norwegian hydropower system can be more economically beneficial than new gas power plants in Northern Europe, even when including additional costs of subsea cables across the North Sea and corresponding reinforcements of the mainland grid.

6.2.3. Future operational patterns in reservoirs

In a future where Norwegian hydropower is used for balancing of wind and solar power in Europe, Norwegian reservoirs will be operated differently from today. The main drivers are variability in future prices and future profitable investments in additional hydropower capacity and/or in pumped storage as demonstrated above.

In a study of Suldalsvatn reservoir located in South-Western Norway, we compared the optimised reservoir operations for two cases (Figure 12):

- "Historical operations": Historical prices, existing production system, supply for day-ahead market.
- "Future operations": Future prices, a pumped-storage investment has been carried out, supply for all electricity market types.

Suldalsvatn is the lower reservoir in the considered pumped-storage project. The simulation results show that "future operations" present more frequent and more intense water level variations compared to "historical operations". The average change in the reservoir water level from one hour to the next over four years in the simulation is increased by 73% in the latter scenario.

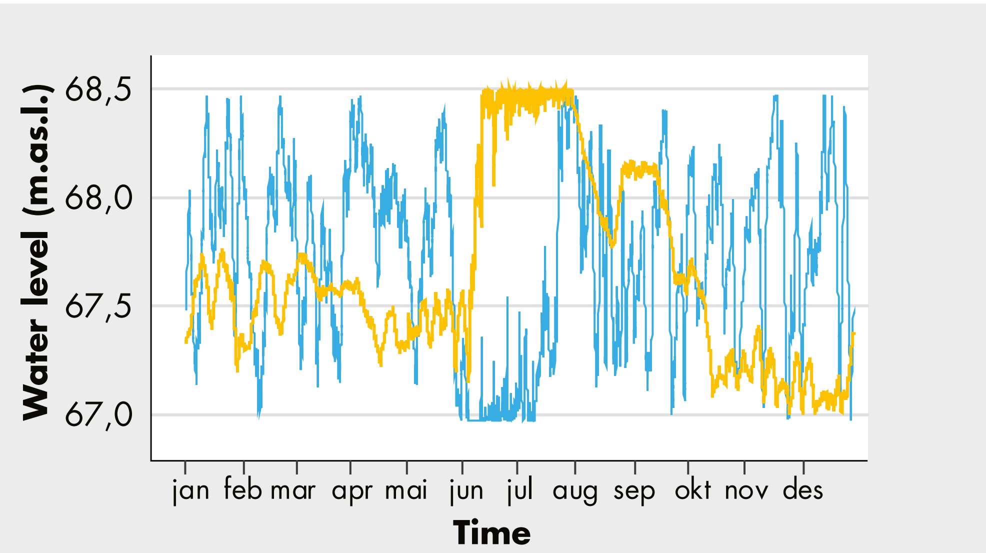


Figure 12. Simulated reservoir operational pattern in Suldalsvatn, averaged over simulated years. Yellow line is "Historical operations", whereas blue line is "Future operations".

6.3. Environmental impacts of hydropower operations in reservoirs

6.3.1. Importance of Norwegian hydropower reservoirs

Upgrading the Norwegian hydropower system for the exchange of balancing services will involve installations of new tunnels, pumps, roads, off-shore cables, power lines etc., which will affect biodiversity in and ecosystem services delivered by the affected landscape. These aspects are not considered in the HydroBalance project, because we have limited our focus to environmental impacts on the reservoirs only. While hydropower impacts on regulated rivers have been studied extensively (Forseth and Harby 2014, Bakken et al. 2016), the knowledge about effects on reservoirs and lake ecosystems are relatively poorly understood. This also holds for Norway, despite the large number of natural lakes that have been turned into hydropower reservoirs. In the HydroBalance project, we have therefore focused exclusively on reservoirs when studying environmental effects, as any new knowledge of hydropower impacts on reservoir ecosystems has the potential to improve regulation and development of sustainable hydropower operations.

The large number of hydropower reservoirs in Norway gives a large potential for balancing services (Killingtveit 2017, Harby et al. 2013, Killingtveit 2012, Solvang et al. 2014). However, the reservoirs show marked natural variation e.g. in size, depth, geology, altitude, climate and species composition (Figure 13), but also in hydropower-induced water level fluctuations (Figure 14) (Hirsch et al. 2017, Eloranta et al. 2018). This variation in local reservoir characteristics should be considered in planning, management and mitigation of hydropower operations. Moreover, many of the Norwegian reservoirs are natural lakes turned into hydropower reservoirs. Hence, they contain ecosystems that are close to natural, and environmental regulations will prohibit substantial degradation of these ecosystems.

Before one can predict future changes in reservoir ecosystems, it is necessary to understand the mechanisms behind present-day environmental impacts of hydropower production. The present environmental regulations of reservoir operations in Norway are based on limiting

While hydropower impacts on regulated rivers have been studied extensively in CEDREN EnviPEAK and EnviDOOR projects (Forseth and Harby 2014, Bakken et al. 2016), the knowledge about effects on reservoirs and lake ecosystems are relatively poorly understood. Photo: Hans-Petter Fjeldstad the upper and lower regulated water level and in some cases the timing for reservoir filling. Hence, these regulations do not consider how rapidly or frequently the water level fluctuates. Many Norwegian reservoirs are already experiencing frequent water level fluctuations (Eloranta et al. 2018), and such regulation patterns (i.e. operational regimes) might increase with more flexible services in future markets (Killingtveit 2017, Harby et al. 2013, Solvang et al. 2014). Hence, to avoid severe environmental impacts and improve environmental regulations, better knowledge of how a given operational regime may influence reservoir ecosystems is needed.

6.3.2. Known environmental impacts of today's operational regimes

The key impact of hydropower in reservoirs is water level regulation. More rapid and frequent fluctuations in water level will cause changes in physical and chemical properties, such as temperature, ice cover, erosion, resuspension of nutrients and mixing of water, which in turn will change the living conditions for aquatic organisms (Hirsch et al. 2017). Fish populations are often used as indicators of ecosystem health in lakes, since they are top predators and thus may reflect changes at any ecosystem level. Furthermore, fish have a high socio-economic value and many reservoirs are used for recreational or commercial fisheries. Supported by previous research, our results from single reservoirs (Eloranta et al. 2017) and modelling of multiple lakes across Norway (Eloranta et al. 2016) indicate decreased abundance of fish in hydropower reservoirs compared to unregulated lakes. The hydropower operations also seem to alter the lake food webs. Reduction of biological productivity in the shallow littoral areas seems to cause the fish to feed more in the deeper, open water pelagic areas. This increased use of pelagic planktonic food may, in turn, increase parasitic infections and hence reduce the quality of fish for human consumption. However, it seems that in some cases, the decreased population size and hence reduced competition for food resources may lead to increased growth rate and larger size of the remaining fish.

The mechanisms behind hydropower effects on reservoir fish are difficult to predict. This is because reservoir ecosystems and hydropower operations have unique local characteristics and hence the environmental effects are case-specific.

Although several studies have indicated negative impacts of hydropower operations, we concluded in a review paper that the mechanisms behind hydropower effects on reservoir fish are difficult to predict (Hirsch et al. 2017). This is because reservoir ecosystems and hydropower operations have unique local characteristics and hence the environmental

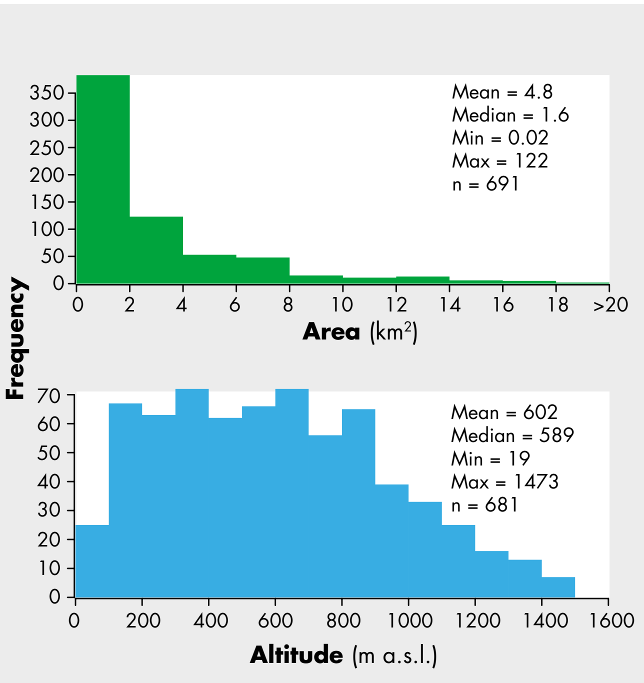


Figure 13. Frequency distribution of the size (area) and location (altitude) of Norwegian hydropower reservoirs.

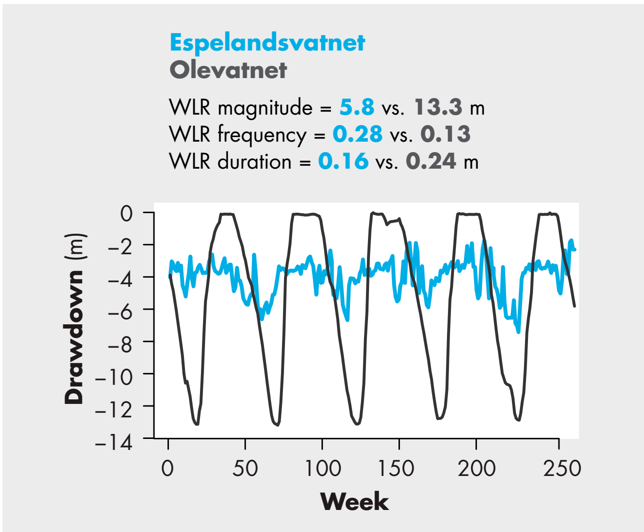


Figure 14. Examples of contrasting water level regulation (WLR) patterns in two Norwegian hydropower reservoirs across five years. Magnitude is the maximum regulation amplitude, frequency is the relative proportion of weeks with a sudden rise or drop in water level, and duration is the relative proportion of weeks with exceptionally low water levels (see Eloranta et al. 2018 for details).

Photo: Anders Finstad

Brown trout responded differently to the water level fluctuations depending on several local environmental properties, such as reservoir morphometry and presence/absence of coexisting fish species.

effects are case-specific. This complexity was illustrated by a modelling study using data from more than 100 Norwegian reservoirs, aiming to investigate in more detail how the operational regimes affect brown trout populations (Eloranta et al. 2018). We calculated the magnitude, frequency and duration of water level fluctuations in each reservoir and tested how brown trout were affected by these three impacts. We found that brown trout responded differently to the water level fluctuations depending on several local environmental properties, such as reservoir morphometry and presence/absence of coexisting fish species. Moreover, we found that increasing water level regulation frequency may lead to increased population density but at the same time decreased condition of brown trout individuals. Hence, our results show that it is difficult to find a "one size fits all" measure for or response of fish to hydropower operations in reservoirs.

Essential factors that affect the abiotic and biotic conditions in reservoirs, but which usually have been neglected in environmental studies, are the operational regime of the hydropower plant as well as the reservoir's vertical and horizontal shape, geology, succession stage and location of intake tunnels.

Drawing any definitive conclusions and generalizations without reliable scientific proof is dubious and risky since this may prevent sustainable development of hydropower operations. Shortly caution is recommended. It is important to perform proper, reservoir-specific monitoring and assessment of potential environmental and societal impacts. The local environmental conditions, such as climate and lake morphometry, not only determine the presence of species and biological interactions in reservoirs, but also how hydropower companies can regulate water levels. These interlinkages between reservoirs' physical and chemical properties, ecological communities and hydropower operations create a fundamental challenge for monitoring, prediction and mitigation of environmental impacts. Therefore, we have suggested a few factors that should be considered in future studies to disentangle effects of hydropower operations from natural processes in reservoir ecosystems (Hirsch et al. 2017). Essential factors that affect the abiotic and biotic conditions in reservoirs, but which usually have been neglected in environmental studies, are the operational regime of the hydropower plant (e.g. traditional versus pumped-storage operation, the amplitude, timing, frequency and rate of water level change) as well as the reservoir's vertical and horizontal shape, geology, succession stage and location of intake tunnels.

If more targeted reservoir studies are performed, one should seek to expand the concept of environmental design for reservoirs. At present, the concept is developed for regulated salmon rivers (Forseth and Harby 2014) but it would be feasible and useful to develop a handbook for "Environmental design in hydropower reservoirs". For example, brown trout exists in numerous hydropower reservoirs, and several hydropower-induced ecological bottlenecks, such as reduced access to spawning habitats or reduced food availability, are already known for this species. However, this knowledge needs to be systematised and properly tested, as neither the diagnostic tools nor the design solutions are yet developed for brown trout populations in reservoirs.

6.3.3. Prediction of future effects in single waterbodies

In the HydroBalance project, we have developed a new procedure aiming at predicting how environmental conditions may change under future hydropower operations. As discussed in chapter 6.2, it is predicted that future operational regimes will cause changes in the yearly, seasonal and daily fluctuations in the reservoir water levels. By combining power price simulations from future market scenarios with hydrodynamic modelling of a given reservoir, it is possible to test how different operational regimes can influence water level fluctuations, temperature, ice cover and mixing of water. So far, we have tested this approach in one reservoir, and the findings indicate that this approach is promising for future work. The power price simulations from the European market are based on assumptions from the HydroBalance scenarios and used as an input to ProdRisk, a model used by Nordic hydropower producers for optimisation and planning of power production. The resulting water discharge from these simulations is thereafter used as an input in a hydrodynamic lake model (CE-QUAL-W2) to identify changes in reservoir water temperature (Figure 15). We believe that such a direct link between market optimisation of the hydropower operation and environmental impacts in reservoirs will be very important for predicting potential future changes. However, to use this method, it is necessary to have access to detailed data. We found that bathymetric maps and continuous seasonal water temperature data measured at different depths are missing for many Norwegian reservoirs. Hence, to rerun our model in more cases, such data should be collected from various reservoirs. Both types of data are easy to produce at relatively low costs, e.g. by using an echo-sounder and temperature loggers, respectively.

By combining power price simulations from future market scenarios with hydrodynamic modelling of a given reservoir, it is possible to test how different operational regimes can influence water level fluctuations, temperature, ice cover and mixing of water.

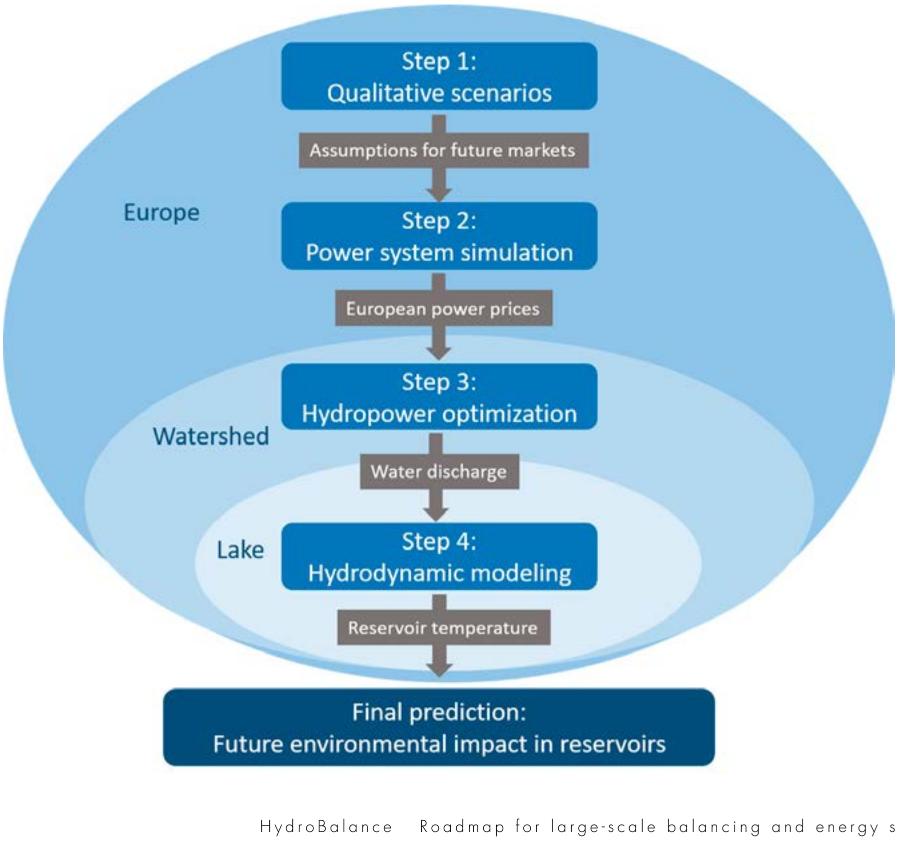


Figure 15. Description of methodological approach linking market simulations and future environmental impacts in reservoirs.

6.3.4. Identification of promising reservoirs with low environmental risk

Investigating and predicting effects in each waterbody can be time consuming, and therefore costly. Hence, before doing detailed environmental assessments in single reservoirs, it would be helpful to identify what kind of locations are least sensitive to potential negative environmental and socio-economic impacts. Although quantitative models for doing this are still lacking, we have aimed to illustrate which reservoir types are most prominent targets for balancing power, based on existing literature and our expert knowledge. We believe that deep, isolated, glacier-fed mountain reservoirs that are formed on solid bedrock and have low recreational and/or ecological value are generally most resistant to negative environmental and societal impacts (**Table 2**). In contrast, heavy water level fluctuations would likely have severe negative impacts in reservoirs that provide important recreational and ecological services and/or are vulnerable e.g. to erosion, resuspension of inorganic and organic matter, species' invasions and decreased ice cover stability associated with pumping and rapid daily water level fluctuations (Patocka 2014, Killingtveit 2017, Harby et al. 2013, Solvang et al. 2014). An important note here is that reservoir operations are tightly linked to impacts on river ecosystems and therefore it is necessary to evaluate the whole lake-river network before identifying promising locations.

Table 2. Summary of the characteristics of reservoirs that are resistant or vulnerable to more frequent and rapid water level variations induced by hydropower operations.

Characteristic	Resistant reservoirs	Vulnerable reservoirs
Geology	Solid bedrock	Loose substrate (e.g. clay, peatland)
Morphometry	Deep Simple shoreline	Shallow Complex shoreline
Water supply	Isolated Glacier-fed	Part of a complex river-lake system
Biotic community	Common and/or tolerant taxa Dominated by pelagic organisms Low biodiversity Low risk of unfavourable invasions	Endangered and/or sensitive taxa Dominated by littoral organisms High biodiversity High risk of unfavourable invasions
Fish community	Dominated by pelagic or generalist species Deep- and/or lake-spawning fishes	Dominated by specialized littoral species Shallow- and/or riverine-spawning fishes
Recreational use	Little recreational activities Low human population density	Numerous recreational activities High human population density
Importance for terrestrial ecosystem	No major habitat and/or migration routes for terrestrial animals or waterfowl	Important habitat and/or migration routes for terrestrial animals or waterfowl

6.4. Societal acceptance and regulatory framework

6.4.1. European market integration and national policy

European market integration

We identified two very important processes regarding the future policy development in Europe and within the EU (Qvenild et al. 2015). Firstly, capacity market mechanisms and national concerns for securing the energy supply is part of the national considerations pertaining to the market integration process. Secondly, transmission system operators' (TSO 's) decisions related to infrastructure development and more specifically to the EU Commission's recent proposal for a broader interconnector strategy are efforts to provide opportunities for cross-border energy flows. Changes in the transmission system can emerge as part of a realised European Energy Union, and a reinforced mandate to ACER, concerning further cross-border energy policy development in Europe.

Capacity market mechanisms and national concerns for securing the energy supply is part of the national considerations pertaining to the market integration process.

In November 2016, the European Commission adopted a revised RES policy. The provisions are adapting the framework for renewable energy development to the 2030 perspective, aiming at providing certainty and predictability to consumers while promoting low-carbon solutions.

The Clean Energy proposal (European Commission, 30.11.2016) covers energy efficiency, renewable energy, the design of the electricity market, security of electricity supply and the governance rules for the Energy Union. The proposal has three main goals: (1) putting energy efficiency first, (2) achieving global leadership in renewable energies, and (3) providing a fair deal for consumers.

It also emphasizes that the transition towards renewables is the growth sector of the energy market in the future, but this will require significant systemic safeguards to secure sufficient electricity supplies in times with little solar or wind power. A back-up system is needed.

Today's interconnector capacity between Norway and Europe is 6200 MW, which equals 20% of the Norwegian production capacity in 2017. Currently, the exchange capacity is a bottleneck regarding Norway's potential for balancing services to Europe (Qvenild et al.

Transmission system operators' (TSO 's) decisions related to infrastructure development and more specifically to the EU Commission's recent proposal for a broader interconnector strategy are efforts to provide opportunities for crossborder energy flows.

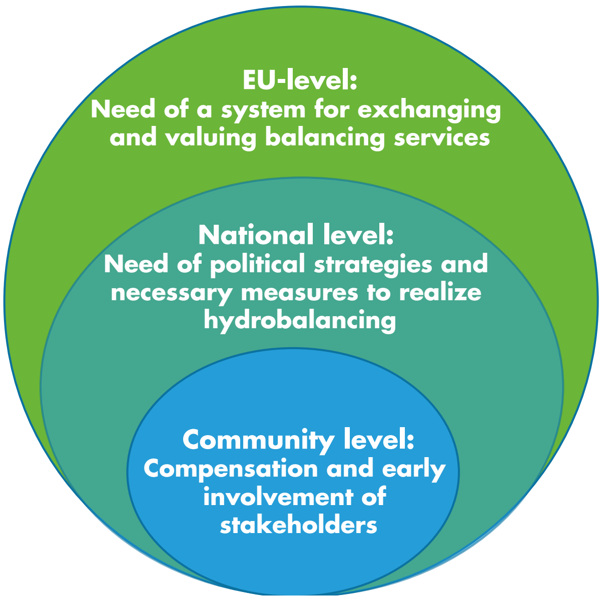


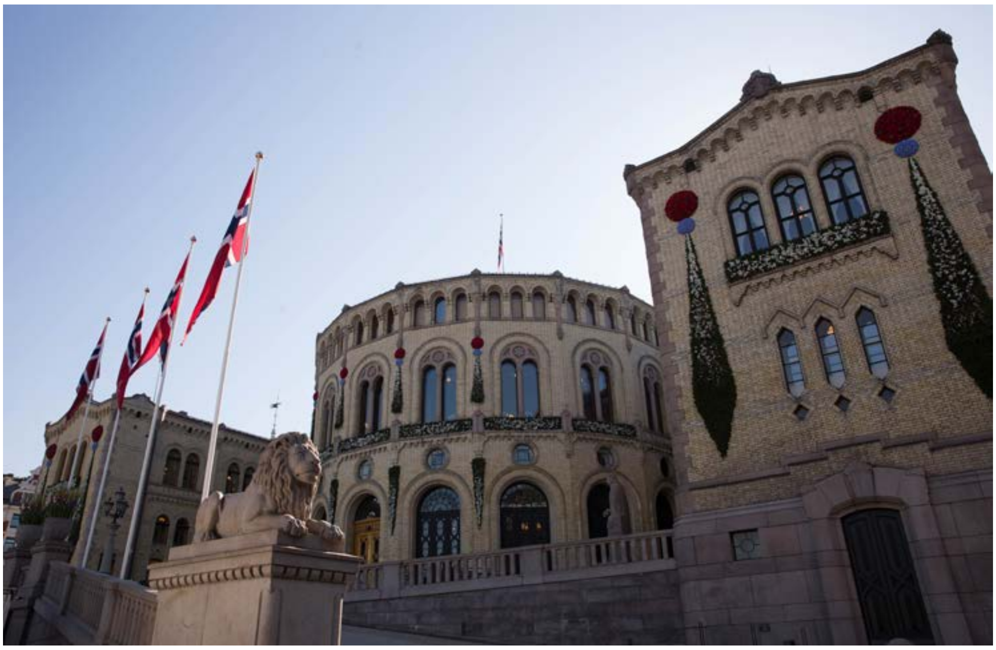
Figure 16. Illustration of scales and the main challenges for large- scale storage and balancing hydropower from Norway to Europe on EU-, National-, and community level.

2015). There are two ongoing interconnector projects from Norway to Europe (NordLink to Germany and North Sea Link to the UK). When these projects are finished (around 2020), the interconnector capacity will increase to 9000 MW. There is also a new commercial project proposal from the Norwegian west coast to the UK (North Connect) with an estimated capacity of 1400 MW. These initiatives are related to the North Sea Offshore Grid Initiative (NSCOGI) [7] and interconnector projects being supported in the Ten Year Network Development Plan (TYNDP) [8]. However, the Norwegian parliament recently decided that interconnectors should be owned by the Norwegian TSO.

National policy

Important policy documents include Report to the parliament (white paper) no. 25 (2015-2016), recent changes in the EU's Renewable Energy Sources (RES) Directive, and changes in the Norwegian Energy Act (§ 4-2, implemented in December 2016) allowing private actors to own and operate interconnectors.

The Norwegian parliament has defined four key areas regarding the energy policy towards 2030 (White paper no. 25, 2015-2016): (1) Securing the supply of electricity, including strengthening the capacity of the national and international transmission systems. (2) By using new technology (such as smart grid solutions), and cost reductions in renewable energy technology, more flexible production of RES in relation to changing demand patterns is expected. By generating energy at home (e.g. from wind and solar, consumers may actively participate in the energy market by supplying their surplus energy into the grid. (3) More efficient and climate-friendly energy solutions may be realised. New standards of energy performance of buildings, heating and cooling systems may also reduce the energy consumption. Furthermore, within the industry and transportation sector, reduction in CO_2 emissions are expected, both on land (road) and at sea. (4) Value creation through effective use of profitable RES should be achieved by strengthening the supplies of electricity from Norway to the European markets, including transmission cables to Europe to increase the balancing capacity.



Research conducted by CEDREN has confirmed a need for more coordinated political steering across sectoral interests and levels of decision-making. Photo: Morten Brakestad, Stortinget

[7] *Further info: http://www.benelux.int/nl/kernthemas/energie/nscogi-2012-report/*
[8] *http://tyndp.entsoe.eu/*

The Norwegian energy policy is describing a future towards 2030 which is in line with the new EU RES directive, in which increased cross-border market capacity for energy exchange will be important. Increased flexibility in the transmission and distribution systems will also be important, due to an expected increase in domestic and local generation of renewable energy, particularly from sun and wind.

Our study has shown that several factors hamper the development of Norwegian balancing services to Europe.

Our study has shown that several factors hamper the development of Norwegian balancing services to Europe. These are insufficient coordination of national and regional grid development, and unpredictable distribution of costs and benefits of new interconnectors which provides economic consequences for domestic energy consumption. Besides, negative environmental and social impacts may be manifested. A major barrier is the lack of coordinated political measures to realize and secure increasing but acceptable balancing services from Norway.

In most cases, balancing services should consider grid development at national, regional and preferably also local level. Interconnectors can be perceived as a major building block for balancing services anchored within the TSO Statnett's realm, but other grid companies can also be involved given the needs for regional and local up-grading. All energy infrastructures must be realised within local settings, implying the need for appropriately addressing stakeholders and affected local inhabitants. A coherent and comprehensive planning framework, concerning the potential for balancing services related to grid development, is currently not in place. Such a framework could make balancing projects more feasible.

The possibility to use Norwegian hydropower for balancing services is not clearly reflected in the regulatory framework at the European or national level – not even in Norway.

The possibility to use Norwegian hydropower for balancing services is not clearly reflected in the regulatory framework at the European or national level – not even in Norway. Consequently, the concerns on balancing services are significant at the local community level. Through better coordination of plans, regulations, interested parties and public concerns, the potential for balancing services towards Europe may be enhanced.

6.4.2. Social acceptance of balancing services at the local community level

Social studies within the HydroBalance project showed that local authorities primarily were concerned with local benefits and environmental impacts rather than contributing towards climate-friendly solutions internationally. Implicitly, there is a need for more environmentally friendly solutions for operating hydropower systems (i.e. hydropeaking and pump-storage) locally to reduce negative local environmental and societal impacts (Forseth and Harby 2014), (Ruud et al. 2016).

Hydropower regulation is related to different aspects of social acceptance. Photo: PK Foto

Increased social acceptance of renewable energy technology projects can be obtained in various ways.

Based on scientific literature, increased social acceptance of renewable energy technology projects can be obtained in various ways. One important finding is that hydropower developers should avoid projects that have considerable negative impacts on environmental values and in areas that are of high importance to locals. Therefore, procedural issues related to local involvement may be more relevant than specific siting questions if the community acceptance of balancing services should be ensured. Acceptance may increase if local groups are given the opportunity to provide direct inputs during the planning and construction phase (Cohen et al. 2014). This suggestion is in line with extensive research on other renewable energy technology projects (e.g. grid development and wind farm projects) demonstrating how social acceptance is closely linked to procedural justice, i.e. perceptions of fairness in the decision-making process (Ruud et al. 2016). Although there are extensive mechanisms for public consultations (e.g. public hearings and guidelines to enhance participation) in planning and licensing of transmission line projects, Knudsen et al. (2015) demonstrates how public opposition in Norway and the UK was triggered particularly by insufficient early involvement of local inhabitants. In line with this study Steffen, (2012) argues that participation in the planning process improve the community acceptance for pumped-storage projects. Extensive and transparent information to the public is therefore of vital importance (Ruud et al. 2016). A related aspect is the issue of community compensation for bearing local negative impacts of construction and balancing operations. It seems that, instead of merely focussing on monetary compensation, a variety of physical measures and investments in community infrastructure and well-being, may increase community acceptance and even approval of balancing services.

The photo shows people demonstrating against a new power line crossing the scenic Hardanger fjord. Photo: © Helge Sunde/ SAMFOTO

The stakeholders emphasized that consultation at the planning phase and possibilities for compensation measures are likely to reduce opposition of projects, assuming that the environmental and visual impacts are minimized. However, it may be difficult to completely avoid local resistance towards balancing projects. Together with previous studies of export grid projects, our results indicate that community compensation and early involvement may be sufficient measures to enhance community acceptance.

The stakeholders emphasized that consultation at the planning phase and possibilities for compensation measures are likely to reduce opposition of projects, assuming that the environmental and visual impacts are minimized.

We recommend formulation of a policy strategy that encompasses and balances different societal interests. This should be done both at the national and local levels, with more comprehensive guidelines for coordination of plans, regulations, interests and public concerns. Such a comprehensive strategy should further address the political, economic, societal and technological trends, which may influence the demands of European countries' such as Great Britain, Germany and Denmark.

We recommend formulation of a policy strategy that encompasses and balances different societal interests.

Conflicts often arise when new power lines are planned and constructed. Studies carried out in HydroBalance show that disagreements can be avoided or significantly reduced Photo: Øystein Aas

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