HydroCen
NORWEGIAN RESEARCH CENTRE FOR HYDROPOWER TECHNOLOGY

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

HydroCen Report nr.18

AlternaFuture

Final Report

Kaspar Vereide, Birger Mo, Torbjørn Forseth, Leif Lia, Arne Nysveen, Ole Gunnar Dahlhaug, Linn Emelie Schäffer, Ana Adeva Bustos, Line Sundt-Hansen, Eirik Øvregård, Pål Glimen, Trygve Hesthagen, Margrete Skår and Torbjørn Kristian Nielsen.

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HydroCen

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The FME-centres can be established for a maximum period of eight years HydroCen was established in 2016.

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EDITOR
Kaspar Vereide

COVER PHOTO
AlternaFuture researchers during field work in Mandal river © NTNU

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CONTACT DETAILS

HydroCen www.hydrocen.no
Vannkraftlaboratoriet,
NTNU
Alfred Getz vei 4
Gløshaugen,
Trondheim

Abstract

Vereide K., Mo B., Forseth T., Lia L., Nysveen A., Dahlhaug O. G., Schäffer L. E., Bustos A. A., Sundt-Hansen L., Øvregård E., Glimen P., Hesthagen T., Skår M., Nielsen T. K. 2020. AlternaFuture Final Report. HydroCen Report 18.

AlternaFuture has been a multidisciplinary research project in Hydrocen to investigate the potential of extreme upgrading of existing hydropower system with a positive effect on the environmental conditions. The project is a desk study and is carried out through developing future scenarios of an extreme upgrading of an existing hydropower system, to create potential for new innovations and solutions from the multidisciplinary scientists within the project. The existing hydropower system in the Mandal river has been applied as a case-study, where the current situation has been the baseline for developing alterative future scenarios and evaluating the economic and ecological results.

The project has been divided in three main activities; (A1) mapping the current situation and defining environmental restrictions for reconstruction, (A2) developing physical scenarios consisting of hydropower projects, environmental projects and use of new innovations, and (A3) economic and environmental evaluation of the scenarios. Three main scenarios were developed for the Mandal river; (1) triple installed capacity, (2) maximum flexibility, and (3) flood protection. The hydropower optimization program ProdRisk was used to compare the hydropower operation and water management in present situation with the three scenarios. Energy price forecasts from HydroCen where used to assess the economic income from hydropower production, which in turn where compared with the estimated construction costs of each scenario to consider the economic feasibility. Thereafter, the impacts on the environmental status and recreational value in different parts of the watercourse, including reservoirs, lakes and river reaches are evaluated for three hydropower scenarios and compared with the present situation.

In conclusion, it is found possible to realize extreme upgrading of existing hydropower systems, and at the same time in sum have a positive effect on the environmental conditions. It is noted that the positive effects require a significant effort in mapping and planning the environmental measures. For such upgrading consisting of multiple projects, single projects that have severe negative ecological impacts must be cancelled and cannot be included in the final scheme. Planning of such upgrading projects therefore must include environmental experts from the very beginning. The main conclusions from the AlternaFuture research project are presented below.

1. Extreme upgrading of existing hydropower systems can be done while also in sum improving the environmental conditions.
2. Extreme upgrading of hydropower systems that include pumped storage plants are economically feasible if the energy price variability increases sufficiently. For the Mandal river, the necessary increase is in between the 2030 price forecast and the 2030-scaled forecast as described in Memo 1.
3. It is the pumped storage plants that generate the main increase of revenue in the upgrading scenarios. Extreme upgrading without pumped storage plants has not been found economically feasible for any price forecast.
4. The pumped storage plants result in a reduction of the total energy production for the hydropower system, but a higher income. In the current tax regime, the pumped storage plants result in reduced taxation to the local municipalities because some of the Norwegian hydropower taxes are related to produced energy. The taxation to the central government increases depending on the economic profit from the pumped storage plants.
5. There is potential to find new hydropower projects in existing hydropower systems.
6. It is possible to construct a flood power plant to mitigate the flood challenges in the Mandal river. The flood power plant is not found to be economically feasible only from hydropower production, and the remaining costs have to be financed by other stakeholders such as insurance companies or local municipalities. The flood power plant can reduce a 200-year flood to a 20-year flood.
7. The extreme upgrading scenarios have a positive impact on flood mitigation owing to new reservoirs and pumped storage plants. This positive impact has not been quantified in this project.
8. Recommended future work includes developing a best-practice guideline for environmentally friendly upgrading of existing hydropower systems based on the methodology developed and applied in this project. In addition, 18 new research projects have been proposed and are described in Memo 5.

Kaspar Vereide, NTNU, Department of Civil and Environmental Engineering, S.P. Andersen veg 5, 7031 Trondheim, kaspar.vereide@ntnu.no.

Birger Mo, SINTEF Energy Research, Sem Sælands vei 11, 7034 Trondheim, birger.mo@sintef.no.

Torbjørn Forseth, NINA, Høyskoleringen 9, 7034 Trondheim, torbjorn.forseth@nina.no.

Leif Lia, NTNU Department of Civil and Environmental Engineering, S.P. Andersen veg 5, 7031 Trondheim, leif.lia@ntnu.no.

Arne Nysveen, NTNU Department of Electrical Power Engineering, O.S. Bragstads Plass 27, 7034 Trondheim, arne.nysveen@ntnu.no.

Ole Gunnar Dahlhaug, NTNU Department of Energy and Process Engineering, Alfred Getz vei 4, 7034 Trondheim, ole.g.dahlhaug@ntnu.no.

Linn Emelie Schäffer, SINTEF Energy Research, Sem Sælands vei 11, 7034 Trondheim, linnemelie.schaeffer@sintef.no.

Ana Adeva Bustos, SINTEF Energy Research, Sem Sælands vei 11, 7034 Trondheim, ana.bustos@sintef.no.

Line Elisabeth Sundt-Hansen, NINA, Høyskoleringen 9, 7034 Trondheim, line.sundt-hansen@nina.no.

Eirik Øvregård, NTNU Department of Civil and Environmental Engineering, S.P. Andersen veg 5, 7031 Trondheim, eirik.odegard@ntnu.no.

Pål Glimen, NTNU, Department of Electrical Power Engineering, O.S. Bragstads Plass 27, 7034 Trondheim, pal.glimen@ntnu.no.

Trygve Hesthagen, NINA, Hjalmar Johansens gate 14, 9007 Tromsø, trygve.hesthagen@nina.no.

Margrete Skår, NINA, Vormstuguvegen 40, 2624 Lillehammer, margrete.skar@nina.no.

Torbjørn Kristian Nielsen, NTNU Department of Energy and Process Engineering, Alfred Getz vei 4, 7034 Trondheim, torbjorn.nielsen@ntnu.no.

Content

Foreword

Over the last decade the hydropower sector has risen from obscurity; from being classified as a conventional technology, it has re-established itself as a highly efficient, flexible and clean energy technology for the future.

Large scale hydropower schemes are compounded systems affecting strings of factors from water to wire, encompassing technology, water management, environment, business models, safety and security of supply. Thus, future operation of hydropower is not solved by one silver bullet or a single-fix technology mode. An integrated web of solutions across disciplines and separate components is necessary, and innovation within these interfaces are required to prepare hydropower for the next generation of sustainable and renewable energy production.

The project AlternaFuture targets such a new, integrated approach and it addresses a critical aspect of all modern energy production: How do we balance considerations for both environment and energy production? And to stretch the challenge even further: Is it possible to do this within already existing physical systems?

With this backdrop it is extremely uplifting to see the conclusions of the final report from AlternaFuture. AlternaFuture is not your usual scientific project. It has challenged all parties involved, including the scientists themselves. Rather than to delve into a single expert area, the project has targeted the rim of several expert areas, investigating a mesh of opportunities and solutions in the cross sections. AlternaFuture opens a toolbox for a novel approach to planning hydropower schemes, balancing production and environment, and even concluding with a net worth benefiting the environmental conditions. In addition to the scientific conclusions, the project also presents a new and concrete methodology (Deck-of-Cards) for how to approach problem solving within a multi-disciplinary research context.

AlternaFuture also summarizes the foundation of HydroCen as a research centre, and its predecessor, the Norwegian Hydropower Centre (NVKS). Innovation and development can benefit vastly by crossing territories and working across disciplinary and sectoral borders. Bringing together engineers, economists, programmers, biologists and industry players facilitate for robust and optimal solutions. This has been the 'modus operandi' in both HydroCen and NVKS from the start.

It has been a joy to be a part of this project's fellowship and contributing to its establishment and now see the results. I give a very special credit to AlternaFuture's project manager, Kaspar Vereide. Without his efforts and capabilities, it would not have been possible to bring together all the out-of-the-box thinking, expertise and disciplines. He has been instrumental for this project's intentions, implementation and its outcome.

Lastly, I will give my acknowledgement to the project group overall, including the industrial partners. It is a remarkable and valuable project and collaboration.

Trondheim, November 2020
Hege Brende
Former Director of HydroCen and Norwegian Hydropower Centre (NVKS)

1 Introduction

This chapter presents the background and scope of the project, the methodology and the applied case-study, and finally the organization and financing of the project.

1.1. Background

The AlternaFuture project was initiated by the researchers in HydroCen. The motivation was to strengthen cross-disciplinary cooperation within the research center. The scope of work has been proposed by the four work-package (WP) leaders, and four goals were identified:

- The work shall be visionary
- The work shall trigger cooperation between the disciplines in HydroCen
- The work shall result in innovation
- The work shall determine the state-of-the-art for upgrading of existing hydropower systems.

The final results from the project have to a large degree answered these goals. The main remaining work is determining the state-of-the-art for upgrading, for which a single case-study cannot fully fulfill this purpose. However, within the case-study, state-of-the-art technology and environmental solutions have been applied to design the scenarios for extreme upgrading.

The project has been conducted with a strong involvement of the Norwegian hydropower industry and governmental agencies. Through HydroCen, the project scope of work, and research methodology have been discussed and developed in cooperation with the industry and government partners. The final scope of work and research methodology is a result of this interaction.

The researchers working in the project have consisted of professors and researchers from the five main disciplines in hydropower; civil, mechanical, electrical, environmental and market analysis.

1.2. Scope of Work

The AlternaFuture project has been a one-year multidisciplinary research project. The main research objective has been to: *Investigate the potential of extreme upgrading of existing hydropower systems, that also have a positive effect on the environmental conditions.* Secondary objectives have been to:

- Stress-test the innovations from HydroCen in a case-study
- Develop new innovative solutions for reconstruction of hydropower systems
- Shall generate new research project

To research methodology has been selected to answer the main objective. The secondary objectives have been answered by producing the so-called «innovation cards» and «research project cards» with assessments of the different innovations from HydroCen, and proposal for new research projects that can be a continuation of the work from AlternaFuture. The innovation cards and research project cards will be presented later in this report.

1.3. Organization and funding

The AlternaFuture has been organized according to Fig. 1. The industrial and governmental user partners have been involved both in the definition of the scop-of-work, and have also contributed in the actual research.
The project has been an internal HydroCen owned project. The steering committee has consisted of the four work package leaders in HydroCen, and the project work has been coordinated and led by an appointed project coordinator.

The project has been divided in three main activities; (A1) mapping the current situation and defining environmental restrictions for reconstruction, (A2) developing physical scenarios consisting of hydropower projects, environmental projects and use of new innovations, and (A3) economic and environmental evaluation of the scenarios. Each of the activities has been managed by a dedicated activity leader and conducted by a team of researchers (3-4 researcher per activity).

To ensure cross-disciplinary cooperation, biweekly meetings with scientific discussions has been organized. The work has also been presented at HydroCen events and three workshops with the user partners have been conducted as a part of the research work. One field trip to the Mandal river hydropower system was conducted together with the hydropower operator Agder Energi.

The project has been funded through the Open-Calls budget in HydroCen. The purpose of the Open-Calls budget is to initiate new research projects and can finance application writing and project development. The total budget of AlternaFuture has been a total of 2.4 mill. NOK over a 12-month period. The funding was initially split in 0.65 mill. NOK to each of the three activities in the project and 0.45 mill. NOK was reserved for common expenses, administration, and project management. Some adaptations have been made during the course of work.

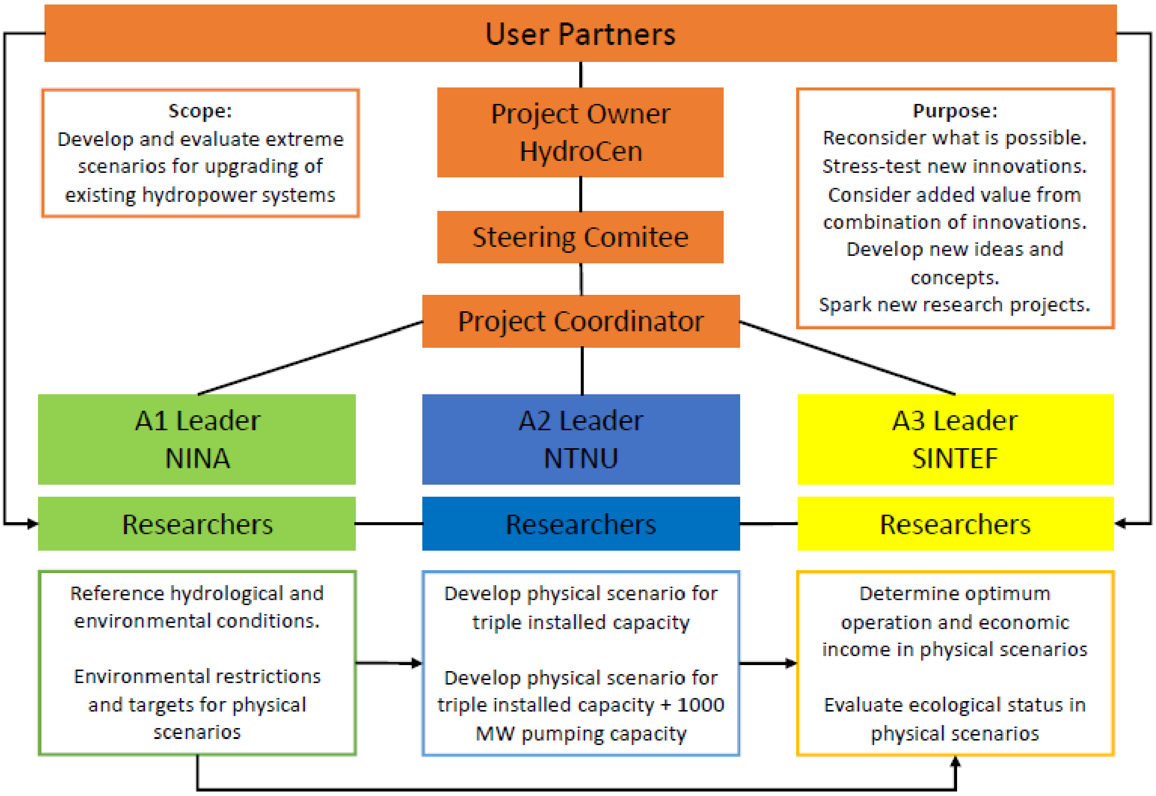


Figure 1: Organization of the AlternaFuture project.

2 Methodology

The work has been conducted as a desk-study based on a case-study of the Mandal river hydropower system. A field trip to the Mandal river was also conducted together with the hydropower system owner and operator Agder Energi. The project has been divided in three main activities; (A1) mapping the current situation and defining environmental restrictions for reconstruction, (A2) developing physical scenarios consisting of hydropower projects, environmental projects and use of new innovations, and (A3) economic and environmental evaluation of the scenarios. The methodology for each activity is presented and discussed below.

2.1. Activity A1: Mapping the current situation

For activity A1 the current situation (the reference case) was mapped through available reports, documentation and online tools presented in the table below. Three groups of reference indicators were identified; (1) hydrological indicators, (2) ecological indicators, and (3) recreational indicators. The hydrological indicators for reservoirs are based on the Vann-Nett classification of heavily modified water bodies (small, moderate, large and unknown) depending on the level of regulation of the reservoir (Direktoratsgruppen, 2018). For the river reaches, the classification was carried out following the classification from the environmental design handbook (Forseth and Harby, 2014), a comparison of the indices for summer low flow and winter low flow before and after regulation were used to indicate possible hydrological bottlenecks.

The ecological indicators for reservoirs and river stretches where chosen with the aim to rank the different water bodies with regards to the potential for increased ecological status. To increase ecological status, it is important to identify current “bottlenecks”, which are factors which limits the current ecological status, such as production of juvenile brown trout. Common factors leading to bottlenecks for the local fish populations are typically water quality (low pH due to acidification), lack of spawning habitat or recruitment areas. Data from previous studies with test-fishing carried out using standard gill-net series has been available in the work. Catch per unit effort (CPUE) is defined as number of fish caught per 100 m^2 net area per night. This measurement is used as an indicator for the density of the fish population. Further the size of females and the percentage they represent in a population indicates the quality of the fish population (Ugedal et al. 2005). Refence values for CPUE, LAI, PH are according to the classification levels published in Sandlund et al. 2013.

Three main reference indicators for the recreational value have been selected; conservation of pristine areas, recreational use for humans, and water management for recreational use. These values can be contradictory and a subjective assessment of what is most valuable is made. The least possible nature intervention will be regarded as highly valuable for several people. At the same time, several construction roads increase accessibility to areas that would otherwise not be as easily accessible, and construction of skiing track in pristine areas are very popular for recreational use. Water is regarded as valuable to anyone who lives by or travels on roads with views to reservoirs and streams. Some reservoirs and river stretches are used for swimming and paddling. However, to much water during flood may hinder recreational use.

Table 1: Sources of information

Source of information	Description	Reference
Reports and documentation	The Mandal river has been subject to a number of previous research projects.	See reference list.
NVE Atlas	An online map-based tool with access to publicly available data on land-use, hydrology, power plants, the power grid, geological surveys, and much more.	https://atlas.nve.no/
NEVINA	An online map-based tool for hydrological surveys based on publicly available data.	https://nevina.nve.no/
Vann-Nett	An online map-based tool for work and information related to the EU Water Framework Directive.	https://vann-nett.no/portal/

NVE cost base	A report with expected costs of hydropower construction in Norway per component. Based on statistical data of completed hydropower projects.	http://publikasjoner.nve.no/rapport/2016/rapport2016_46.pdf
HydroCen Price Series	Energy price series for various future scenarios developed in the HydroCen research center.	Schäffer, L.E. and Graabak, I. 2019. Power Price forecasts. HydroCen Report 5. Norwegian Research Centre for Hydropower Technology. Trondheim
NVE hydrological data series	Publicly available hydrological data series with high quality and for many years.	

Activity A1 also includes selecting the price forecasts for evaluation of the economic feasibility of the upgrading scenarios. The price forecasts are used to simulate the economic income and water management from operation the current hydropower system (the reference case). The simulation program ProdRisk, developed by SINTEF and widely used in the Nordic hydropower industry, was used. The researchers working in activity A1 has been:

Table 2: Researchers working in activity A1

Name	**Title**	**Expertise**
Torbjørn Forseth (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Line Elisabeth Sundt-Hansen (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Torbjørn Hesthagen	Senior Researcher	Acid rain, Trout, Aquatic ecology
Margrete Skår	Senior Researcher	Social science, Social geography, Social anthropology
Ana Adeva Bustos (SINTEF)	Research Scientist	Hydrology, Ecohydraulics
Linn Emelie Schäffer (SINTEF)	Research Scientist	Production simulation and optimization, Power markets, Price forecasts
Birger Mo (SINTEF)	Chief Scientist	Production simulation and optimization, Power markets, Price forecasts

2.2. Activity A2: Scenarios for extreme upgrading

The scenarios for upgrading of the existing hydropower system was developed in activity A2. Each scenario consists of a combination of hydropower projects and environmental projects. Three scenarios were developed:

1. Triple installed capacity [MW]
2. Maximum flexibility
3. Flood protection

The technical design of the hydropower projects and environmental projects is determined through a desk-study of maps, and the available information about inflow from activity A1. The construction costs are estimated based on the NVE cost base (NVE, 2016). The selection of hydropower projects and environmental projects has been based on a simple methodology hereafter referred to as “the deck-of-cards method” presented in Vereide et al. (2019).

The deck-of-cards method proceeds by first mapping all potential hydropower projects and environmental projects in the Mandal river. A workshop with researchers and user partners in HydroCen was organized as a part of this work. The most unrealistic projects in terms of constructions costs and environmental impacts were discarded. The remaining projects have been described on a two-page document referred to as “hydropower cards” and “environmental cards”, with information about technical details, costs and impact on hydropower production.

To determine the final scenarios, a selection of the hydropower cards where selected by the researchers according to the strategy reflected by the title of each scenario. Thereafter, the environmental experts determine how many and which environmental cards are necessary to balance the environmental impact. A final discussion is conducted between the hydropower engineers and environmental experts to make final adjustments and finalize the scenarios. The selection of projects is based on the subjective judgement of the researchers and cannot be regarded as optimal. The researchers acknowledge that there is potential for improvement of the scenarios. However, the final environmental impact is methodically investigated in activity A3 and is regarded as reasonable.

In addition to the work with developing the three scenarios for reconstruction, an assessment of the innovations from HydroCen, and proposals for new research projects have been made in activity A2. A total of 16 “innovation cards” present two-page assessment of the innovations from HydroCen. Each innovation has been tested on a case-study in the Mandal river hydropower system, and the potential economic or environmental benefits are quantified and compared with the estimated costs. These assessments are limited by the selection of potential case-studies in the Mandal river. As an example of the consequences, sediment related innovations will yield limited value as there are limited sediment in the river. The “innovations cards” should be regarded as a simple screening of the potential of the innovations from HydroCen.

A total of 18 potential research projects have been identified and described on two-page “research project cards”. The purpose has been to identify research projects that can provide a continuation of the work in the AlternaFuture-project. As a part of the multidisciplinary cooperation in AlternaFuture, several interesting potential research projects where discussed and the most promising are now described on the “research project cards” with problem description, assumed impact, need for funding and cooperation partners. The researchers working in activity A2 has been:

Table 3: Researcher working in activity A2

Name	Title	Expertise
Leif Lia (NTNU)	Professor	Civil and Hydraulic Engineering, Hydropower planning, Dam engineering
Kaspar Vereide (NTNU/Sira-Kvina kraftselskap)	Adj. Ass. Prof./Project Developer	Civil and Hydraulic Engineering, Hydropower planning
Eirik Øvregård (NTNU)	Scientific Assistant	Civil and Hydraulic Engineering
Arne Nysveen (NTNU)	Professor	Electrical Power Engineering, Generator design
Pål Glimen (NTNU)	Lecturer	Electrical Power Engineering, Control systems
Torbjørn Kristian Nielsen (NTNU)	Professor	Mechanical Engineering, Turbine design
Håvard Barkved (NTNU)	M.Sc. student	Engineering Geology
Torbjørn Forseth (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Line Elisabeth Sundt-Hansen (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Ana Adeva Bustos (SINTEF)	Research Scientist	Hydrology, Ecohydraulics

2.3. Activity A3: Quantifying the effects

In activity A3, the economic income and the impacts on the environmental status for each of the three scenarios is evaluated and compared with the present situation. The production optimization program ProdRisk has been used to determine the hydropower plant operation and water management for each of the scenarios, based on defined price forecasts and the environmental and technical restrictions. The reservoir water levels and river flows are analyzed and compared with the present day situation to evaluate the environmental impacts based on the hydrological, ecological and recreational reference indicators. The researchers working in activity A3 has been:

Table 4: Researchers working in activity A3

Name	Title	Expertise
Torbjørn Forseth (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Line Elisabeth Sundt-Hansen (NINA)	Senior Researcher	Environmental design, Atlantic salmon, Aquatic ecology
Torbjørn Hesthagen	Senior Researcher	Acid rain, Trout, Aquatic ecology
Margrete Skår	Senior Researcher	Social science, Social geography, Social anthropology
Ana Adeva Bustos (SINTEF)	Research Scientist	Hydrology, Ecohydraulics
Linn Emelie Schäffer (SINTEF)	Research Scientist	Production simulation and optimization, Power markets, Price forcasts
Birger Mo (SINTEF)	Chief Scientist	Production simulation and optimization, Power markets, Price forcasts

2.4. Selection of case-study

It was decided to base the research on a case-study to make the results more relevant and applicable. Several hydropower systems where considered. The Mandal river hydropower system was selected because of availability of environmental data and because of the owner's, Agder Energi, willingness to accept the study of extreme upgrading and to provide assistance. Another reason was that this river has many relevant challenges regarding upgrading of the hydropower plants:

- Several protected nature parks
- One protected river contributary
- A salmon population of national importance
- Flooding problems in the downstream area
- Housing areas, cabin areas, agriculture, and recreational use

These and other aspects make it challenging to upgrade and expand the hydropower system. Exactly for this reason, the selection of this river is beneficial as it generates interesting research questions and challenges.

A field trip to the Mandal river was conducted the 3-4th of June 2019. The field trip was conducted together with researchers and personnel from Agder Energi, the operator of the Mandal river hydropower system. The purpose of the field trip was to get familiar in the river basin and with the power plants, identify the potential positions of new dams, intakes power plants and outlets, and consider construction of the environmental measures. A workshop with engineers and environmental experts from Agder Energi was conducted on the 4th of June.

3 Mapping the current situation (A1)

This chapter presents results from activity A1. The Mandal river hydropower system currently consists of six hydropower plants with a total installed capacity of 384 MW with an average annual energy production of 1.7 TWh. The river has a total catchment area of 1810 km^2, starting from 1160 to 0 masl., and an average annual runoff of 2650 mill. m^3. The hydropower development took place between 1932 and 1961. Fig. 2 presents a map with of the river basin and the existing hydropower system.

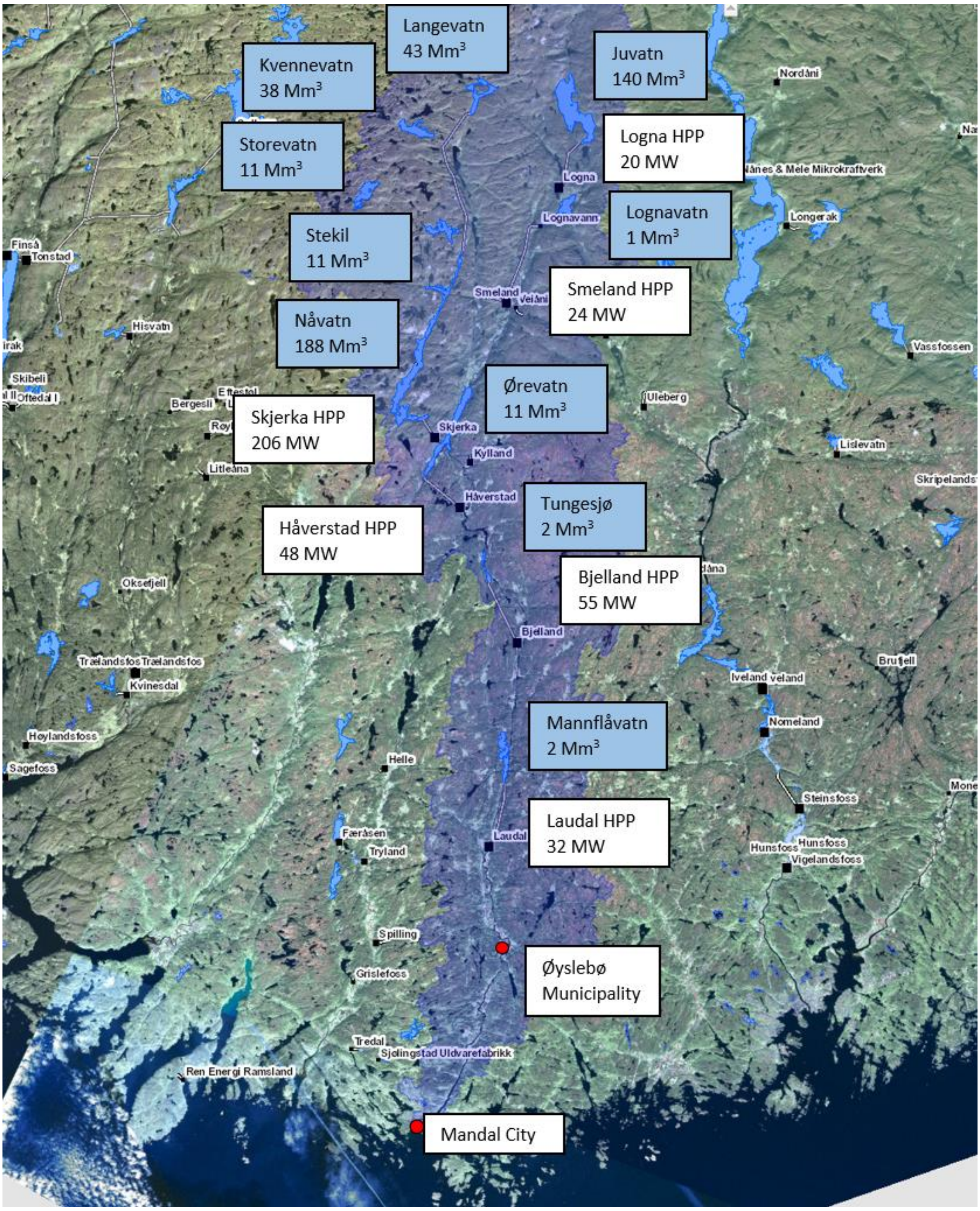


Figure 2: Mandal river hydropower system (background from NEVINA). Existing hydropower plants and reservoirs in white and blue boxes respectively. The two major inhabited areas Øyslebø and Mandal shown with red circles.

3.1. ProdRisk modelling and price forecasts

The present hydropower system and the future scenarios are analyzed using the same assumptions for the energy price and hydrology. Three price series are used: 1) simulated prices for year 2015 that has been scaled to match variability and mean of the historical price in 2017, 2) simulated prices for year 2030, and 3) simulated prices for year 2030 with increased variability. All the price series are stochastic, meaning that the simulated price series include prices for a range of different weather years given the same system. To ensure a good reference for comparison, three simulations of the current system, assuming different energy prices, have been conducted. The price forecasts are based on previous work from HydroCen presented in Schäffer and Graabak (2019).

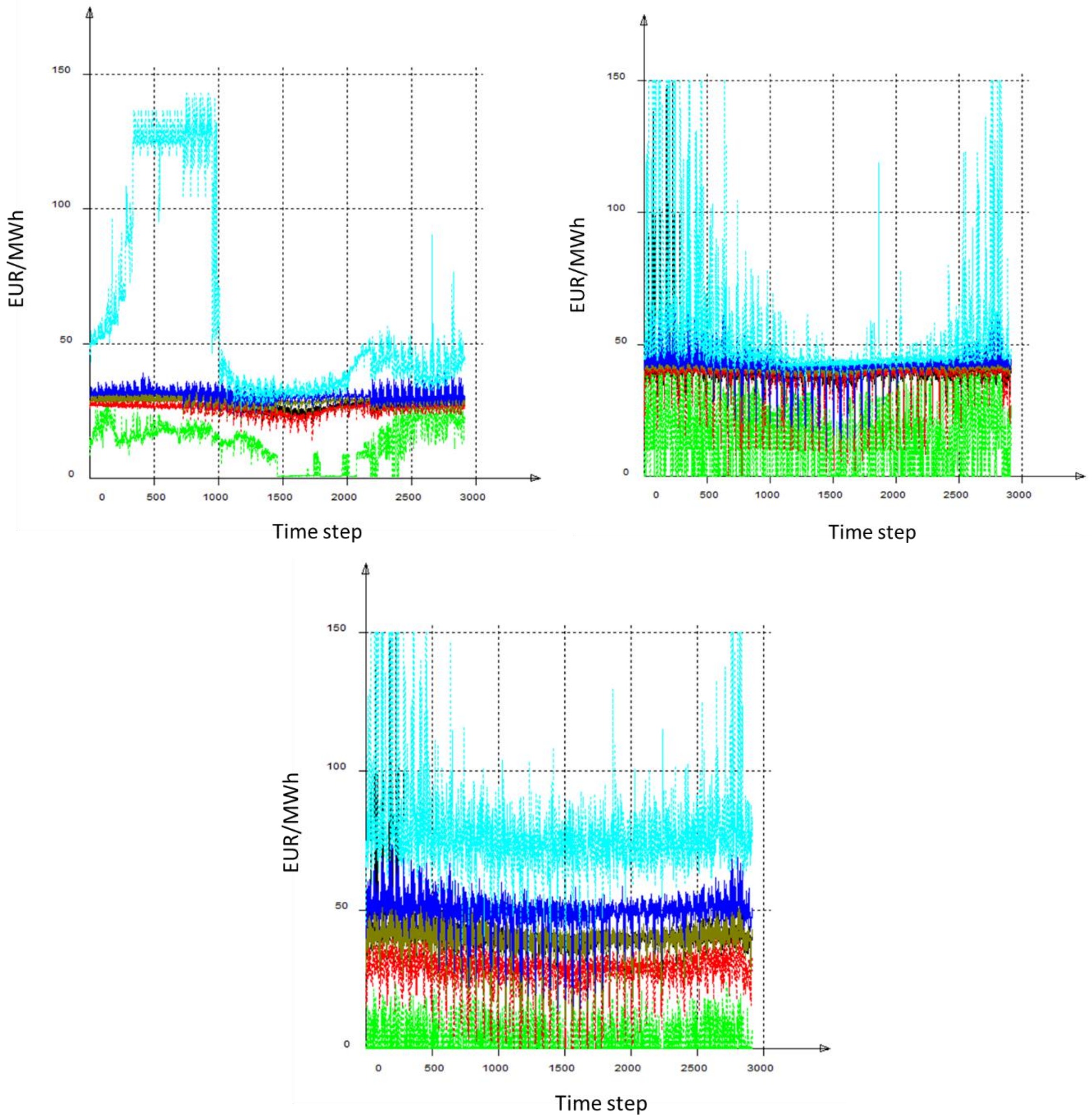


Figure 3: Percentile plots of the applied energy price forecasts. Prices for 2015 are top left, prices for 2030 is top right and the prices for 2030 with increased variability is on the bottom. The plot shows the 0, 25, 50, 75 and 100% percentiles as well as the average energy price. The time resolution is three hours. The y-axis has been capped at 150 EUR/MWh. The maximum price reaches almost 3000 EUR/MWh for the two 2030 scenarios.

The Mandal hydro system has been modelled in ProdRisk using a description of the system provided by Agder Energi. Minor updates of the model were done in cooperation with Agder Energi, such as including a new hydropower plant (Skjerka HPP) and new dams (Skjerkevassdammen, Dam Langevatn). The applied model includes currently ongoing construction projects as finalized.

The system consists of several intakes, reservoirs and power plants. The power plants in the system can include several units but are modelled as one plant. Operation of the system is optimized to maximize profit honoring the physical limitation of the system and existing environmental constraints. There are six power plants in the system where Skjerka is by far the largest power plant in the system with a maximum power output around 200 MW.

The system consists of three subsystems; (1) Skjerka power plant and Skjerkevann reservoir with several intakes and smaller reservoirs upstream, (2) Smeland power plant with Logna power plant, Juvann reservoir and two intakes upstream, and (3) downstream of Skjerka and Smeland where the water from the two arms meet and goes through Haaverstad, Bjelland and Laudal power plants. All the reservoirs in the lower part of the system are quite small. Spillage and bypassing water can run from the first to the second part of the system, connecting the two arms. We have divided the system into three parts because it will make it easier to discuss the changes made to the system in the development scenarios in later analyses. An overview of the entire system is provided in the figure below. The red boxes illustrate power plants, the numbers within the boxes are the max power output in MW, flow in m^3/s and associated energy equivalent in kWh/m^3. The blue lines illustrate reservoirs or intakes with the storage volume given in mill. m^3. The arrows give the yearly inflow to that part of the system in mill. m^3. The unbroken lines show the destination of the discharge water from a plant, while broken lines show the destination of spillage and bypass if this deviates from the discharge water.

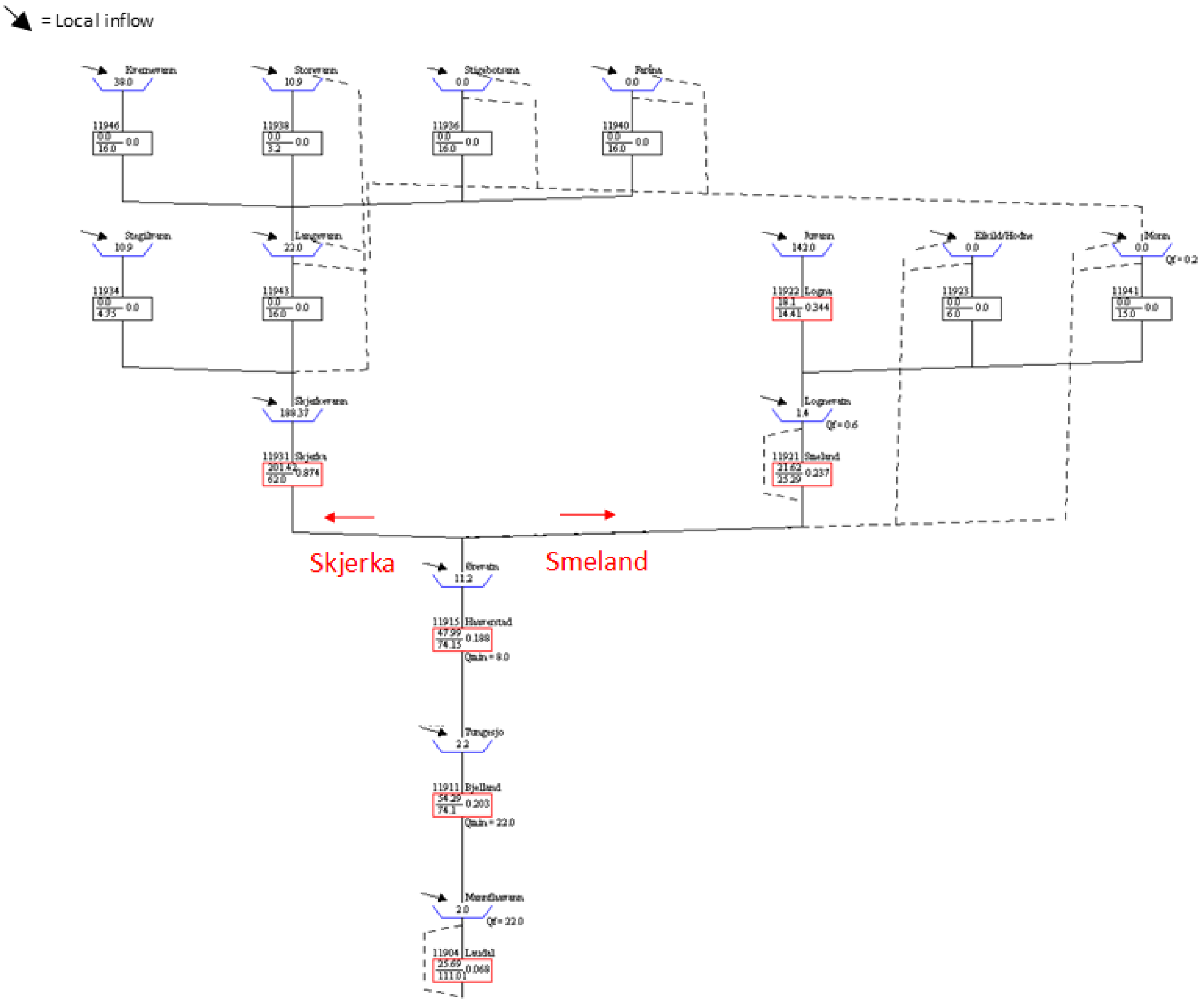


Figure 4: ProdRisk model

The results from the ProdRisk model is presented in detail in Memo 2. An example of the results is presented in the figures below. The first figure shows the reservoir water level in Skjerkevann, simulated for 60 different inflow years, for the three different price forecasts. We see a difference in the seasonal profile where the 2030 simulations give one more distinct peak in spring before the reservoir level is drawn down during summer. Furthermore, we see that the 2030 price with increased variability (2030 price scaled) seems to keep a slightly higher reservoir filling in the beginning of the year. The second figure shows a duration curve of the operation of the Skjerka power plant. As can be seen the power plant is operated to produce more on peak power for the 2030-scaled price forecast.

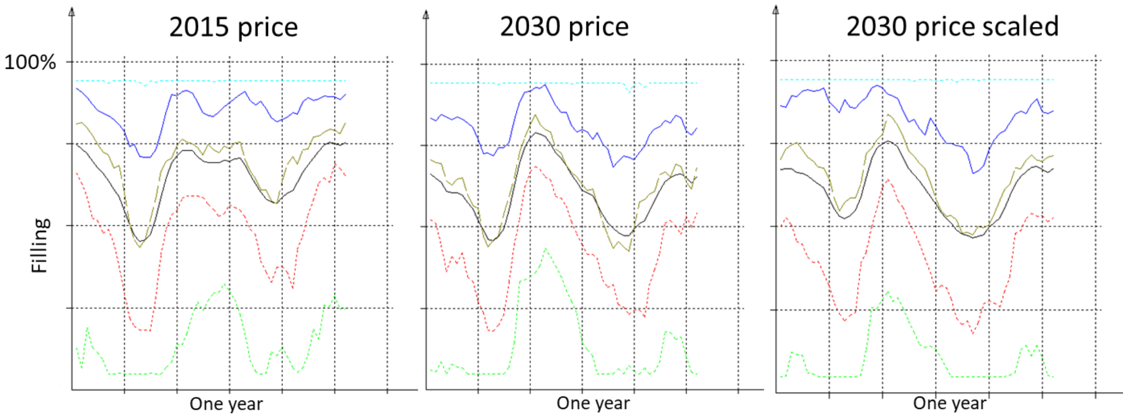


Figure 5: Percentile plot of the reservoir water level in Skjerkevann based on 60 weather years. The plot shows the 0, 25, 50, 75 and 100% percentiles as well as the average water level.

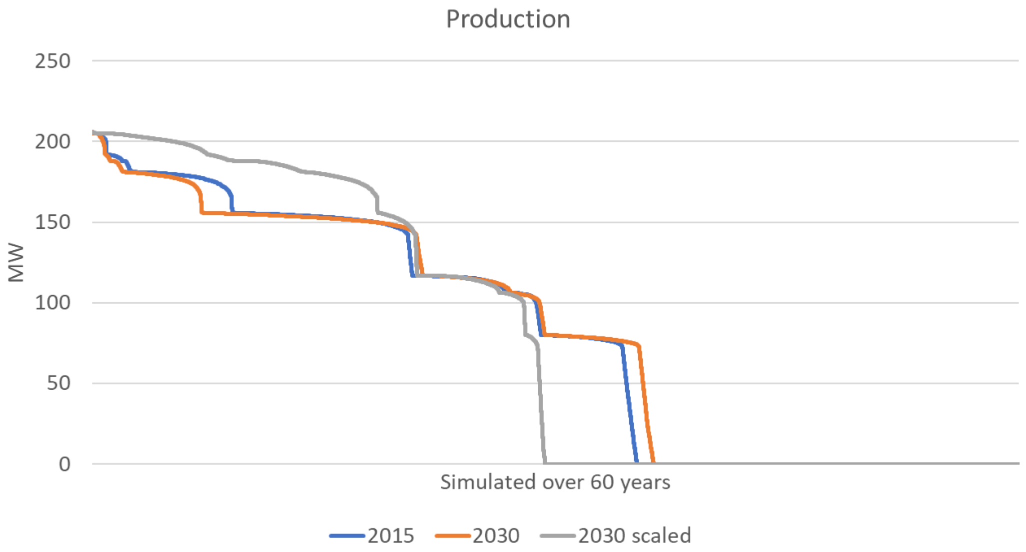


Figure 6: Duration curve of the power production per time step from Skjerka power plant. The plot shows the results from simulations over all 60 years given the three different price forecasts.

The results from the simulations are given in the table below. The total yearly income increases from just above 50 million EUR for the 2015 price forecast to just above 80 million EUR for the 2030-scaled price forecast.

Table 5: ProdRisk results for the current system

Price forecast	Energy production [GWh]	Net income [Mill. €]	Achieved price [€/MWh]
2015	1730	51	29.7
2030	1740	73	41.6
2030-scaled	1710	81	47.5

3.2. Mapping of the environmental conditions and reference indicators

This section presents the results from the mapping of the present status of the environmental condition in the Mandal river, both with focus on hydrology and aquatic biology. Reference indicators to quantify the change in ecological status and to determine environmental restrictions for reconstruction scenarios and targets for improving the current ecological status are identified. A total of eight reservoirs and lakes and four river stretches in the Mandal basin has been evaluated based on hydrological and ecological reference indicators.

It has been chosen to focus mostly on the upper part of the river, upstream of the anadromous stretch. This stretch is much less studied than the anadromous stretch, which has been the subject of several research projects in the recent years assessing impact of hydropower production and improving environmental conditions. The largest potential for improvements is therefore assumed to be found in the upper part of the river.

For the unregulated period hydrological data was obtained from NEVINA (http://nevina.nve.no/) and for the regulated period from the ProdRisk model. For reservoirs the following hydrological indicators were chosen:

- Lowest regulated volume
- Highest regulated volume
- Minimum water surface elevation (Min)
- 10% percentile water surface elevation (Pctl 10th)
- Average water surface elevation (Avg)
- 90% percentile water surface elevation (Pctl 90th)
- Maximum water surface elevation (Max)

For the river reaches, six hydrological indicators that are ecologically relevant for fish populations and for hydromorphological changes (Richter et al., 1996, Poff and Zimmerman, 2010) were calculated for the unregulated and regulated period.

- Annual mean flow (AMF)
- 5% percentile flow (Q95)
- Annual mean flood (AMFlood)
- Ten-year flood (10YFlood)
- 7-days minimum summer low flow (summer low flow)
- 7-days minimum winter low flow (winter low flow)

Reference indicators for the ecological condition where selected to rank different reservoirs and river stretches with regards to the potential for increased ecological status. The following reference indicators have been identified:

- Acidity (pH). The Mandal river has low pH owing to acidification and hard rock geology.
- Amount of spawning habitat or recruitment areas.
- Acid neutralizing capacity (ANC), which is a measure of the overall buffering capacity against acidification and is usually included as a potential predictive variable in models that evaluate the effects of acidification on fish populations. ANC has also been used to estimate the tolerance limits of nature to acidification and for setting a goal for future deposition rates to avoid future damage and assure recovery of fish populations. The lower ANC threshold for Norwegian lakes has been set to 20 ueqL-1 to avoid damaged stocks (Hesthagen et al. 2012). The relationship between ANC and biological response is indirect because changes in ANC also involve changes in parameters such as pH and labile aluminum (LAl). Any specific ANC value may represent a wide range of pH and LAl levels.
- Labile aluminum (LAl).
- Catch per unit effort (CPUE) defined as number of fish caught per 100 m^2 net area per night. This measurement is used as an indicator for the density of the fish population.
- The size of females and the percentage they represent in a population indicates the quality of the fish population (Ugedal et al. 2005).

The water quality parameters for are found from Vann-Nett and are classified according to the levels published in Sandlund et al. (2013). Studies of the fish population in Juvatn, Sandvatn, Lognavatn are published in Hesthagen and Haugland (2007, 2008). Studies of the aquatic biology from different reservoirs in Mandal river is presented in Hesthagen and Walseng (2012, 2013, 2014, 2015). These reports have provided the documentation of the current situation in the Mandal river.

The three reference indicators for the recreational values presented below have been chosen. These values are considered based on qualitative assessments and the assumed effects of construction of hydropower and environmental measures.

- Conservation of pristine areas
- Recreational use for humans
- Water management for recreational use.

The upper part of the Mandal River is located close to Setesdal-Vesthei-Ryfylkeheiane conservation area in the west, and serves as a gateway to trips further into the mountains. There are also many summer tours and ski trails in the northern part due to the proximity to two large cabin areas (Ljosland and Bortelid). The cabin areas also have alpine resorts, in addition to the Eikerapen alpine resort southwest of Øre. The northernmost reservoirs are believed to be the most utilized areas for recreational activity.

All of these factors indicate that the least possible nature intervention will be regarded as highly valuable for many people. At the same time, new construction roads increase the accessibility to areas that would otherwise not be as easily accessible. The southern reservoirs are located in areas where there are fewer cabins, while there are permanent scattered settlements in several places. Water is regarded as a valuable to anyone who lives by or travels on roads with views to reservoirs and streams. Some reservoirs and river stretches are used for swimming and paddling, such as Juvatn and Øre.

The resulting mapping of the current situation can be found in Memo 3. An individual assessment of each reservoir and each river reach is provided. An overview of the current hydrological and ecological condition in the Mandal river is presented in the figures on the next pages.

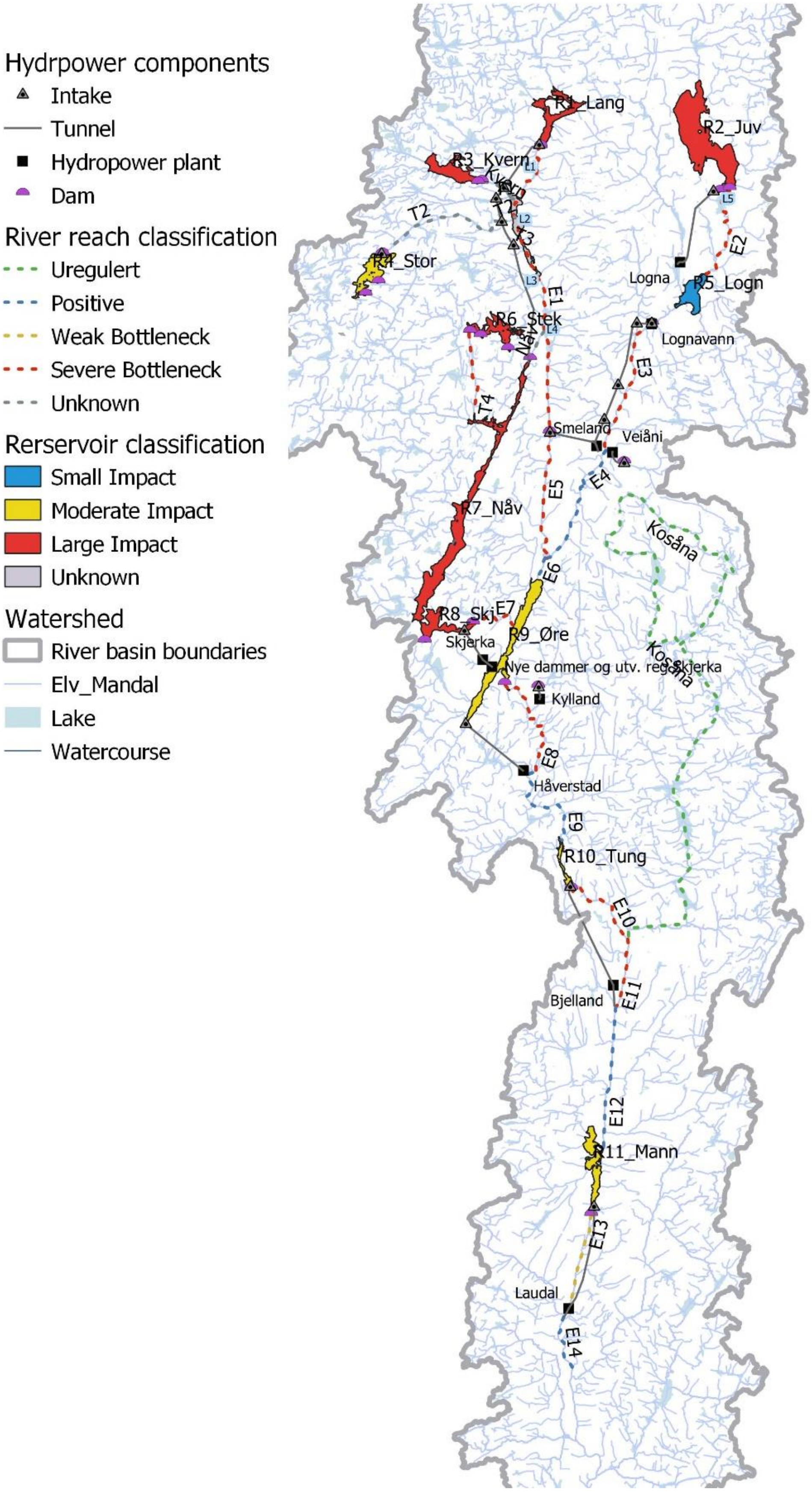


Figure 7: Hydrological classification for reservoirs and river reaches

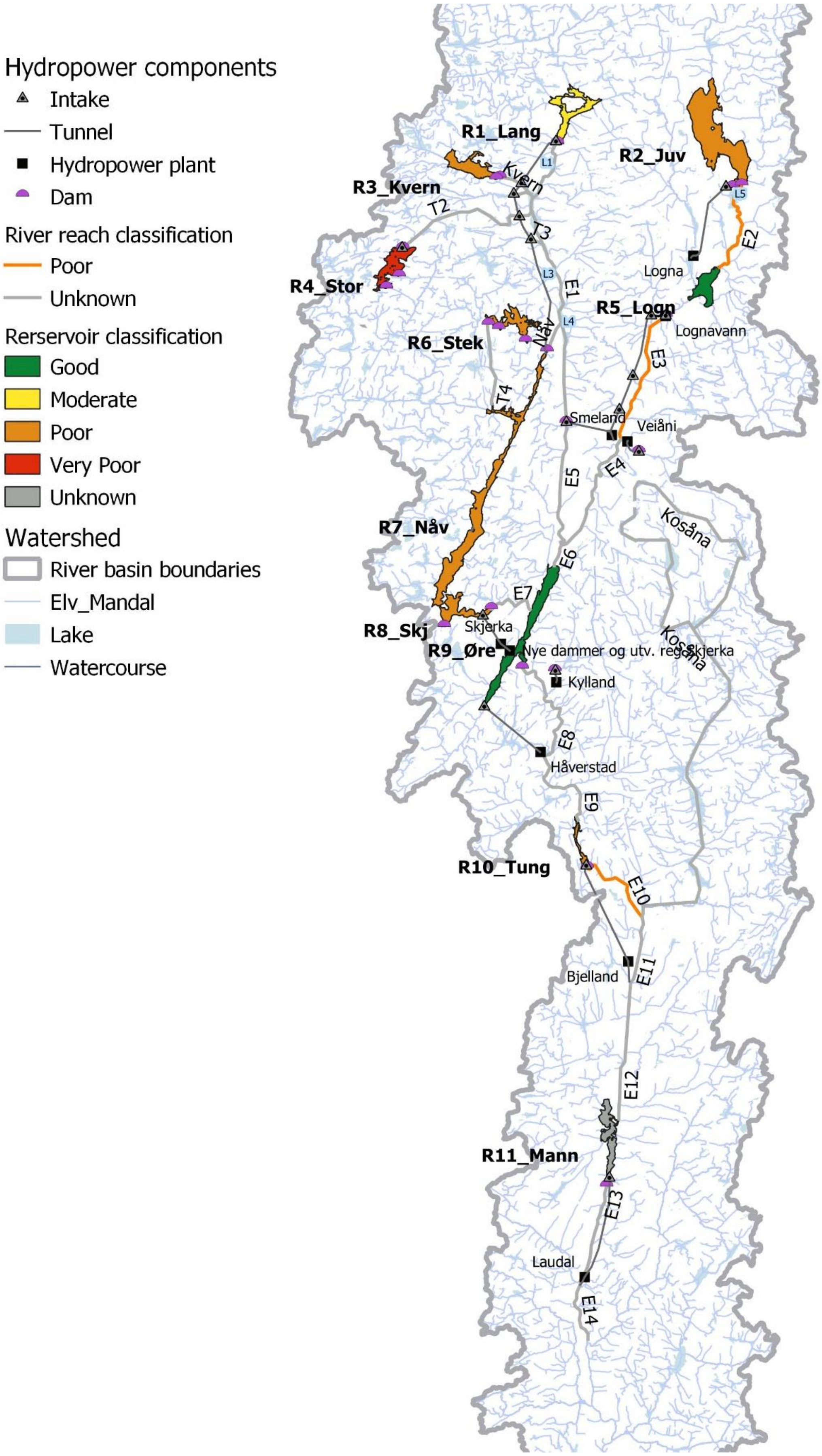


Figure 8: Ecological classification for reservoirs and river reaches.

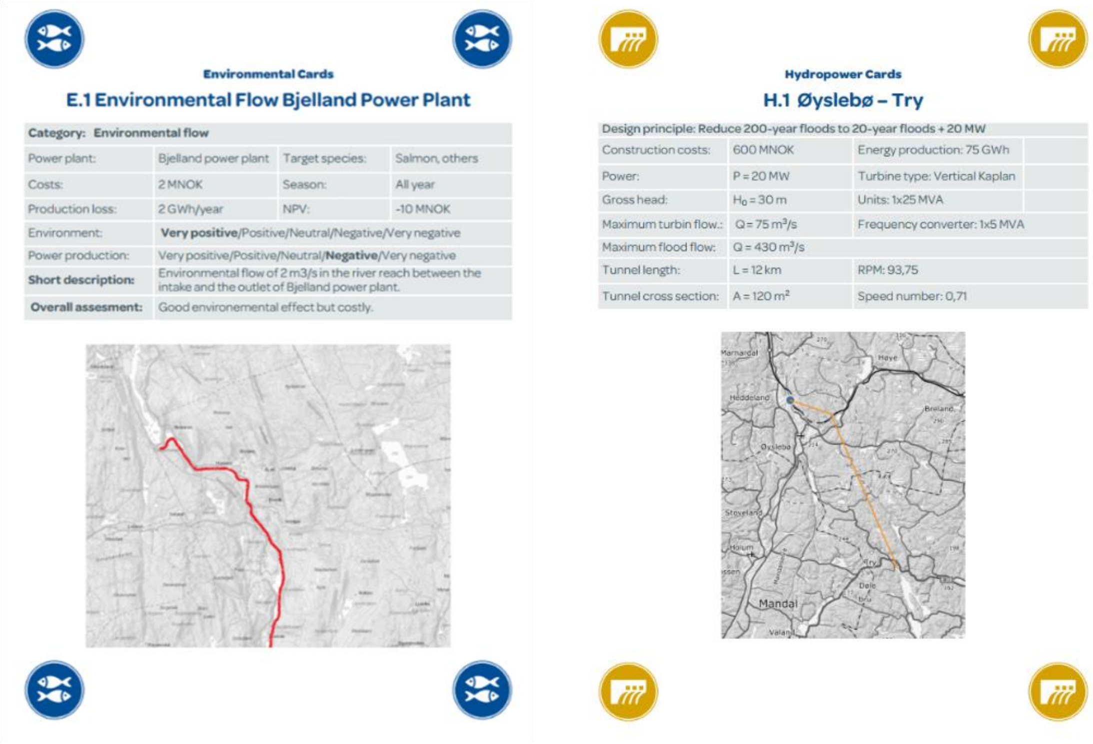
4 Scenarios for extreme upgrading (A2)

4.1. Hydropower cards and environmental cards

This section presents the screening and selection of hydropower projects and environmental projects for extreme upgrading of the Mandal hydropower system. To provoke new ideas and solutions, some challenging design criteria were introduced:

- The installed capacity [MW] in the system should be tripled
- The environmental conditions in the river should be improved

By combining hydropower projects and environmental projects, three scenarios for extreme upgrading of the Mandal hydropower system with potentially positive environmental impact have been selected. Two-page "hydropower cards" and "environmental cards" presenting each of the projects are given in Memo 3&4. These cards present the key information, costs and evaluation of each project. The figure below presents an example of one environmental project and one hydropower project.



Environmental Cards

E.1 Environmental Flow Bjelland Power Plant

Category: Environmental flow			
Power plant:	Bjelland power plant	Target species:	Salmon, others
Costs:	2 MNOK	Season:	All year
Production loss:	2 GWh/year	NPV:	-10 MNOK
Environment:	**Very positive**/Positive/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/Neutral/**Negative**/Very negative		
Short description:	Environmental flow of 2 m3/s in the river reach between the intake and the outlet of Bjelland power plant.		
Overall assesment:	Good environemental effect but costly.		

Hydropower Cards

H.1 Øyslebø – Try

Design principle: Reduce 200-year floods to 20-year floods + 20 MW			
Construction costs:	600 MNOK	Energy production: 75 GWh	
Power:	P = 20 MW	Turbine type: Vertical Kaplan	
Gross head:	$H_0 = 30$ m	Units: 1x25 MVA	
Maximum turbin flow.:	$Q = 75\ m^3/s$	Frequency converter: 1x5 MVA	
Maximum flood flow:	$Q = 430\ m^3/s$		
Tunnel length:	L = 12 km	RPM: 93,75	
Tunnel cross section:	$A = 120\ m^2$	Speed number: 0,71	

Figure 9: Example environmental card and hydropower card

The screening and selection of environmental projects is presented in the subchapters "potential" in Memo 3. The method has been to identify "bottlenecks", which factors that currently limit the ecological status. Based on the bottleneck, appropriate measures to improve the ecological status have been proposed.

Screening and selection of the hydropower projects is presented in Memo 4. The screening was done by using the webservice NVE Atlas that holds maps and information about all existing and planned hydropower plants in Norway. Online maps were used to look for suitable areas for new reservoirs and new power plants. In addition to the ideas from the researchers, some ideas were proposed by Agder Energi, and other ideas came up during a workshop with researchers and user-partners from HydroCen. These ideas were then evaluated by the researchers in activity A2. All ideas with potential were moved to the next phase where dimensions, costs and productions were roughly estimated. In June 2019 the researchers visited the Mandal river and the locations of the proposed projects. Further improvements were made to the projects. The proposed solutions have been distributed on a hearing among all participants and the solutions have been iterated several times. In the end the most favorable projects were identified, and a two-page "hydropower card" were made for each of them.

Table 6: Environmental projects

No.	Type	Name	Description
E1	Fish habitat	Juvatn reservoir	Improve conditions for the local trout population. Reservoir restrictions during migration, cell weirs and spawning river entrances
E2	Ecological status	Logna river	Improve ecological status of the river segment between intake and outlet of Logna HPP. Increased environmental flow and make small ponds to heighten the water table and improve spawning and hatching conditions for trout.
E3	Ecological status	Nåvatn reservoir	Improve ecological status and conditions for local trout. Shellsand chalking, make small ponds and provide spawning gravel in Uvdalsåni. Floating docks for boats for the local inhabitant.
E4	Fish habitat	Ørevatn reservoir	Mitigate the current overpopulation of local trout. Close off some side rivers to reduce spawning.
E5	Fish ladder	Kavfossen fish ladder	Prolong the anadromous reach of the Mandal river and improve the ecological conditions in regulated river segment between intake and outlet of Bjelland power plant. Construct a fish ladder in Kavfossen and increase the environmental flow from Bjelland power plant.
E6	Fish migration	Laudal river	Improve habitat and migrating conditions for migrating fish including Atlantic salmon. Increase the environmental flow and reconstruct the intake of Laudal power plant.
E7	Flood mitigation	Mandal flood protection	Reduce 200-year floods to 20-year floods. Construct a flood power plant that can function as a bypass tunnel during damaging floods. Must be constructed with a fish friendly intake and must have a high environmental flow.
E8	Fish habitat	Stekil reservoir	Improve conditions for the local trout population. Reservoir restrictions, cell weirs and spawning river entrances
E9	Fish habitat	Storevatn reservoir	Progress from artificial recrutation to natural recrutation of local trout. Make cell weirs at entrance to side rivers to ease fish migration to spawning rivers.
E10	Fish habitat and recreation	Langevatn reservoir	Improve natural recrutation of local trout. Make cell weirs to ease fish migration to spawning rivers.

Cost-benefit optimization of projects has not been carried out. This was regarded as too time consuming and not necessary for the scope of the project. The main parameters for the technical design of the hydropower projects were set based on established rules-of-thumb to estimate acceptable dimensions of the hydropower structures and electromechanical installation.

All real limitations are accounted for in selection of hydropower projects. The hydropower projects should not be placed in protected nature, urban areas, or infrastructure. Tributaries protected from hydropower development cannot be used. Diversion projects to other rivers are not considered. Projects with severe negative environmental impacts where discarded. Upgrading of roads and the power grid has not been accounted for. However, the national power grid in this area is currently being upgraded. In addition, as there is already a significant existing power grid serving the existing hydropower plants, the costs for upgrading the power can be expected to be reasonable.

The hydropower cards are divided into four categories: (A) conventional power plants, (B) pump storage hydropower plants, (C) flood power plants, (D) New reservoirs. The hydropeaking projects entail making new power plants in parallel with the existing ones, sometimes combining two old power plants into one new. The pumped storage projects are all new projects utilizing larger reservoirs in the system. The flood power plants are hydropower plants that are designed to significantly reduce damaging floods in the river reach, from 200-year return periods to 20-year return periods. The flood power plants function as simple bypass tunnels during large floods and operate as normal hydropower plants utilizing the same tunnel and infrastructure during periods of normal flow. The reservoir projects are increasing the dam heights of existing reservoirs and one potentially new reservoir. The finally proposed hydropower projects are presented in the table below.

Table 7: Hydropower projects

No.	Type	Name	Possible capacity	Description
A1	Hydropeaking	Juvatn HPP	80-100 MW	Parallel to Logna HPP and Smeland HPP
A2	Hydropeaking	New Skjerka HPP	200-600 MW	Parallel to Skjerka HPP
A3	Hydropeaking	New Bjelland HPP	100-300 MW	Parallel to Bjelland HPP
A4	Hydropeaking	New Laudal HPP	50-100 MW	Parallel to Laudal HPP
B1	Pumped storage	Storavatn PSP	200-600 MW	From Ørevatn to new Storavatn reservoir
B2	Pumped storage	Ørevatn PSP	200-400 MW	Parallell to Håverstand and Bjelland HPP
B3	Pumped storage	Nåvatn PSP	50-100 MW	From Nåvatn to Stekil, Storevatn, Kvennevatn and Langevatn
B4	Pumped storage	Langevatn PSP	50-100 MW	From Langevatn to Juvatn
C1	Flood power plant	Try FPP	10-50 MW	Flood bypass tunnel from Øyslebø municipality to the sea
D1	Reservoir	Storavatn reservoir	100-300 mill. m3	New reservoir connected to Nåvatn
D2	Reservoir	Kvennevatn reservoir	50-100 mill. m^3	Raising Kvennevatn dam
D3	Reservoir	Juvatn reservoir	300-600 mill. m3	Raising Juvatn dam

4.2. Selected scenarios for extreme upgrading

Three scenarios combining hydropower projects and environmental projects have been proposed. The three scenarios are developed to provide one alternative for each of the characteristics described in the table below. The figure below shows the northern part of Mandalsvassdraget in the maximum flexibility scenario.

Table 8: Selected scenarios for extreme upgrading

Name	Hydropower projects	Environmental projects
Hydropeaking (triple installed capacity)	A1, A2, A3, A4, C1	E1, E2, E3, E4, E5, E6, E7
Maximum flexibility (pumped storage)	B1, B2, B3, B4, M1, M2, M3	E1, E4, E5, E8, E9, E10
Flood protection	A4, C1, B1, B2, M1	E4, E5, E6, E7, E8

The first two scenarios adhere to the original design criteria, more than tripling the installed capacity, while the third scenario was included due to interesting research topics. These scenarios are forwarded for production simulations with ProdRisk for comparison with the present situation

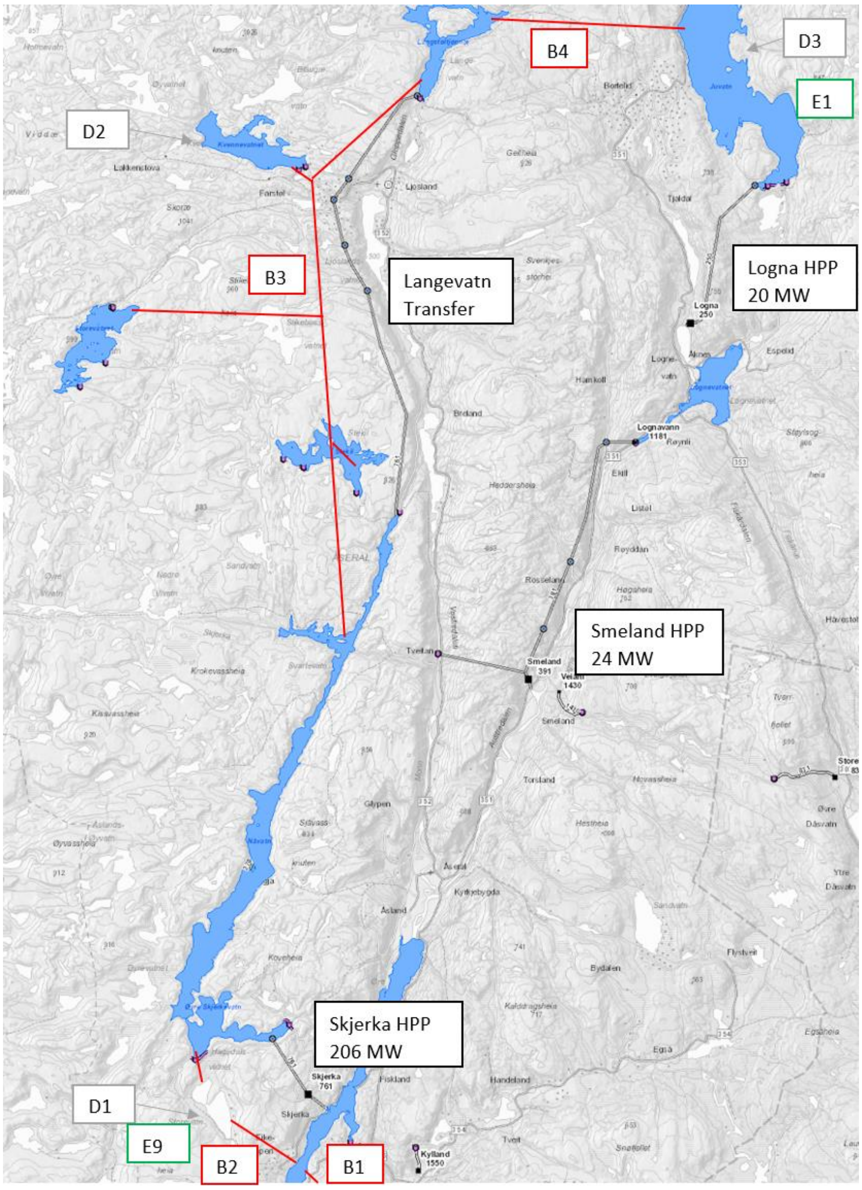


Figure 10: Overview of the maximum flexibility scenario

4.3. Innovation cards and research project cards

In addition to the screening and selection of environmental and hydropower cards, an assessment of the innovations from HydroCen has been conducted based on case-studies from the Mandal river. Also, research project cards, describing potential research projects that are regarded as necessary to enable extreme upgrading of hydropower systems in the future are proposed. A total of 16 innovation cards and 18 research project cards are presented in Memo 5.

At the time of writing, a total of 16 innovations have been generated directly or indirectly as a part of the work in HydroCen. To consider the potential and establish a benchmark for the innovations, they have been "stress-tested" on case-studies in the Mandal river. This has been done as a part of the AlternaFuture-project to provide insights to how new technology may enable extreme upgrading of hydropower systems in the future. The table below presents an overview of the innovations generated directly or indirectly from the work in HydroCen. The table is color coded based on a TRL grading based on a subjective assessment by the authors.

Table 9: Innovations from HydroCen

No.	Name	Type	TRL
1	Deck-of-Cards-Method	Scientific Method	8
2	SediSluicer for Brook Intakes	Sediment Handling	8
3	SHOP-ProdRisk Coupling	Production Optimization	6
4	OMGvanes	Mechanical Engineering	5
5	Flexible Sandtraps	Hydraulic Engineering	5
6	Tunnel Balloon Plug	Operation and Maintenance	5
7	Fault Detection in Generators	Electrical Engineering	5
8	Snorkel for Large Coanda Screen Intakes	Civil Engineering	5
9	Guideless Francis Turbine for Reduced Sediment Abrasion	Sediment Handling	5
10	Improved Design of ACSC	Civil Engineering	5
11	LeakReg	Mechanical Engineering	4
12	VarSpeed Pumping to Multiple Reservoirs	Electromechanical Design	4
13	Anti-Diving Sickness	Fish-Friendly Design	3
14	AcurLE	Hydropeaking Mitigation	3
15	AcurHE	Reservoir Optimization	3
16	Fish Friendly Hydropower Tunnels	Fish-Friendly Design	2

Table 10: Proposed research projects

No.	Name	Discipline	Type	Funding (MNOK)	Period (years)
1	The Value of Hydropower Flexibility	Multi	KPN	20	4
2	Flood Power Plants	Multi	KPN	20	4
3	Fish Friendly Intakes for Pumping	Fish/Hydraulic	PhD	5	4
4	Fish Friendly Intakes for Flood Power Plants	Fish/Hydraulic	PhD	5	4
5	Generator Capability	Electro	PhD	5	4
6	Temperature-Controlled Water Release	Eco/Hydraulic	PhD	5	4
7	Draught Period Water Release	Eco/Hydraulic	KPN	20	4
8	Cell Weirs in Reservoir	Fish/Hydraulic	PhD	5	4
9	Thermic Inertia for Reactive Power	Electro	PhD	5	4
10	Heat Energy in Hydropower Plants	Electro/Mech.	IPN	20	4
11	Fish Friendly Hydropower Tunnels	Fish/Hydraulic	PhD	10	4
12	Tunnels as Reservoirs	Hydraulic	PhD	5	4
13	Cost Reduction 50% for Hydropower	Multi	IPN	20	4
14	Virtual Inertia	Electro/Mech.	PhD	5	4
15	Digital Twin Turbine Governor	Mech.	IPN	20	4
16	Social Acceptance for Hydropower	Social	IPN	20	4
17	Pumped Storage with Multiple Upper Reservoirs	Electro/Mech.	PhD	5	4
18	Underground Pumped Storage Plants	Multi	KPN	20	4

5 Quantifying the effects (A3)

5.1. Economic assessment

This section presents the simulation results for the three scenarios for reconstruction of the Mandal hydropower system using the ProdRisk model. Details concerning the implementation of the scenarios (the changes made in the model of the Mandal system) and simulation results using three different price series are described in Memo 6.

The simulation results are compared to simulations of the current system to evaluate the impact of the scenario on the economic results and environmental conditions in the system. Three different price forecasts have been used to understand how the system will be operated for different future development of the European power system and its impact on energy prices in Norway, and assess the potential income for different market scenarios.

The results from the ProdRisk simulations are presented in the figure and table below, and some trends can be observed. For all the scenarios, the hydropower plants without pumping capability are operated fewer hours when the price variability increases. They are also start-stopping and changing load more often with increasing variability. The pumped storage plants are also changing operation mode and load more often with higher price variability, but these plants are also found to operate in more hours with increasing price variability. Economically, scenario 2 (maximum flexibility) is the scenario with the highest economic potential. We also see that the income from this scenario increase the most with increasing variability. In the scenario with highest price variability, the two scenarios with pumping capacity (scenario 2 and 3) have a much larger increase in income compared with scenario 1. The increase in income between price forecast 2030 and 2030-scaled is modest for scenario 1 compared to scenario 2 and 3. We see that there is a large difference in the income from the new power plants. Especially, New Skjerka, Storavatn PSP, New Bjelland, and Ørevatn PSP have high incomes. However, it is also necessary to see the change together with change for corresponding parallel power plant, as well as the changed operation for the rest of the system. For example, we find that New Juvatn PSP in scenario 2 for price forecast 2015 has a net negative income. Still, the plant is used for pumping, as the water pumped by the plant can be used for power production in other power plants. The economic results in this study only include sale of energy in the day-ahead market. In the future power system, flexible power plants are also expected to have an increasing income from supplying ancillary services, such as providing frequency reserves, and potentially also from delivering services that are not compensated today, such as rotational inertia. It is uncertain how much income these types of services will contribute with in the future.

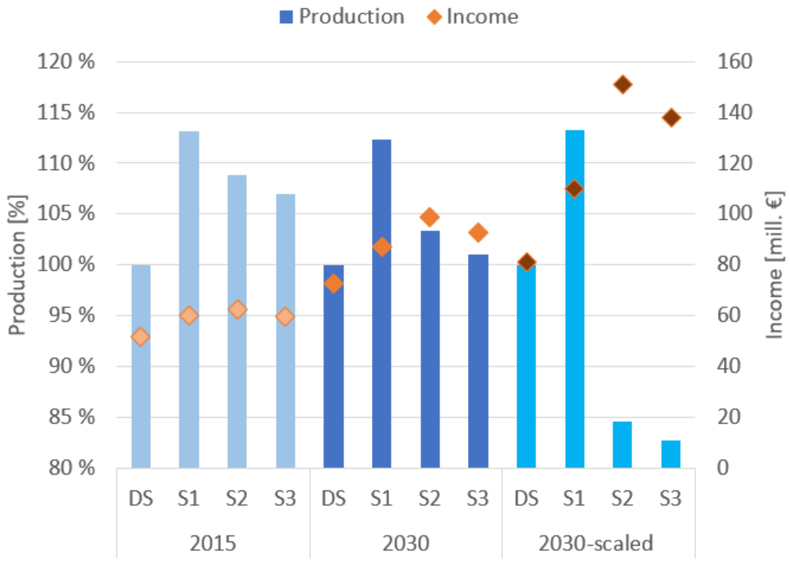


Figure 11: Energy production and income for each scenario. Values are relative to the current situation.

Table 11: ProdRisk results

		2015				2030				2030-scaled			
		CS	S1	S2	S3	CS	S1	S2	S3	CS	S1	S2	S3
Spillage	GWh	223	197	103	262	211	198	102	264	229	202	119	296
Pumping	GWh	-	-	424	221	-	-	764	581	-	-	2276	1930
Gain from pumping	GWh	-	-	361	181	-	-	617	449	-	-	1833	1506
Net pump energy	GWh	-	-	-63	-40	-	-	-147	-132	-	-	-444	-424
Start reservoir	GWh	349	391	943	684	316	405	918	623	325	325	859	577
End reservoir	GWh	352	394	952	690	320	408	924	628	328	327	865	582
Total production	GWh	1732	1960	1885	1853	1742	1957	1801	1759	1706	1931	1442	1410
Net income	Mill. €	51	60	62	59	73	87	99	93	81	110	151	138
Compared to current system	Mill. €		9	11	8		15	26	20		29	70	57
Achieved price	€/MWh	29.7	30.7	33.0	32.0	41.6	44.6	54.7	52.8	47.5	56.9	104.6	97.7

All the scenarios are seen to generate a higher annual income from power production. However, there is a large difference between the scenarios and for the different price forecasts. The maximum flexibility scenario is seen to generate the highest income for all the price forecasts. And the 2030-scaled prices are seen to generate the highest income for all reconstruction scenarios.

To assess the potential profitability of the reconstruction scenarios, a net present value (NPV) calculation is conducted. The NPV is calculated based on a 40-year lifetime and with standard industry values for discount rate, taxes and operational costs. The construction costs from Memo 4, the simulated production and income from Memo 6. The NPV is calculated based on the marginal production, income and price compared with the 0-alternative (the current system). As can be seen the marginal production and price for the 2030-scaled scenario is negative, owing to efficiency loss during pumping. However, the resulting marginal income and calculation of NPV is correct. The table below presents the main values for calculation of the NPV. Additional details concerning the NPV calculation can be found in Memo 8.

Table 12: Input parameters for NPV-calculation

Parameter	Value	Unit
Discount rate	3.5	%
Economic lifetime	40	Years
Interest rate, loan	0	%
Loan % of costs	0	%
Grid tariff	0.0018	€/kWh
Tax, nature resources	0.0013	€/kWh
Tax, company	22	%
Tax, hydropower	37	%
Norm free income	2	%
Tax, concession	0.0007	€/kWh
Tax, property	0.0016	€/kWh
Amount of concession power	10	%
Price concession power	0.0113	€/kWh
Green certificates	0	€/kWh
Income from system services	0	€/kWh

Table 13: Net present value results

		2015			2030			2030-scaled		
		S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Construction costs	Mill. €	393	514	460	393	514	460	393	514	460
Marginal production	GWh	228	153	121	215	59	17	225	-264	-296
Marginal income	Mill. €	9	11	8	15	26	20	29	70	57
Marginal price	€/MWh	39.5	71.9	66.1	69.8	440.7	1176.5	128.9	-265.2	-192.6
NPV	Mill. €	-300	-387	-363	-252	-265	-262	-142	98	31

The results show that the scenarios for extreme reconstruction are not profitable with the current prices (2015). It is also not profitable for the assumed 2030 prices. However, for the 2030-scaled prices, scenario 2 (extreme flexibility) and scenario 3 (flood protection) are found profitable. The main contribution to the increased income is the pumped storage plants which are able to exploit the increasing variability in energy prices. A discussion of these results is found in the discussion chapter.

5.2. Environmental assessment

This section presents the environmental assessment for the three scenarios for reconstruction of the Mandal hydropower system based on the results from the ProdRisk simulations. The evaluation of environmental impact was made based on hydrological, ecological and recreational reference indicators.

The expected environmental (hydrological + ecological) and recreational effects are scored in the tables below. The score ranges from very negative (---), via no effects (0) to very positive (+++) for each of the assessed water bodies. The total effect is summarized. The first two columns are based on the simulated values from ProdRisk without mitigation measures, whereas the latter two tabulates the effects including the environmental projects. Signs in brackets indicate particularly uncertain effects. UE indicate unknown effects.

Table 14: Environmental assessment of scenario 1.

Waterbody	Environmental effects	Recreational effects	Environmental effects including environmental projects	Recreational effects including environmental projects
R2 Juvatn	++	+	++	+
R5 Logna	0	0	0	0
R7-8 Nåvann/Skjerka	-	-	0	0
R9 Ørevann	0	0	+	+
EI Langvann-Monn	-	UE	+	UE
E2 Logna	++	+	++	+
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0(+)	+	0(+)	+
TOTAL EFFECT	**+**	**+**	**++**	**++**

Table 15: Environmental assessment of scenario 2.

Waterbody	Environmental effects	Recreational effects	Environmental effects including environmental projects	Recreational effects including environmental projects
R1 Langevann	(-)	0	0	0
R2 Juvatn	+	0	++	(+)
R3 Kvennevann	(-)	-	+	-
R4 Storevann	---	--	-	-
R5 Logna	UE	UE	UE	UE
R6 Stekil	0	0	+	(+)
R7-8 Nåvann/Skjerka	---	---	---	---
R9 Ørevann	0	0	0	+
EI Langvann-Monn	-	UE	+	UE
E2 Logna	++	+	++	+
T4 Uvdalsåni (river stretch	0	0	0	0
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0(+)	+	0(+)	+
TOTAL EFFECT	**-**	**-**	**++**	**++**

Table 16: Environmental assessment of scenario 3.

Waterbody	Environmental effects	Recreational effects	Environmental effects including environmental projects	Recreational effects including environmental projects
R7-8 Nåvann/Skjerka	---	---	---	---
R9 Ørevann	0	0	0	+
EI Langvann-Monn	0	UE	0	UE
E2 Logna	0	UE	0	UE
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0 (-)	0	0	0
TOTAL EFFECT	**-**	**0**	**0**	**+**

In scenario 1 the total installed capacity in MW of the Mandal river hydropower system was tripled, including a flood power plant. The effect on the ecological and recreational values varied among the assessed water bodies. However, with the implemented mitigation or compensation measures the total effect was classified as weak positive, but if additional measures were implemented, the total effects are classified as positive.

In scenario 2, full flexibility, the current installed capacity was tripled, and pumping capacity of 750 MW was included. Strong negative environmental and recreational effects were found for the new Nåvann-Skjerka-Storavatn reservoirs, whereas the Tungefoss-Kavfossen river stretch was the only strong positive effect (present in all the scenarios). However, if additional measures were implemented the total effect are classified as slightly positive for the environment and neutral for recreation (the positive effects are counteracted by the new Storavatn dam representing a major intervention in an attractive area).

In scenario 3, flood dampening, one flood power plant and pumping capacity of 620 MW was included. The effects on the ecological and recreational values were strongly negative for the Nåvann/Skjerka/Storevann reservoir, whereas the compensatory measures in the Tungesjø-Kavfossen was regarded as strongly positive. Because of the large interest associated with salmonid fishes the total effects are classified as small positive. The positive societal effects of flood protection are considerable, but not considered in this assessment.

In conclusion, it is found potentially possible to realize extreme upgrading of existing hydropower system, and at the same time have a potential positive effect on the environmental conditions. It is noted that the positive effects require a significant effort in mapping and planning the environmental measures. For such overall upgrading consisting of multiple projects, single projects that have severe negative ecological impacts must be cancelled and not included in the final scheme. Planning of such upgrading projects therefore have to include environmental experts from the very beginning.

6 Main findings and discussion

This chapter presents the main findings and a discussion of the results. The AlternaFuture research project has resulted in several interesting and unexpected findings, especially the evaluation of the environmental impacts and economic impacts of extreme upgrading of hydropower.

6.1. Environmental effect of the extreme upgrading scenarios

The project has shown that it is possible to allow extreme upgrading of existing hydropower system, that can also in sum have a positive impact on the environmental conditions. This result has not been found or presented in previous literature and has significant implications. It has traditionally been assumed that reconstruction and upgrading of hydropower projects cannot be done without negative environmental impacts. That assumption has now been proven false.

This result is believed to be valid for a wide range of the existing hydropower schemes in Norway. The case-study, Mandal river hydropower system, has significant challenges such as conserved areas, protected rivers, and a nationally important salmon population. It can be assumed that when it is possible to produce an environmentally friendly design of extreme upgrading including tripling of the installed capacity and pumped storage plants in this river, it will be possible also in other rivers.

To enable environmentally friendly design of hydropower projects, it is vital to include environmental experts from the start. Traditionally, hydropower projects are designed by engineers, are thereafter sent to environmental experts for environmental assessments of an already final design. By including the environmental experts from the very beginning, the boundary conditions for the design can be set from the beginning, and components with severe environmental impacts can be avoided.

6.2. Economic feasibility of the extreme upgrading scenarios

The results show that extreme upgrading of existing hydropower systems can be economically feasible if the energy price variability increases sufficiently. This is an obvious conclusion, but it is now possible to quantify approximately how much the energy price variability must increase. The answer is in between the expected 2030 price forecast and the 2030-scaled forecast. As the extreme upgrading scenarios are not economically feasible for the expected 2030 price forecast, it is hence not expected that the scenarios will be feasible investments. It is seen that extreme upgrading without pumped storage plants is not economically feasible for any of the price forecasts.

The average energy price does not have to increase to make upgrading profitable. It is mainly the energy price variability that determines if upgrading is profitable. As can be seen from the results, the upgrading does not necessarily result in an increase of the power production, and hence it is the increased flexibility to produce power when the prices are high and pump water when prices are low that is the main value.

It is pointed out that the scenarios are not optimized and that the economic feasibility has not been assessed individually per hydropower projects. Thus, there may be certain of the proposed hydropower projects that are economically feasible also in the expected 2030 price forecast.

6.3. Pumped storage plants

The results show that it is the pumped storage plants that generate the bulk of the income for the 2030 and 2030-scaled price forecast. The pumped storage plants are capable of exploiting variations in the energy prices and store water from low price seasons to high price seasons. As is typical for Norway, the large reservoirs with potential for construction of pumped storage plants are located in the upstream part of the river. Hence the operation influence and benefit all the power plants downstream, increasing the potential for production planning optimization and the economic benefits.

The results demonstrate that the pumped storage plants in the proposed upgrading scenarios are net consumers of energy (except when they can reduce flood losses in downstream reservoirs). The energy production in the scenarios with pumped storage plants is decreasing compared with the present hydropower system. This has several special implications, such as reduced taxes on the hydropower production. Several of the Norwegian taxes on hydropower are related to the energy production. Hence, when the energy production decreases owing to operation of pumped storage plants, these taxes are reduced. In the current tax regime, the taxes to the local municipalities decrease. At the same time, the taxes to the central government increase dependent on economic profit from the power plants.

6.4. Potential for new hydropower projects in existing hydropower systems

The researchers were able to identify several new hydropower projects in the Mandal river. The Storavatn reservoir and the Try flood power plant are regarded as especially interesting. The project shows that there is still potential for new projects in existing hydropower systems.

6.5. Flood power plants and flood mitigation through hydropower

The Mandal river has challenges related to flooding. As late as in 2017, a major flood caused severe damages in the urban areas Øyslebø and Mandal. In addition, new flood estimates (NVE, 2019) show that floods become more frequent in the future.

One of the hydropower projects identified in the AlternaFuture project is a flood power plant; a combination of a flood bypass tunnel and a hydropower plant. This type of hydropower plant can potentially allow cost-efficient flood protection for the Mandal river. The project will be able to reduce a 200-year flood to a 20-year flood, basically reducing a very harmful flood to a non-harmful flood. The project has not been found economically feasible only based on hydropower production, and other stakeholder such as insurance companies or the local municipality has to cover the remaining costs. These costs and the environmental impacts can potentially be less compared with other flood protection measures. Such flood power plants can also be expected to be possible also in other major rivers in Norway, as many of the largest cities are located on the outlet of major rivers.

New reservoirs and pumped storage plants in the upstream end of the Mandal river, such as proposed in the reconstruction scenarios, will also have a positive effect on flood dampening in the Mandal river. These effect on flood dampening has not been quantified in this project.

6.6. Limitations of the study

The results are subject to a series of limitations. More descriptions concerning the limitations are presented in the Memos.

- The project has been performed as a desk study, relying on previous studies, available literature and publicly available information and data. The quality of this data influences the results.
- The selection and evaluation of environmental projects and environmental reference indicators are based on a desk study and are partly based on subjective expert opinion.
- The screening and selection of hydropower projects are based on a desk study. The design of the hydropower projects are based on rules-of-thumb.
- The ProdRisk modelling is subject to several simplifications and assumptions as described in Memo 2 and 4. In general, ProdRisk is a model and cannot fully represent all the practical aspect influencing operation of the hydropower plants.
- The future is uncertain!

7 Deliverables

The deliverables from the AlternaFuture project is summarized in this chapter. Work on additional scientific publications is currently ongoing. In total, one scientific paper, eight memos, one final report, one master thesis, nine presentations, three popular-scientific publications were produced.

In addition, nine environmental cards, 15 hydropower cards, 16 innovation cards and 18 research project cards have been produced. These contain descriptions of potential environmental and hydropower project and in the Mandal river, an assessment of each of the innovations from HydroCen on case-studies in the Mandal river, and proposals for new research projects to enable extreme upgrading of existing hydropower projects in the future.

The project is potentially controversial owing to the significant impact from extreme upgrading of existing hydropower systems. It was therefore established a communication strategy for the project at an early stage. For this or other reasons, the project has only received positive publicity.

7.1. Scientific Publications

Vereide K., Mo B., Forseth T., Lia L., Nysveen A. and Dahlhaug O. G. (2019). Research on extreme upgrading of existing hydropower systems. Proc. Hydro2019, Porto, Portugal.

7.2. Innovations

The Deck-of-Cards method. A method for screening and developing environmentally friendly scenarios for extreme upgrading. Presented in Vereide et al. (2019).

Fish-friendly tunnels. Concepts to enable hydropower tunnels to be utilized as habitat by fish. Unpublished.

Cell weirs for reservoirs. A technical solution to allow spawning fish to enter spawning tributaries to reservoirs with large regulation heights. Unpublished.

7.3. Final report and Memos

Schäffer L. E. (2019). AlternaFuture Memo 1: Price series. HydroCen Memo, SINTEF.

Schäffer L. E. (2019). AlternaFuture Memo 2: ProdRisk simulations of the current situation. HydroCen Memo, SINTEF.

Sundt-Hansen L. E., Bustos A. A., Forseth T. and Hesthagen T. (2019). AlternaFuture Memo 3: Environmental restrictions for reconstruction scenarios and targets for improving the current ecological status. HydroCen Memo, NINA.

Øvregård E., Lia L. and Vereide K. (2019). AlternaFuture Memo 4: Hydropower projects and scenarios for extreme upgrading. HydroCen Memo, NTNU.

Vereide K., Øvregård E. and Lia L. (2019). AlternaFuture Memo 5: Innovation cards and research project cards, HydroCen Memo, NTNU.

Schäffer L. E. (2019). AlternaFuture Memo 6: Simulations results from scenario 1,2 and 3. HydroCen Memo, SINTEF.

Sundt-Hansen L. E., Bustos A. A., Forseth T. and Hesthagen T. (2020). AlternaFuture Memo 7: Environmental evaluation. HydroCen Memo, NINA.

Vereide K. and Lia L. (2020). AlternaFuture Memo 8: Economic assessment. HydroCen Memo, NTNU.

Vereide K., Mo B., Forseth T., Lia L., Nysveen A., Dahlhaug O. G., Schäffer L. E., Bustos A. A., Sundt-Hansen L. E., Øvregård E., Glimen P., Hesthagen T., Skår M. and Nielsen T. K. (2020). AlternaFuture - Final report, HydroCen Report 18. Norwegian Research Centre for Hydropower Technology.

7.4. Master theses

Barkved (2019). «Mandalsvassdraget – Optimalisering av tunnelsystem med hensyn til ingeniørgeologiske forhold.» Masteroppgave, NTNU, Trondheim, Norge.

7.5. Presentations

2018-12-13, HydroCen scientific group meetings, Presentation, ca. 50 participants.
2019-02-14, HydroCen scientific seminar, Workshop, ca. 20 participants.
2019-06-04, Eikerapen Gjestegård, Workshop, ca. 10 participants.
2019-09-18, HydroCen scientific group meetings, Presentation, ca. 50 participants.
2019-09-19, HydroCen scientific group meetings, Workshop, ca. 30 participants.
2019-10-16, Hydro2019, Conference presentation, ca. 500 participants.
2019-11-20, HydroCen scientific day, Presentation, ca. 20 participants.
2020-02-05, Hydropower summit, Presentation, ca. 50 participants.
2020-03-02 Production conference (PTK), Presentation, ca. 200 participants.

7.6. Popular-scientific publications

2019-07-21 «AlternaFuture – Et forskningsprosjekt på ekstrem ombygging av vannkraft», One-page information letter.
2020-02-13, EnergiTeknikk, Popular scientific magazine, «Fant flomkraftverk og kjempemagasin», Atle Abelsen.
2020-03-13 Fædrelandsvennen, News paper, «Flomtunnel kan stanse ødeleggelser», Jarle Martinsen

7.7. Social media, online and informal communication channels

Vannposten, HydroCen newletters, weekly circulation to HydroCen user partners.
HydroCen webpages.

8 Conclusions and future work

8.1. Conclusions

The main conclusions from the AlternaFuture research project are presented below.

1. Extreme upgrading of existing hydropower systems can be done while also in sum improving the environmental conditions.
2. Extreme upgrading of hydropower systems that include pumped storage plants are economically feasible if the energy price variability increases sufficiently. For the Mandal river, the necessary increase is in between the 2030 price forecast and the 2030-scaled forecast as described in Memo 1.
3. It is the pumped storage plants that generate the main increase of revenue in the upgrading scenarios. Extreme upgrading without pumped storage plants has not been found economically feasible for any price forecast.
4. The pumped storage plants result in a reduced energy production for the hydropower system, but a higher income. In the current tax regime, the pumped storage plants result in reduced taxation to the local municipalities because some of the Norwegian hydropower taxes are related to produced energy. The taxation to the central government increases depending on the economic profit from the pumped storage plants.
5. There is potential to find new hydropower projects in existing hydropower systems.
6. It is possible to construct a flood power plant to mitigate the flood challenges in the Mandal river. The flood power plant is not found to be economically feasible only from hydropower production, and the remaining costs have to be financed by other stakeholders such as insurance companies or local municipalities. The flood power plant can reduce a 200-year flood to a 20-year flood.
7. The extreme upgrading scenarios have a positive impact on flood mitigation owing to new reservoirs and pumped storage plants. This positive impact has not been quantified in this project.
8. Recommended future work includes developing a best-practice guideline for environmentally friendly upgrading of existing hydropower systems based on the methodology developed and applied in this project. In addition, 18 new research projects have been proposed and are described in Memo 5.

8.2. Future work

A total of 18 new research projects are proposed as continuation of the work to enable environmentally friendly extreme upgrading of existing hydropower system in the future. The projects have been sorted by priority at one of the AlternaFuture workshops with participants from the industry, research institutions and the governmental agencies. The list is not complete.

The most crucial project is considered to be an assessment of the value of hydropower flexibility. The AlternaFuture project has assessed the potential economic benefit only based on the value in the spot market for one case-study. A wider study to also assess frequency and voltage reserves, and the large-scale effects of hydropower flexibility in the national and European power grid is warranted.

The proposed research projects on flood power plants and fish friendly intakes for pumping are direct results from the work in AlternaFuture. These projects are regarded as necessary to unlock potential for environmentally friendly upgrading of existing hydropower and cost-efficient flood mitigation.

In addition to the proposed new research projects, it is also recommended to develop a best-practice handbook for design of environmentally friendly upgrading of existing hydropower systems, based on the methodology developed and applied in the AlternaFuture project.

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10 Appendix

Memo 1 – Price series used in simulations of operation (10 pp.)

Memo 2 – ProdRisk simulations of the current Mandal hydro system (11 pp.)

Memo 3 – Environmental restrictions for reconstruction scenarios and targets for improving the current ecological status (31 pp.)

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HydroCen
v/ Vannkraftlaboratoriet, NTNU
Alfred Getz vei 4,
Gløshaugen, Trondheim

www.hydrocen.no
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HydroCen Report nr.18

AlternaFuture

Final Report - APPENDIX

Kaspar Vereide, Birger Mo, Torbjørn Forseth, Leif Lia, Arne Nysveen, Ole Gunnar Dahlhaug, Linn Emelie Schäffer, Ana Adeva Bustos, Line Sundt-Hansen, Eirik Øvregård, Pål Glimen, Trygve Hesthagen and Torbjørn Kristian Nielsen.

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AlternaFuture MEMO nr.1

AlternaFuture

A1: Price series used in simulations of operation

Linn Emelie Schäffer

2019-11-13

1 Introduction

When analysing development scenarios designed for the future, operation of the systems should also be tested on expected power prices for this future. However, to distinguish between the impact of the changes made on the system and the impact of the assumed power price, the current system and the scenarios for the development of the system must be analysed using the same assumptions for the power price. Furthermore, to understand the implications of the price assumptions on the results, several analyses using different price series should be conducted. For this reason, three price series are used: 1) simulated prices for year 2015 that has been scaled to match variability and mean of the historical price in 2017, 2) simulated prices for year 2030, and 3) simulated prices for year 2030 with increased variability. All the price series are stochastic, meaning that the simulated price series include prices for a range of different weather years given the same system. To ensure a good reference for comparison, three simulations of the current system, assuming different power prices, have been conducted.

2 Price series

The simulated price series are meant to illustrate how the system is operated given different assumptions about the surrounding power market, i.e. different assumptions for the development of the European power system. The price series are based on simulated power prices for area Sorland using EMPS on datasets for the Nordic and European power system in different base years (2015 and 2030) and weather data from year 1958 - 2015. All the simulated power prices are on a resolution of 3 hours per time step.

2.1 Simulated power prices based on 2015 system

The simulated price series for year 2015 is meant to illustrate the system as it is today. In addition to the simulated prices based on weather data from year 1958 to 2015, historical price series from 2016 and 2017 in the region have been added, giving power prices for 60 years in total. The simulated power prices have then been scaled to have the same yearly mean as the historical price in 2017. In addition, the simulated prices have been modified based on the observed within the week variation for 2017. Figure 1 shows the percentiles of the power price simulated over 60 years. For most of the weather years the power price is quite flat, centred close to the average price, but in the most extreme years there are considerable higher power prices in the winter and lower prices in summer.

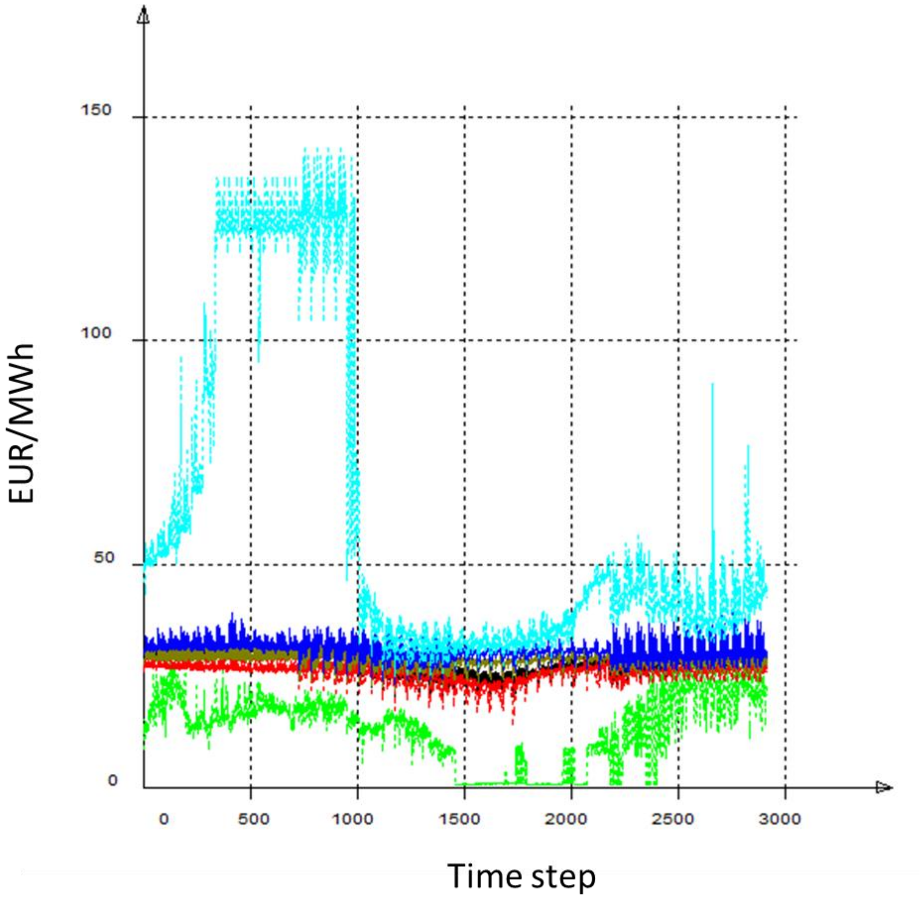

***Figure 1**. Plot of the simulated power price based on year 2015. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.*

2.2 Simulated power prices from the Low Emission scenario in 2030

The simulated price series for year 2030 are taken from the HydroCen Low Emission scenario [1,2]. The simulated prices are based on weather data from 1958 to 2015 but to have power prices for the same the number of years as in the 2015 price series (60 years), two weather years with close to average price characteristics (variation and mean) have been duplicated and added to the end of the series (historical year 1974 and 1988). A very high curtailment price is applied in the simulation of these prices, giving price spikes up towards 3000 EUR/MWh in the most extreme periods, as can be seen in Figure 2. However, in most years and periods the prices are not this extreme. If we focus on the power prices below 150 EUR/MWh, see Figure 3, we see that the power price also varies considerably from time step to time step. There is a significant increase in variability in all years compared to the simulated power prices based on the 2015 system.

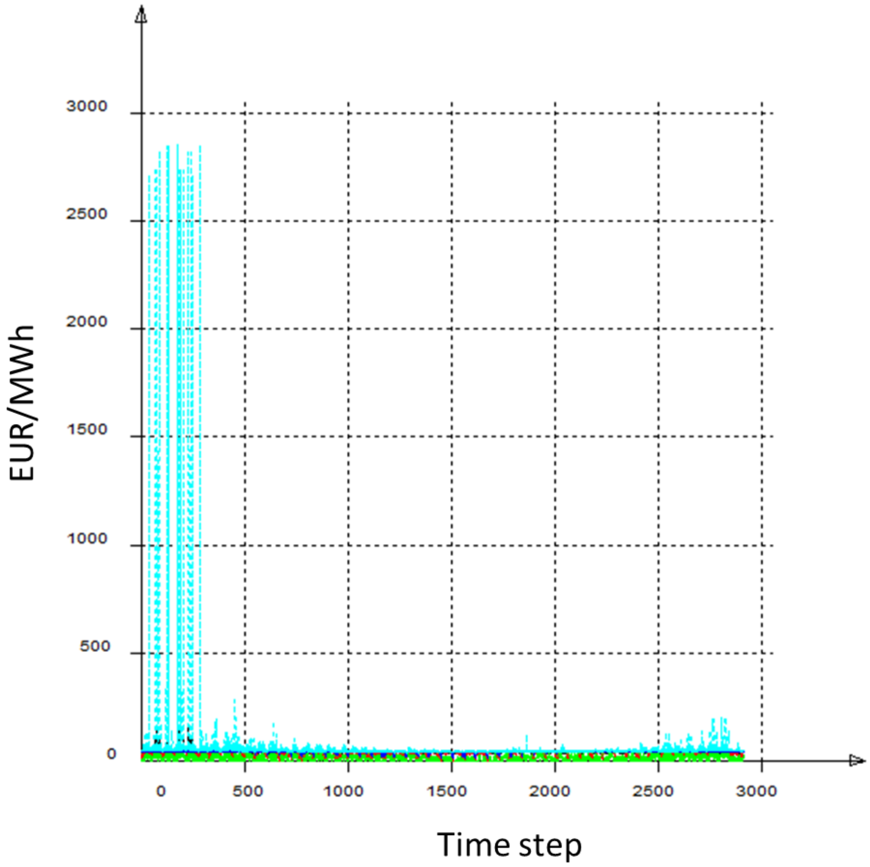

Figure 2. Plot of the simulated power price based on year 2030. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.

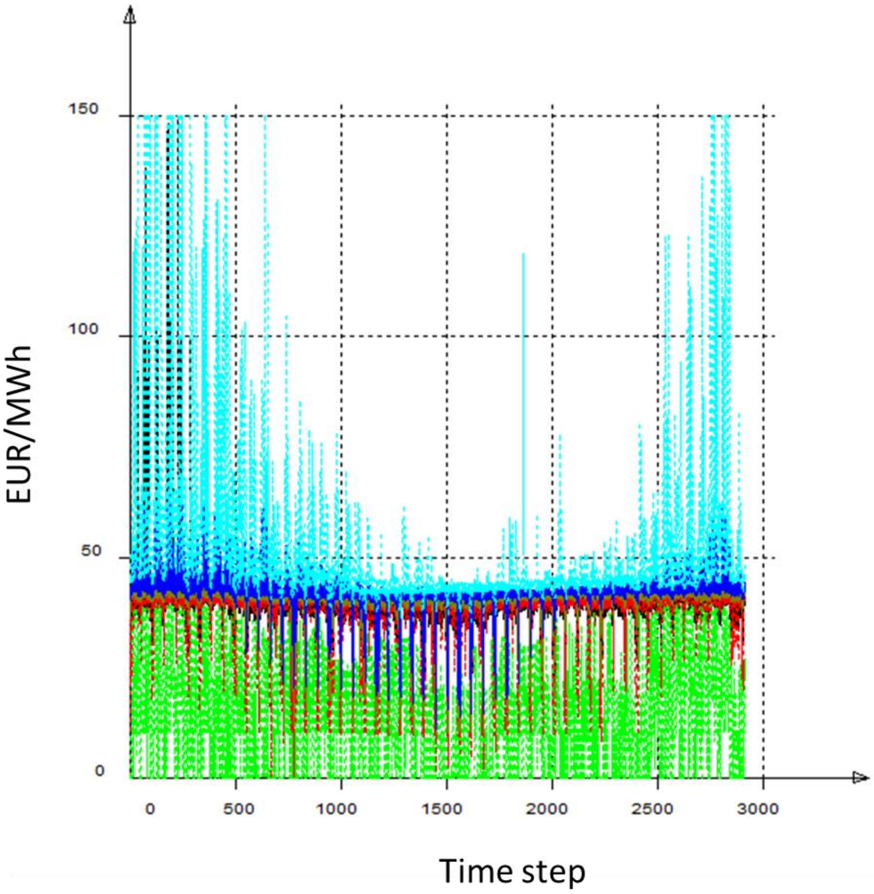

Figure 3. *Plot of the simulated power price based on year 2030. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price. The maximum power price at the y-axis has been capped at 150 EUR/MWh.*

2.3 Simulated power prices for 2030 with increased variability

This price series is based in the second price series, i.e. the Low Emission scenario in 2030, and has been modified to increase short-term variability. In short, in each time step a random error term drawn from a normal distribution N(0,1) has been added to the power price to increase the variability from time step to time step (three hours). The error term was multiplied with 15 to achieve the wanted increase in variability. To measure the increase in time step to time step variability, the standard deviation of the time step to time step difference, excluding absolute differences in price higher than 150 EUR/MWh, was used. This standard deviation was approximately tripled. Hence, this scenario is somewhat extreme and can be seen as an extreme test of the hydro systems. Finally, the average price in each time step (over all 60 simulation years) was adjusted to match the average in the original 2030 price series.

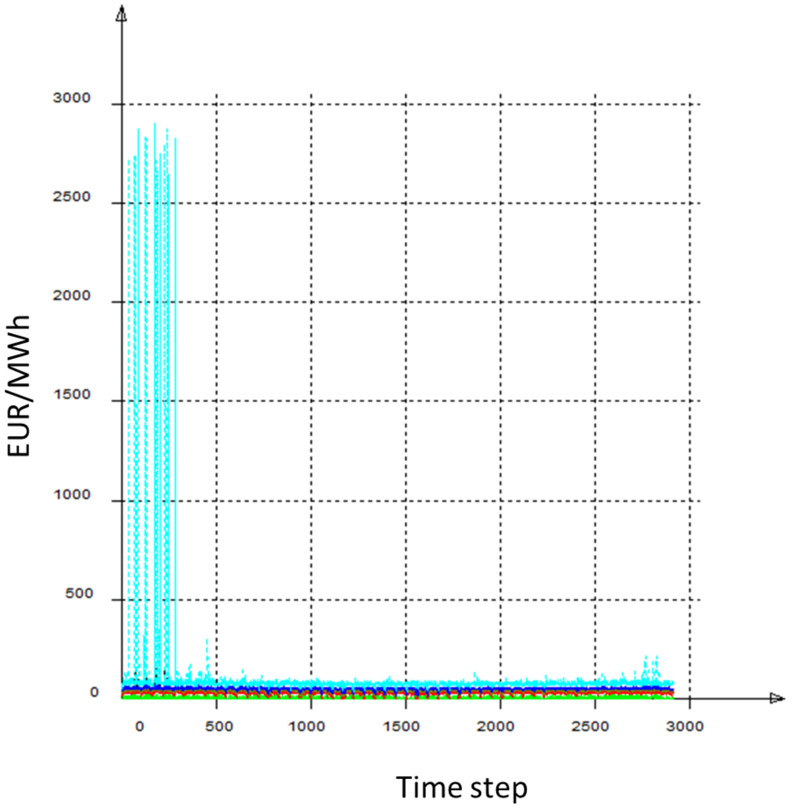

Figure 4. *Plot of the simulated power price based on year 2030 and scaled to increase the variability. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.*

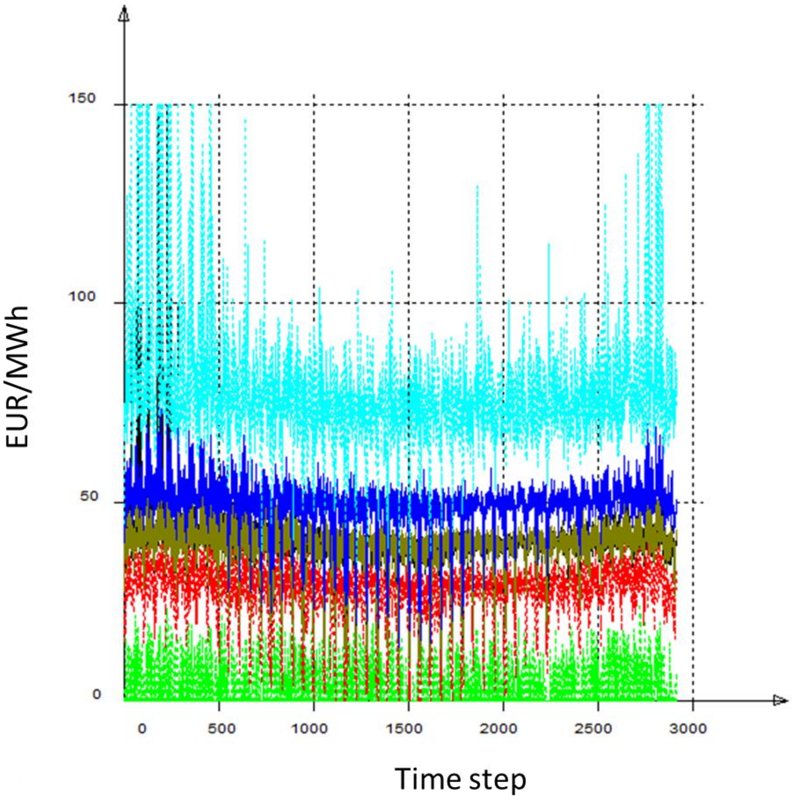

Figure 5. *Plot of the simulated power price based on year 2030 and scaled to increase the variability. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price. The maximum power price at the y-axis has been capped at 150 EUR/MWh.*

3 Comparison of price series

Table 1 gives the average and standard deviation of the three simulated power price series and of the time series describing the time step to time step change in the power price. We see that the average power price is equal in the two 2030 simulations and considerably than in the 2015 simulations. The average change in price from time step to time step over the whole simulation period is zero, which is reasonable as the modelled system is static and there are not modelled any trends. The standard deviation of the power price is much higher in the 2030 simulations than in the 2015 simulation and the difference between the two 2030 simulations are also small. The standard deviation of the price change from time step to time step increases from 2015 to the 2030 simulations. Furthermore, the last column gives the standard deviation when the most extreme values have been excluded. Here the difference in the variability between the two 2030 simulations becomes clearer. Figure 6 and 7 also illustrated these differences between the price series, respectively plotting the duration curve of the power prices and change in power prices.

***Table I**. The table give some characteristics of the different simulated power prices. The average and standard deviation of the simulated power prices are given, as well as the average and standard deviation of the time series of the change in power price from time step to time step. The last column gives the standard deviation of the change in power price excluding the most extreme values.*

	Price series		**Time step to time step difference**		
	Average	Standard Deviation	Average	Standard Deviation	Standard Deviation[1]
2015	28.84	8.58	0.00	2.26	2.26
2030	38.95	29.40	0.00	39.51	6.98
2030 scaled	38.95	32.64	0.00	44.48	21.66

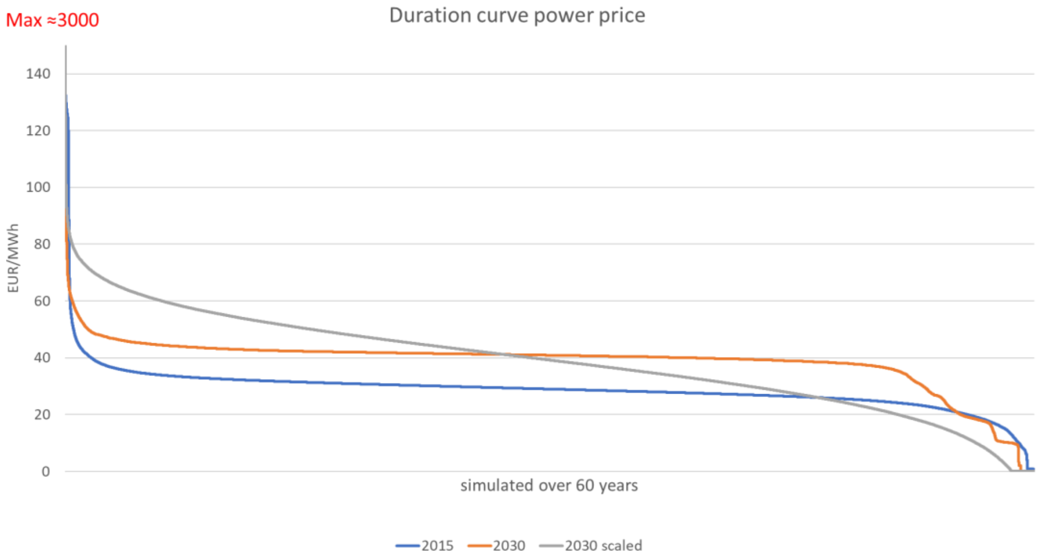

***Figure 6.** Duration curve plot of the power prices used in the simulations. The y-axis is capped at 150 EUR/MWh.*

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[1] Standard deviation of change in power price from time step to time step, excluding absolute changes larger than 150 EUR/MWh to reduce the impact of the most extreme power prices

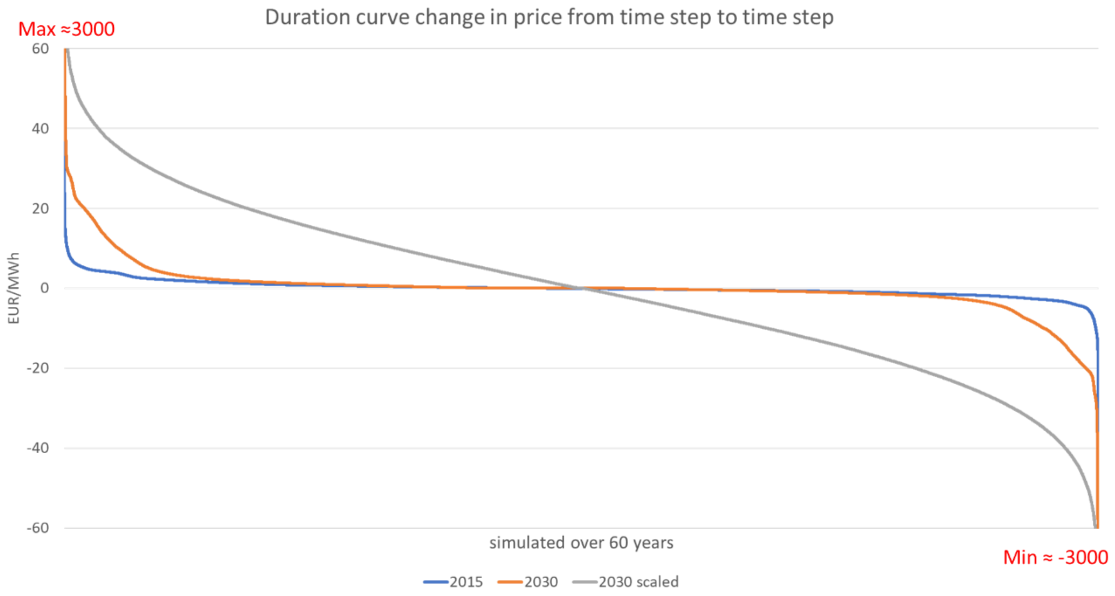

Figure 7*. Duration curve plot of the change in power price from time step to time step. The y-axis is capped at 60 EUR/MWh and -60 EUR/MWh.*

4 References

[1] Schäffer, L.E., Mo, B. and Graabak, I. 2019. Electricity Prices and Value of Flexible Generation I Northern Europe in 2030. 16th International Conference on the European Energy Market -EEM. IEEE conference proceeding, Accepted

[2] Schäffer, L.E. and Graabak, I. 2019. Power Price Scenarios. HydroCen Report 5. Norwegian Research Centre for Hydropower Technology. Trondheim.

AlternaFuture MEMO nr.2

AlternaFuture

A1: ProdRisk simulations of the current Mandal hydro system

Linn Emelie Schäffer

2019-11-12

1 Introduction

This Memo presents simulation results for the current Mandal hydropower system using the ProdRisk model. The model (ProdRisk), the modelling of the physical Mandal system and simulation results using three different price series are described in this memo.

The ProdRisk model dataset has been provided by Agder Energi. Simulations of the current system will be used as reference for economic and environmental comparison with different investment alternatives.

2 Method

Operations of the existing Mandal hydro system have been simulated using ProdRisk, an optimisation model for mid-term hydropower scheduling. It is important to understand how the system will be operated under different price scenarios, since the development of the European power system and the impact on power prices in Norway are highly uncertain. To account for the uncertainty in the long-term development in the power price, simulations with three different stochastic price series have been conducted.

2.1 The ProdRisk model

ProdRisk [1] is a long- and mid-term stochastic hydropower model used for optimal hydropower scheduling of general hydro systems assuming that all individual hydro plants are connected to the same bus bar, i.e. see the same market. Optimal strategy for use of water is found using Stochastic Dual Dynamic Programming (SDDP), which allows for individual representation of a large number of reservoirs. The model has a stochastic time-resolution of one week but enables optimal dispatch within the week on an hourly resolution. The planning horizon for operational scheduling purposes is normally a few years, depending of on the flexibility of the reservoirs.

The hydro system described in the model includes individual representation of each plant and reservoir and separate destinations for discharge, bypass and overflow, as illustrated in Figure 1. Each plant is modelled as one large station, with no detailed modelling of each production unit. The model includes time dependent maximum and minimum constraints on discharge, bypass and reservoir levels. The physical properties that can be modelled in the mid-term model is limited by the convexity requirements of the SDDP method and the use of Linear Programming.

Stochastic power prices and stochastic inflow are exogenously given in the model. Assumed developments and operations of the surrounding power system (e.g. the Norwegian and European power systems) are represented through the stochastic market prices given as input to the model. The main outputs from the model are water values (cuts) for all reservoirs by the end of each week, simulated reservoirs trajectories and optimal hourly dispatch of the hydropower plants in the system.

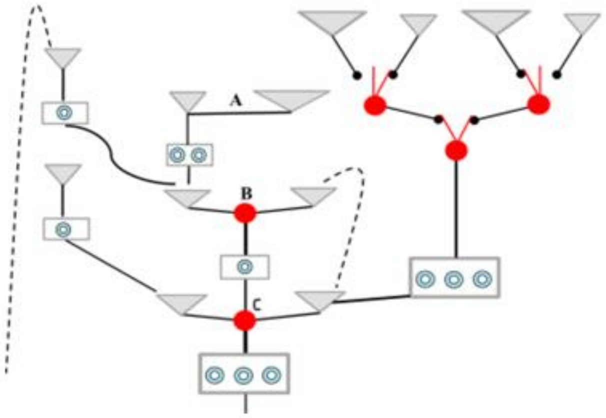

Figure 1*. Illustration of a physical system modelled in ProdRisk. The power plants in the system can include several units but are modelled as one station.*

ProdRisk is in operational use by almost all the largest hydropower producers in the Nordic power market. The main application is long- and mid-term planning of hydro systems to provide strategic input to daily and weekly operations.

2.2 Modelling the Mandal hydro system

The Mandal hydro system has been modelled using a description of the system provided by Agder Energi. The system consists of several intakes, reservoirs and power stations. Operation is optimised to maximise profit honouring the physical limitation of the system and existing environmental constraints. There are six power stations in the system: Skjerka, Logna, Smeland, Haaverstad, Bjelland and Laudal. Skjerka is by far the largest power station in the system with a maximum power output around 200 MW. The two biggest reservoirs are Skjerkevann and Juvann with approximately 188 mm^3 and 142 mm^3 storage volume.

We can divide the system into three main parts 1) Skjerka power station and Skjekevann reservoir with several intakes and smaller reservoirs upstream, 2) Smeland power station with Logna power station, Juvann reservoir and two intakes upstream, and 3) downstream of Skjerka and Smeland where the water from the two arms meet and goes through Haaverstad, Bjelland and Laudal power stations. All the reservoirs in the last part of the system are quite small. Spillage and bypassing water can run from the first to the second part of the system, connecting the two arms. We have divided the system into three parts because it will make it easier to discuss the changes made to the system in the development scenarios in later analyses. An overview of the entire system is provided in figure 2, while figure 3,4 and 5 illustrated the first, second and third part of the system. In the figures the red boxes illustrate power stations, the numbers within the boxes are the max power output in MW, flow in m^3/s and associated energy equivalent in kWh/m^3. The blue lines illustrate reservoirs or intakes with the storage volume given in Mm^3. The arrows give the yearly inflow to that part of the system in Mm^3. The unbroken lines show the destination of the discharge water from a station, while broken lines show the destination of spillage and bypass if this deviates from the discharge water.

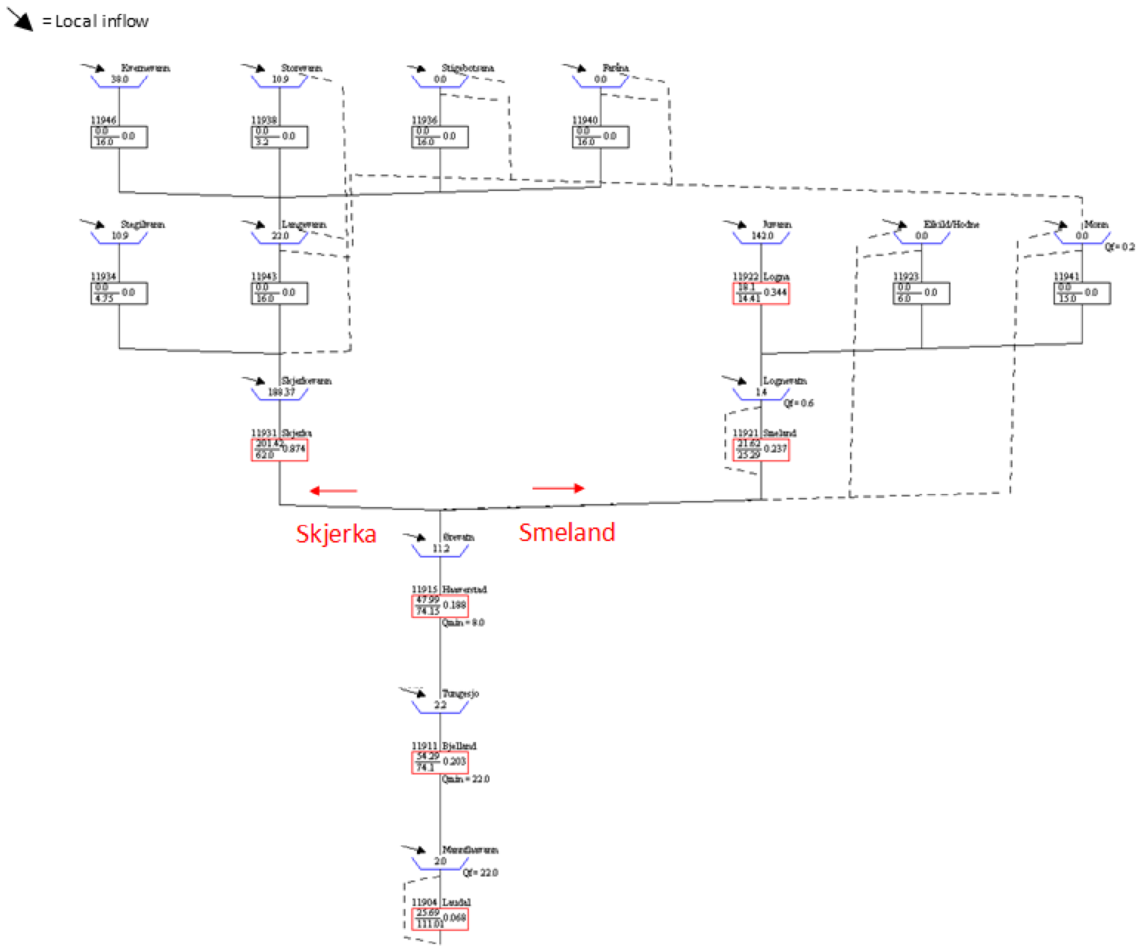

Figure 2. *Illustration of the Mandal hydro system modelled in ProdRisk.*

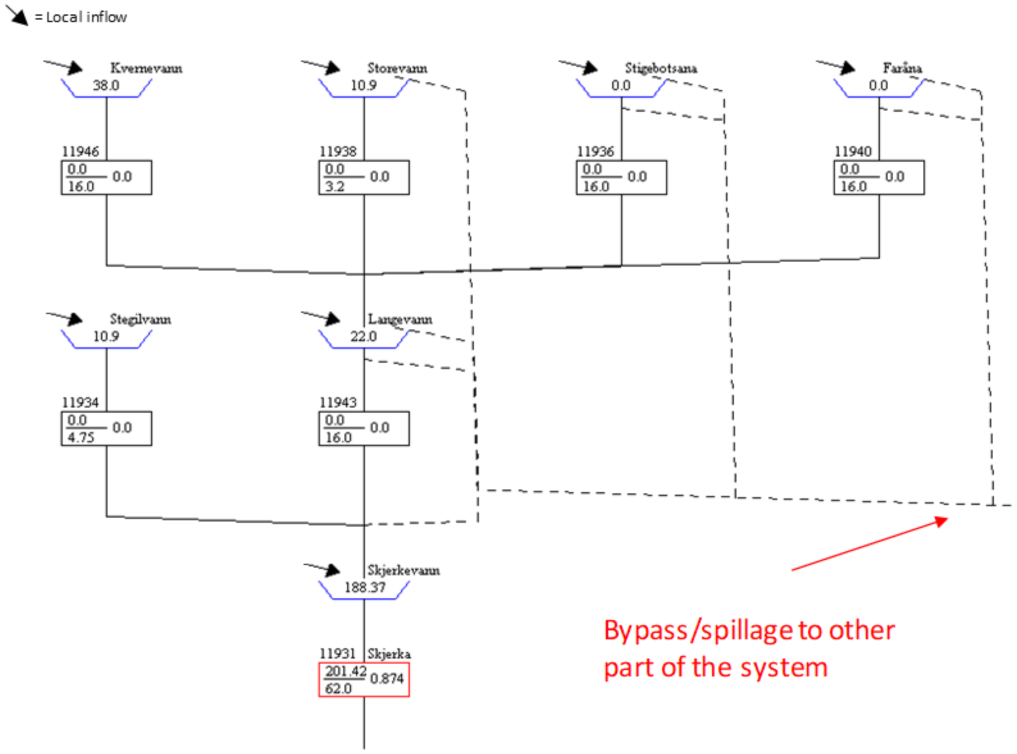

__Figure 3__. Illustration of part one of the Mandal hydro system modelled in ProdRisk.

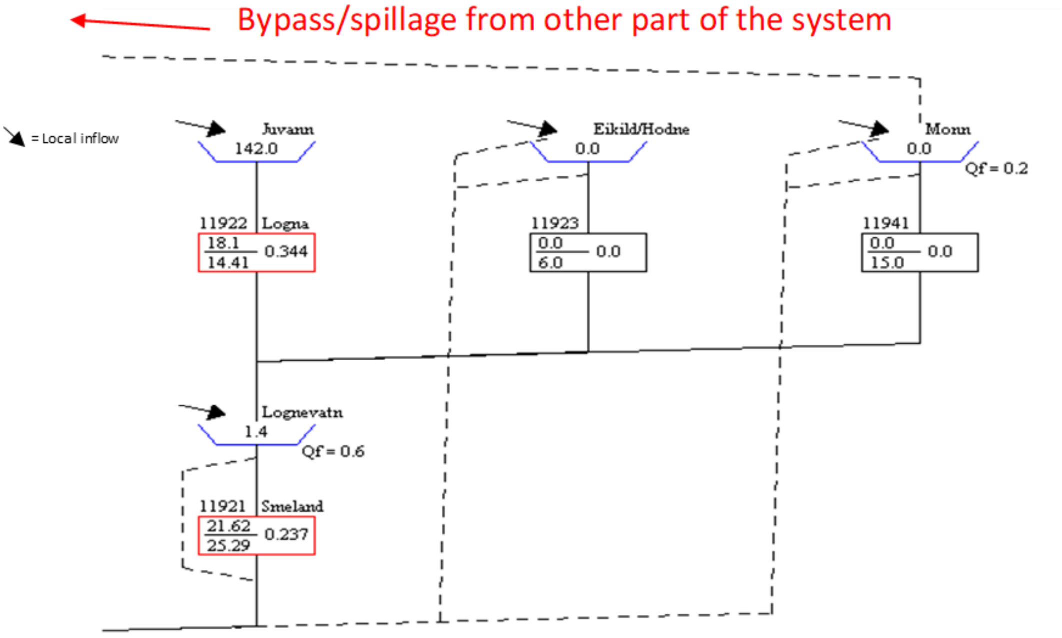

__Figure 4__. Illustration of part two of the Mandal hydro system modelled in ProdRisk.

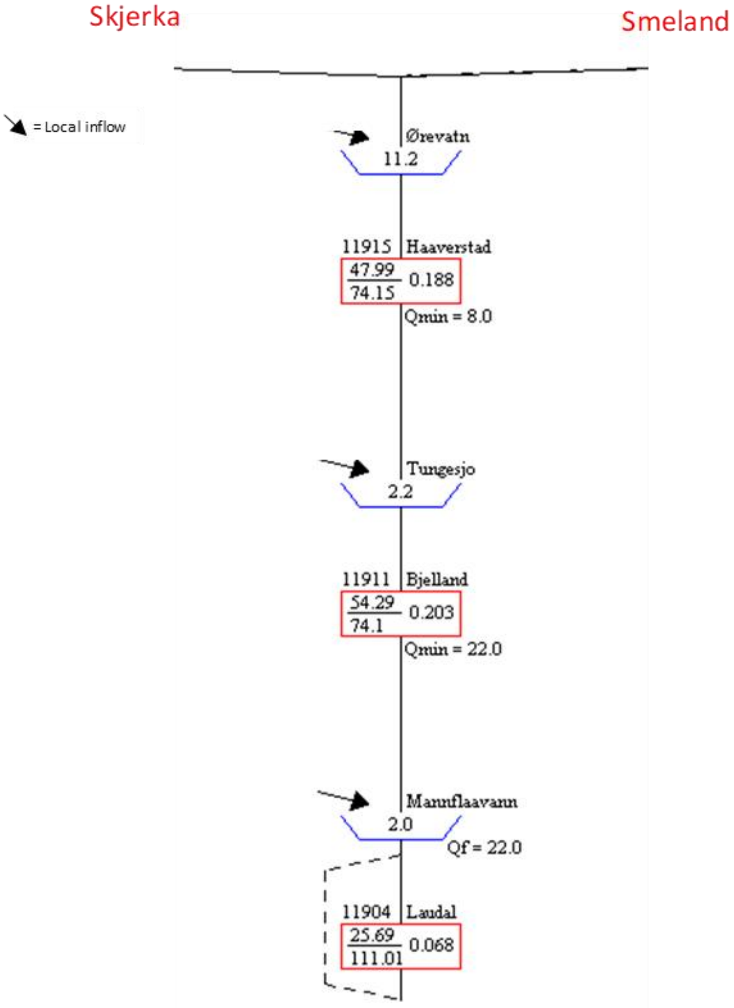

***Figure 5**. Illustration of part three of the Mandal hydro system modelled in ProdRisk.*

3 Results

This chapter present some results from the simulated operation of the current system. The results will serve as a reference when evaluating the development scenarios. The focus is on the two largest reservoirs in the system and the connected power stations.

3.1 Skjerkevann

3.1.1 Reservoir management

Figure 6 shows the reservoir developments in Skjerkevann, simulated for 60 different inflow years, given the different assumptions on power price. We see a difference in the seasonal profile between the 2015 price and the two 2030 prices, where the 2030 simulations give one more distinct peak in spring before the reservoir level again is drawn down during summer. Furthermore, we see that the 2030 price with increased variability (2030 price scaled) seems to keep a slightly higher reservoir filling in the beginning of the year.

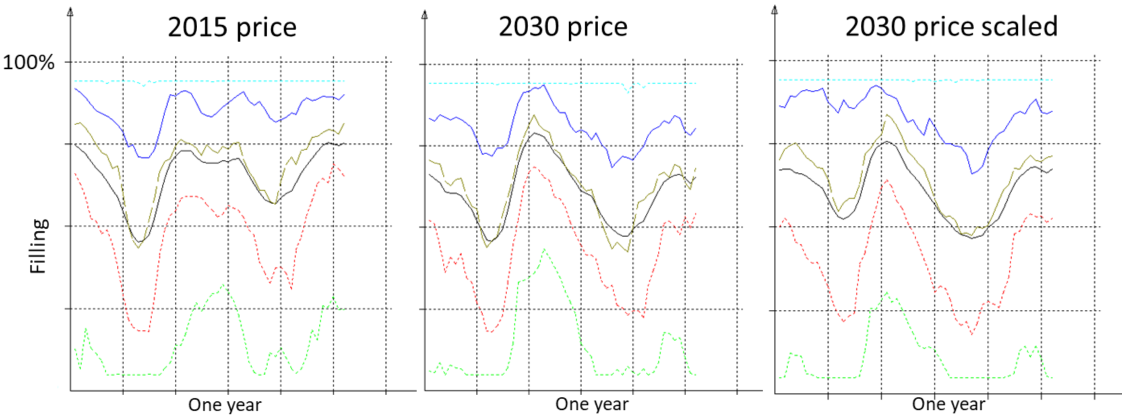

Figure 6. *Percentile plot of the reservoir development in Skjerkevann over one year (simulation results over 60 years), given the different input prices. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.*

3.1.2 Production Skjerka

The production per time step from Skjerka power station over all 60 simulated weather years is plotted in figure 7. The production is plotted as a duration curve, including all hourly production values in the simulation period, given each of the price scenarios. The clearest difference is in the simulation using the 2030 power price with increased variability. In this scenario we see that the power station is operated more at the extremes (close to maximum and minimum production) than in the two other scenarios. Figure 8 shows the frequency in and magnitude of change in production, plotting the duration curve for change in production from time step to time step. Most of the time the power station is operated at one level. We see a clear difference in the results from the simulations with the 2030 price with increased variability. In this scenario, the power station is operated at the same level in less hour and the changes are often more extreme, i.e. the power production is increased or reduced more rapidly.

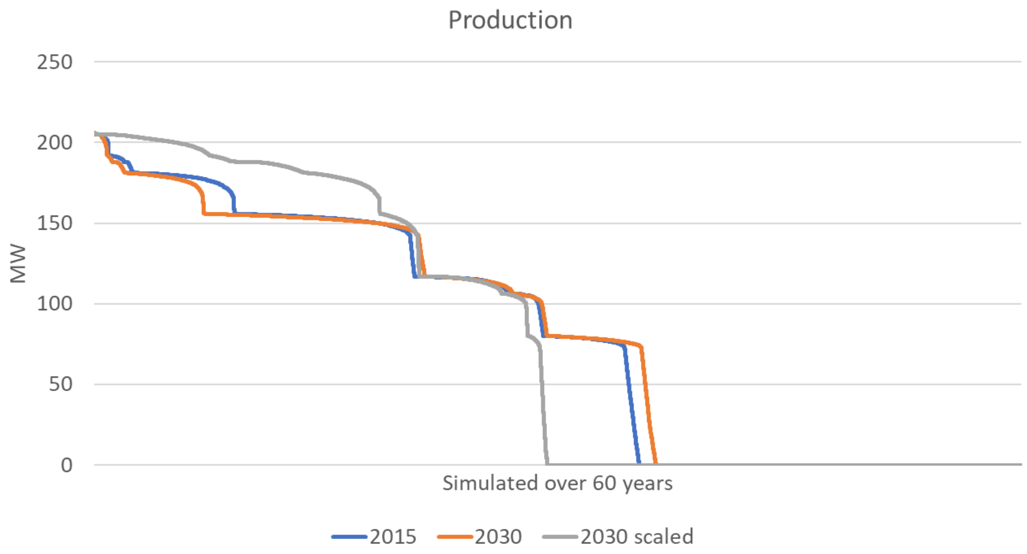

Figure 7. *Duration curve of the power production per time step from Skjerka power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.*

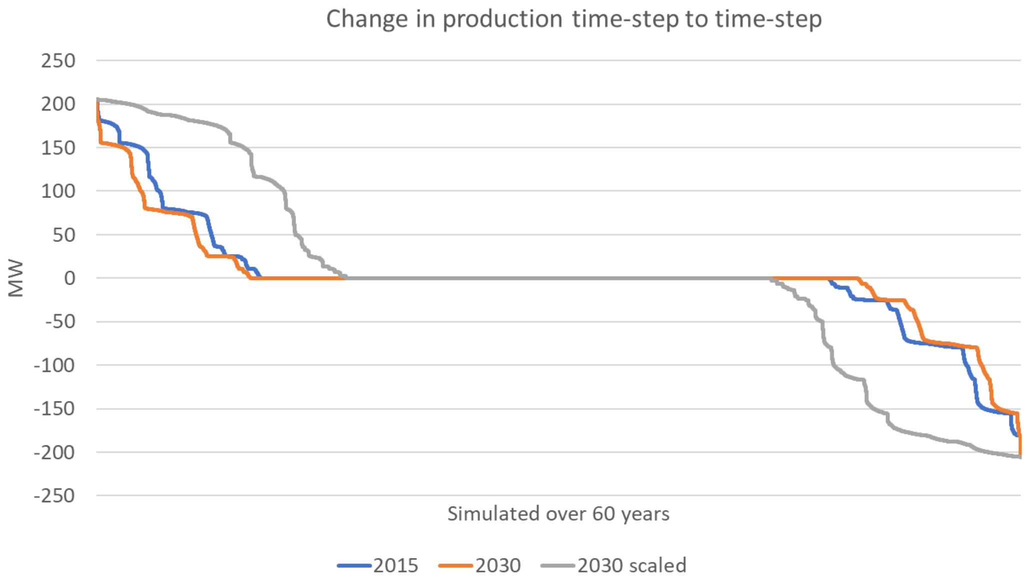

Figure 8. *Duration curve of the change in power production per time step from Skjerka power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.*

3.2 Juvann

3.2.1 Reservoir management

Figure 9 shows the development in reservoir level over one year based on simulations for 60 years of weather data. Comparing the results from the different simulations based on different rice assumptions, there are some smaller differences in the reservoir curves but not a change in the seasonal profile as observed for Skjerkevann.

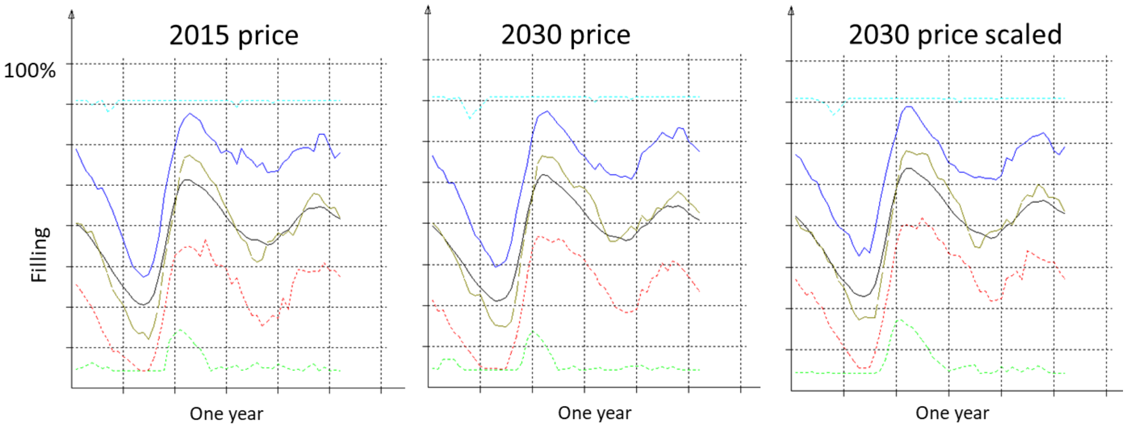

Figure 9. *Percentile plot of the reservoir development in Juvann over one year (simulation results over 60 years), given the different input prices. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.*

3.2.2 Production Logna

The production per time step from Skjerka power station over all 60 simulated weather years is plotted in figure 10. The production is plotted as a duration curve, including all time step production values in the simulation period, given each of the price scenarios. The production curves are quite similar for all three price scenarios. Figure 11 shows the frequency in and magnitude of change in production, plotting the duration curve for change in production from time step to time step. Most of the time the power station is operated at one level. We see that the production in the results from the simulations with the 2030 price with increased variability (2030 scaled) change more frequently than in the other scenarios.

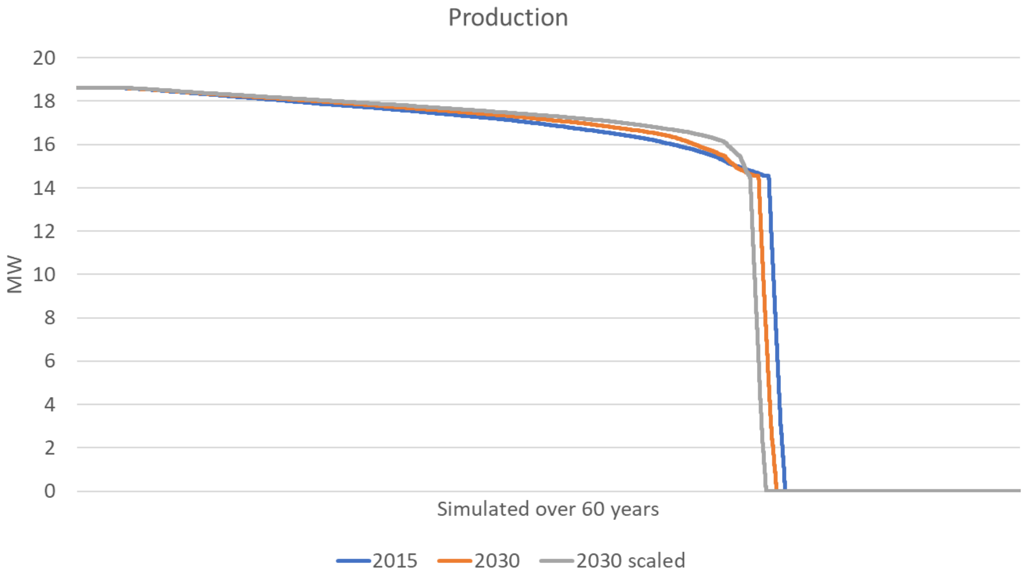

Figure 10. *Duration curve of the power production per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.*

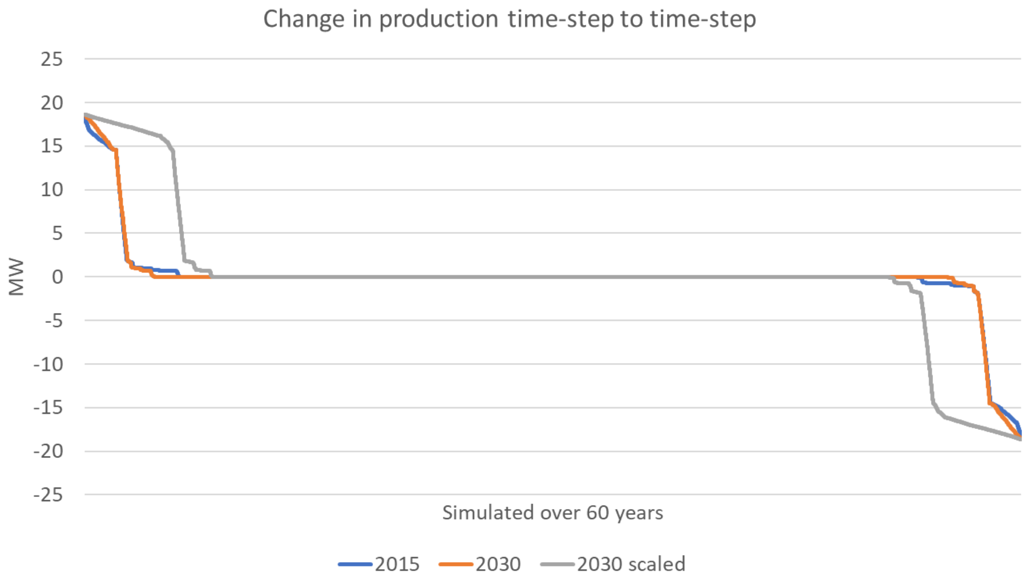

Figure 11. Duration curve of the change in power production per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.

3.3 Overall system

Total production, income and achieved power price are given in table 1 for the overall system, given all three price scenarios. The total production, total income and achieved power price are all higher for the 2030 scenario than the 2015 scenario, and for the 2030 – scaled scenario than the 2030 scenario. The total yearly income ranges from just above 50 million EUR to just above 80 million EUR.

Table 1. Yearly power production, income and achieved power price for the overall system (current system), given all three price scenarios.

	Power production [GWh]	**Net Income [MEUR]**	**Achieved price [EUR/MWh]**
2015	1731.9	51.4	29.7
2030	1742.3	72.5	41.6
2030 - scaled	1705.8	81.1	47.5

4 References

1. Gjelsvik, A., Mo B., Haugstad A., ”Long- and Medium-term Operations Planning and Stochastic Modelling in Hydro-dominated Power Systems Based on Stochastic Dual Dynamic Programming”. *I: Handbook of Power Systems I. (s. 33-56).: Springer,* 2010*.*

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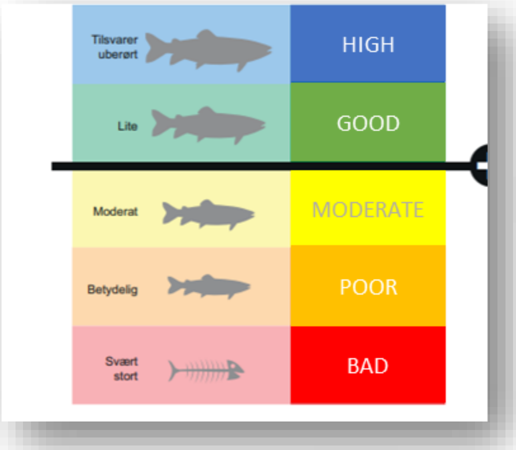
AlternaFuture MEMO nr.3

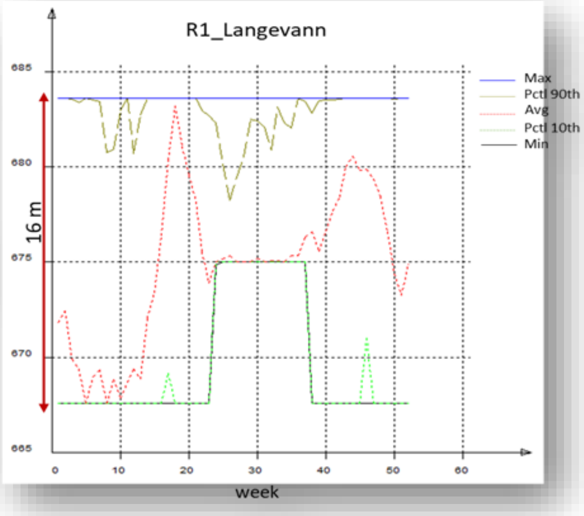
AlternaFuture

A1: Environmental Restrictions for Reconstruction Scenarios and Targets for Improving the Current Ecological Status

Line Elisabeth Sundt-Hansen, Ana Adeva Bustos, Trygve Hesthagen & Torbjørn Forseth

2019-30-12





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1 Introduction

The AlternaFuture project is a multidisciplinary project in Hydrocen utilizing the whole range of expertise present in Hydrocen, including hydropower engineers, hydraulic engineers, hydropower planning engineers, biologist and social scientists. AlternaFuture aims to develop alternative future redesign solutions, focusing on both flexible operation and environmental conditions. AlternaFuture further aims to reconsider what is possible. It is a desk study and the design scenarios are developed to create potential for new innovations from the multidisciplinary scientist within the project.

The case study of AlternaFuture is the Mandal hydropower system, which currently contains six major power plants in the watercourse, which extends more than 100 km from north to south through Vest-Agder county. All the largest lakes in the upper parts are regulated for hydropower, including Juvatn, Langevatn, Nåvatn and Ørevatn, Store Kvernevatn, Storevatn and Stekil. The hydropower regulation took place between 1932 and 1961. This memo focusses on the upper part of the watercourse, above the anadromous stretch. This stretch is much less studies than the anadromous stretch, which has been the subject of several research projects in the recent years assessing impact of hydropower production and improving environmental conditions.

This memo reports from activity A1 of the project which aim is to map the present status of the environment, both with focus on hydrology and aquatic biology, in the area of the Mandal hydropower system. The memo aims to identify reference indicators to quantify the change in ecological status from the currents situation and to determine environmental restrictions for reconstruction scenarios and targets for improving the current ecological status. In this memo a total of eight reservoirs and lakes and four river stretches in the Mandal basin has been evaluated based on hydrological and ecological reference indicators.

2 Method

2.1 Hydrological classification

2.1.1 Hydrological analyses

Outputs from the ProdRisk model (AlternaFuture Memo 2&3) were used to analyse the hydrological characteristics in the reservoirs and river reaches. For reservoirs the following indices were calculated:

- Lowest regulated volume (LRV)
- Highest regulated volume (HRV)
- Minimum water surface elevation (Min)
- Percentile 10 water surface elevation (Pctl 10th)
- Average water surface elevation (Avg)
- Percentile 90 water surface elevation (Pctl 90th)
- Maximum water surface elevation (Max)

For the river reaches, 6 hydrological indices that are ecologically relevant for fish populations and for hydro-morphological changes (Richter et al., 1996, Poff and Zimmerman, 2010) were calculated for the unregulated and regulated period. For the unregulated period data was obtained from NEVINA (http://nevina.nve.no/) and for the regulated period from the ProdRisk model.

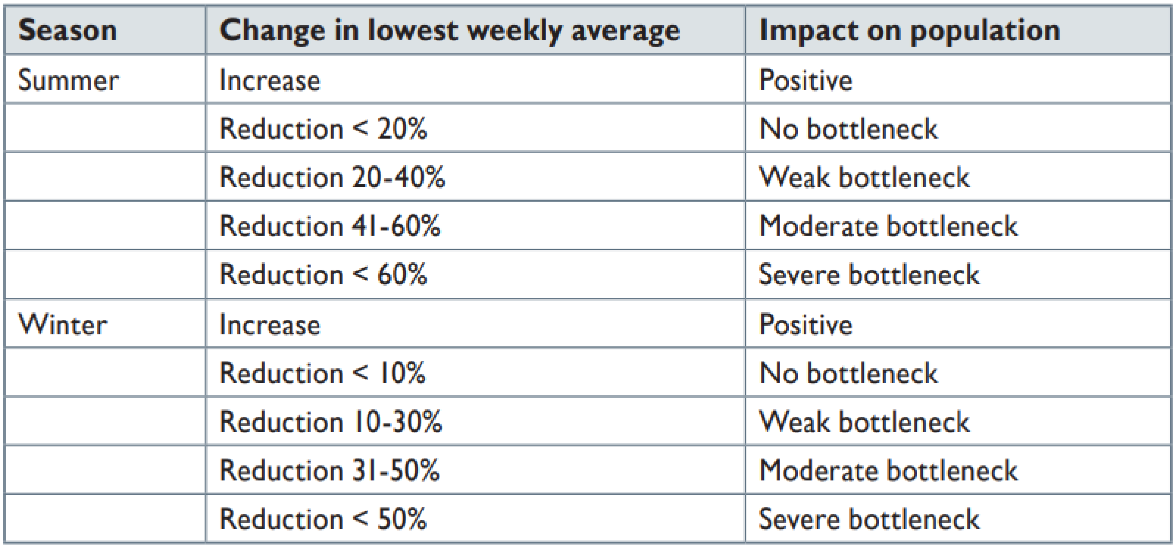
- Annual mean flow (AMF)
- Q95 (the 5-percentile flow)
- Annual mean flood (AMFlood)
- Ten-year flood (10YFlood)
- Summer low flow (7-days minimum summer low flow)
- Winter low flow (7-days minimum winter low flow)

2.1.2 Limitations

It is important to consider that there are some uncertainties included in the results obtained from the model that might affect the results and their classification. Main uncertainties can be linked to the daily resolution of the data used as input in the hydropower model (ProdRisk) which might result in an underestimation for floods, therefore the indices related to floods might just be taken as an indication.

2.1.3 Hydrological classification

The hydrological classification for reservoir was based on Vann-nett classification of heavily modified water bodies which classified the impact from hydropower in: small, moderate, large and unknown based on the level of regulation of the reservoir (Direktoratsguppen, 2018). The hydrological indices calculated from each of the reservoir were used to have a detailed overview of the regulation levels in the reservoir including restrictions in their operational rules. In addition, for the river reaches, the classification was carried out following the classification from the environmental design handbook (Forseth and Harby, 2014), a comparison of the indices for summer low flow and winter low flow before and after regulation were used to indicate possible hydrological bottlenecks (Figure 1).



Season	Change in lowest weekly average	Impact on population
Summer	Increase	Positive
	Reduction < 20%	No bottleneck
	Reduction 20-40%	Weak bottleneck
	Reduction 41-60%	Moderate bottleneck
	Reduction < 60%	Severe bottleneck
Winter	Increase	Positive
	Reduction < 10%	No bottleneck
	Reduction 10-30%	Weak bottleneck
	Reduction 31-50%	Moderate bottleneck
	Reduction < 50%	Severe bottleneck

Figure 1. A classification system of, and to what extent changes in the lowest weekly average flow from unregulated to regulated state in summer and winter represent a salmon population bottleneck.

2.2 Ecological classification

In this study we identified reference indicators for ecological status/condition in reservoirs and river stretches with the aim to rank these locations with regards to the potential for increased ecological status. To increase ecological status, it is important to pinpoint current “bottlenecks”, which are factors which limits the current ecological status, such as i.e. production of juvenile brown trout. Common factors leading to bottlenecks for the local fish populations are typically water quality (low pH due to acidification), lack of spawning habitat or recruitment areas. Further the recreational and landscape values of the reservoir and river sections are also parameters which needs to be assessed to increase ecological status of the reservoir or river stretch.

Acid neutralizing capacity (ANC) is a measure of the overall buffering capacity against acidification and is usually included as a potential predictive variable in models that evaluate the effects of acidification on fish populations. ANC has also been used to estimate the tolerance limits of nature to acidification and for setting a goal for future deposition rates to avoid future damage and assure recovery of fish populations. The lower ANC threshold for Norwegian lakes has been set to 20ueqL-1 to avoid damaged stocks (Hesthagen et al. 2012). The relationship between ANC and biological response is indirect because changes in ANC also involve changes in parameters such as pH and labile Aluminum (LAl). Any specific ANC value may represent a wide range of pH and LAl levels.

In this study we refer to data from test-fishing which has been carried out using standard gill-net series. Catch per unit effort (CPUE) is defined as number of fish caught per 100 m^2 net area per night. This measurement is used as an indicator for the density of the fish population. Further the size of females and the percentage they represent in a population indicates the quality of the fish population (Ugedal et al. 2005).

Refence values for CPUE, LAI, PH are according to the classification levels published in Sandlund et al. 2013.

Figure 2. Ecological classification of environmental conditions in lakes an drivers (from Sandlund et al. 2013).

2.3 Recreation

The upper part of the Mandal River is located close to Setesdal Vesthei Ryfylkeheiane landscape conservation area in the west, and thus serves as a gateway to trips further into the mountains and to cabins such as Gaukelihytta and Lakkenstova. In addition, there are many summer tours and ski trails in the northern part due to the proximity to cabin fields in Ljosland and at Juvatn. There are also alpine resorts, in addition to Eikerapen southwest of Øre. The northernmost reservoirs is believed to be the most utilized areas. All of these factors (Figure 3) indicate that the least possible nature intervention will be regarded as off high value for quite a number of people. At the same time, several construction roads increase accessibility to areas that would otherwise not be as easily accessible. The southern reservoirs are located in areas where there are fewer cabins, while there are permanent scattered settlements in several places. Water is regarded as a valuable to anyone who lives by or travels on roads with views to reservoirs and streams. Some reservoirs and river stretches are used for swimming and paddling, such as Juvatn and Øre.

Figure 3. Example of factors considered to evaluate recreational criteria. Such recreations activities to be evaluated can be skiing, biking and hiking tourism.

3 Results

Results from all the reservoirs are presented, for the river reaches, which have been selected due to their potential for ecological improvement after the proposed measures.

3.1 R1 Langevann

3.1.1 Hydrology

Langevann reservoir has 16 m of regulation (Figure 4), and an increase of 10 m more planned for 2020. The reservoir has a restriction during summer with a minimum volume of 29.41%. The LRV is 667.60 m.a.s.l and HRV is 683.60 m.a.s.l, and a volume of 22 Mill m^3. It is classified as large impacted by hydropower regulation (Figure 5).

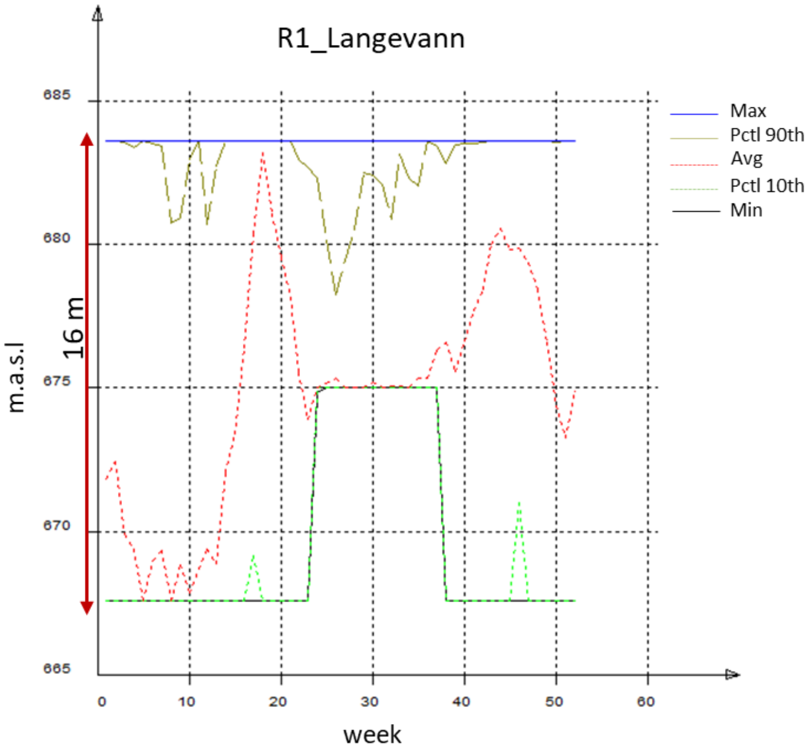


Figure 4. R1, Langevann reservoir curve and meters of regulation.

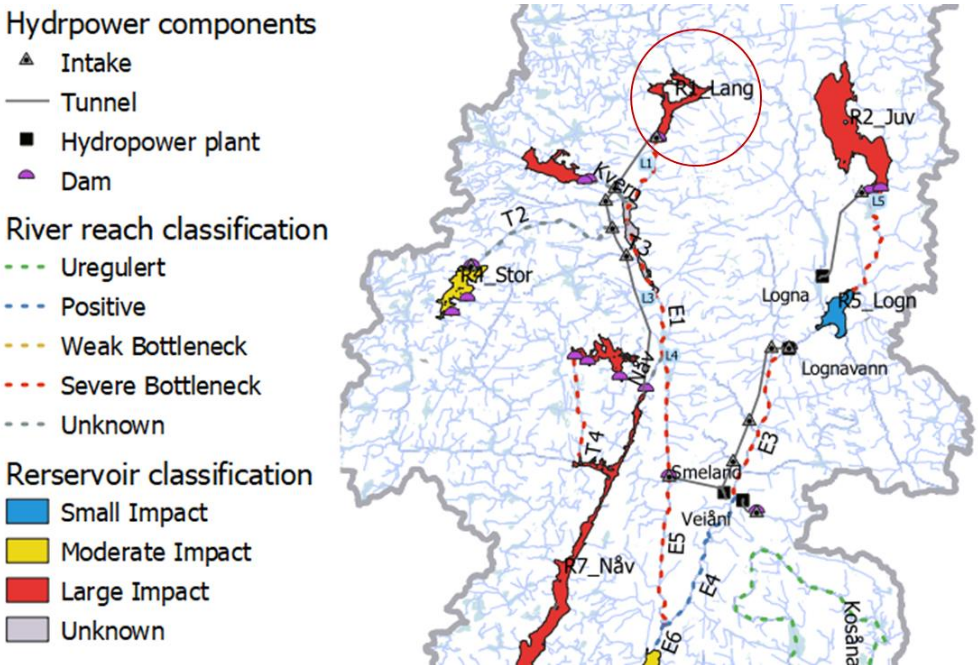


Figure 5. Hydrological classification for R1, Langevann (red circle)

3.1.2 Ecology and recreation

Currently the brown trout population of Langevann has a CPUE of 8,7, which indicates medium density and good recruitment. The average female size is female 26cm and make up 36 % of catch.

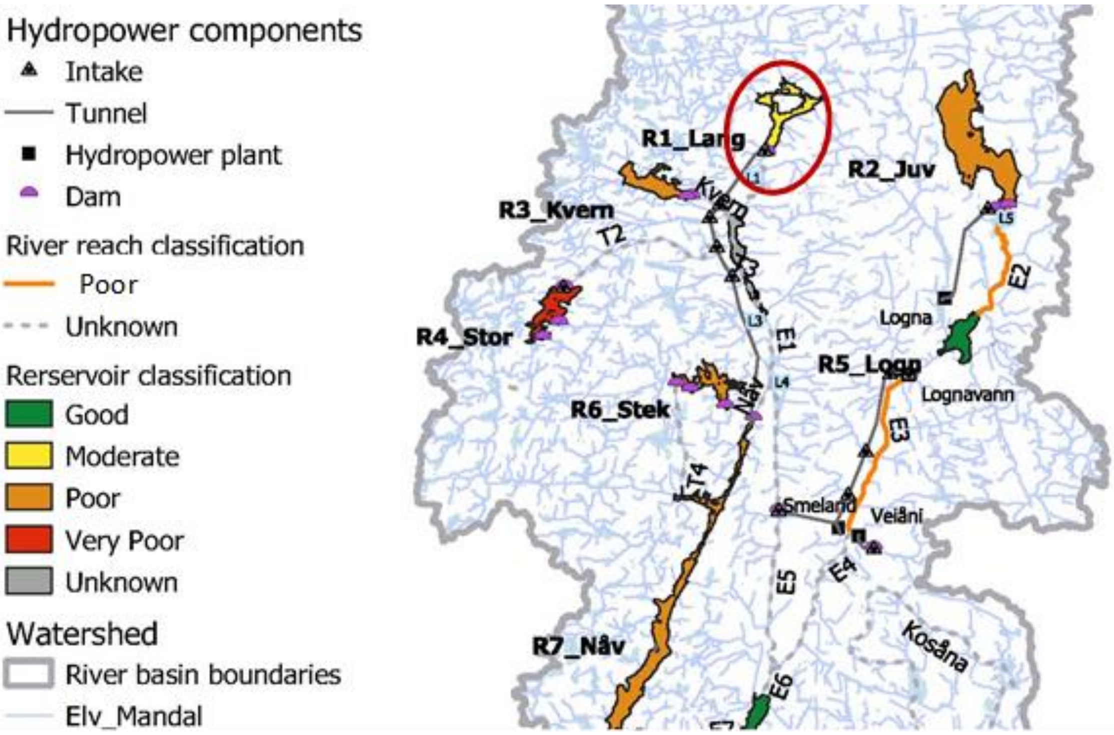


Figure 6. Ecological classification for R1, Langevann (red circle)

The area in the vicinity of lake Langevann is widely used as hiking area in summer and winter, both for hikers and cyclists. The area is the gateway to areas such as Setesdal, Vestheia and Ryfylkeheiane which is situated in a landscape protection area (landskapsvernområde). The area is also home to two tourist cabins (Ljosland fjellstove, Lakkenstova). There is a newly constructed road on the eastside of the lake and there is also a newly established skitrack connecting the area to Lake Juvann

3.1.3 Potential

There is a potential for increased recreational values as Langevann has several cabins and hiking tracks. This can be achieved by avoiding a high regulation height, which may have a negative effect on the aesthetic perception of the lake.

There is a potential to increase the abundance of naturally recruited brown trout of a medium size in this reservoir. A measure to increase ecological potential, through increasing abundance of brown trout, is to secure access to spawning grounds by constructing cell weirs after new regulation height. Such a measure would facilitate natural recruitment and increase abundance. Increased recreational value of fishing.

Construct cell weirs to secure access to spawning grounds to increase abundance of naturally recruited brown trout. Cell structure weirs to secure access for spawning trout after new regulation height.

The costs of such as measure is estimated to be approximately 0.5-1 Mill NOK.

3.2 R2 Juvant

3.2.1 Hydrology

Juvatn reservoir has 24 m of regulation, with a volume restriction during the year of 6% (Figure 7). The LRV is 489 m.a.s.l and HRV is 513 m.a.s.l, and a volume of 142 Mill m^3. It is classified as large impacted by hydropower regulation (Figure 8).

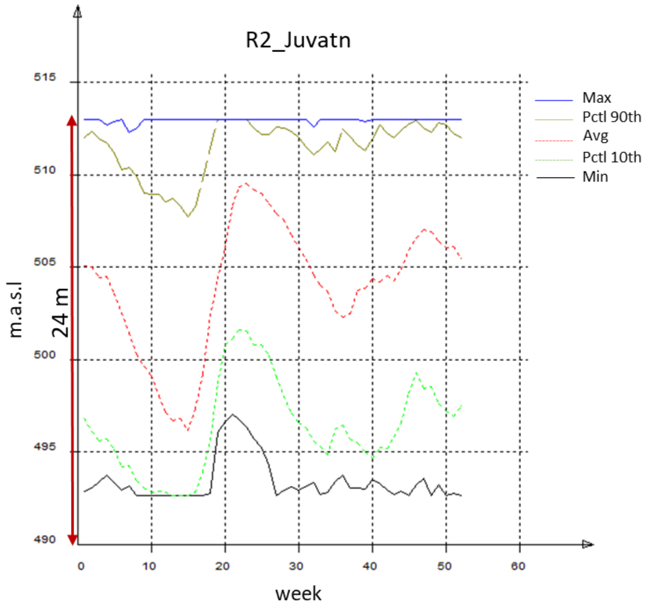


Figure 7. R2, Juvant reservoir curve and meters of regulation.

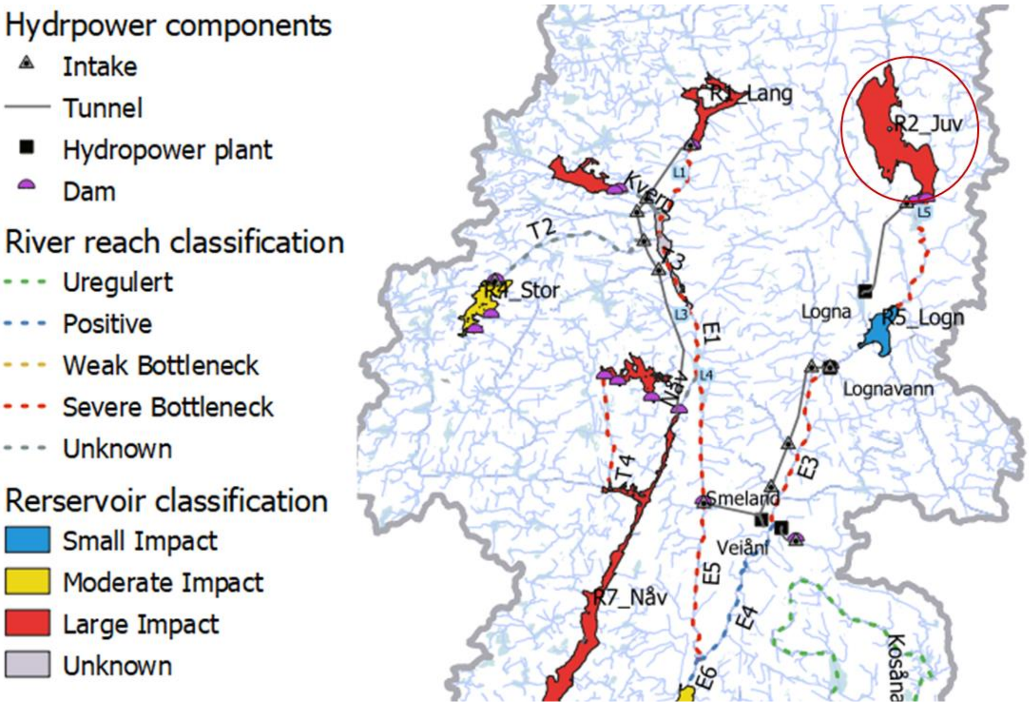


Figure 8. Hydrological classification for R2, Juvant (red circle)

3.2.2 Ecology and recreation

The brown trout population of Juvatn has a CPUE of 1,8 which indicates low density and poor recruitment. The average female size is female 26cm and make up 29 % of catch. There are some natural recruitment, however access to spawning grounds is made difficult when water level is below HRV. This lake also has low level of species diversity of crustaceans, compared to other sites.

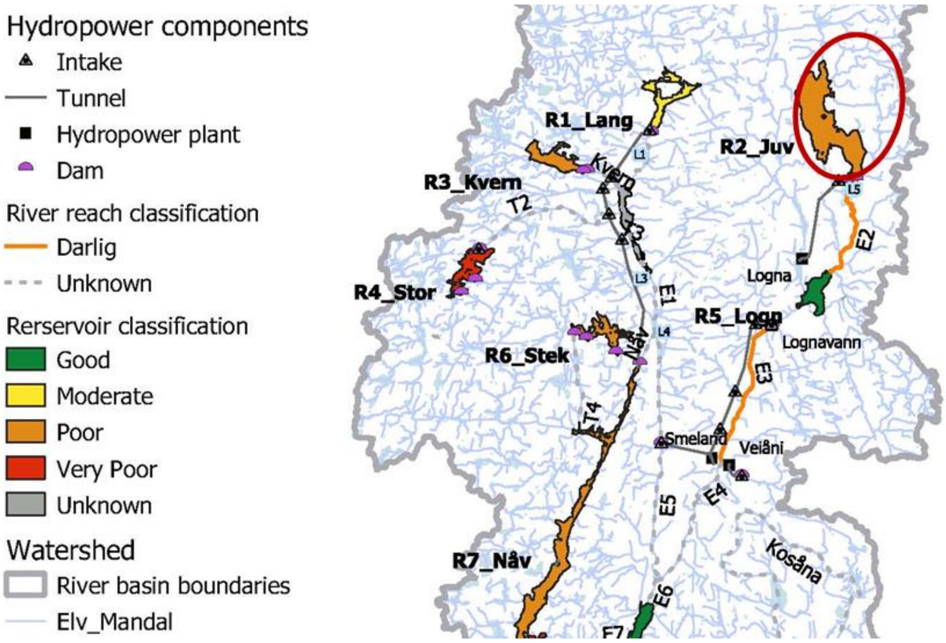


Figure 9. Ecological classification for R2, Juvant (red circle).

Juvatn has a high density of cabins, several hiking- and ski-tracks in the area. There is also a sportscenter in the area, attracting tourists. The Dam has also been fronted as a tourist attraction

3.2.3 Potential

There is a potential to increase abundance of the local brown trout population by mitigating access to spawning grounds when water level is below HRV. This will reduce mortality caused by stranding. This mitigation measure can be fulfilled by increasing minimum discharge to 300 L/sek all year, constructing cell structure weirs to secure access for spawning trout after new regulation height, in addition to establishing pools at the downstream part of the inlet stream.

Currently use of boats on the lake is difficult due to a high regulation height. Establishment of floating pier will increase usability of boats and increase the recreational value of the reservoir, in addition to increased value of fishing.

3.3 R3 Kvennevann

3.3.1 Hydrology

Kvennevann reservoir has 25.8 m of regulation (Figure 10). There is not restriction specified from the reservoir. The LRV is 745.20 m.a.s.l. and HRV is 771 m.a.s.l, and a volume of 38 Mill m^3. From Vann-Nett it is classified as high impacted by hydropower regulation (Figure 11).

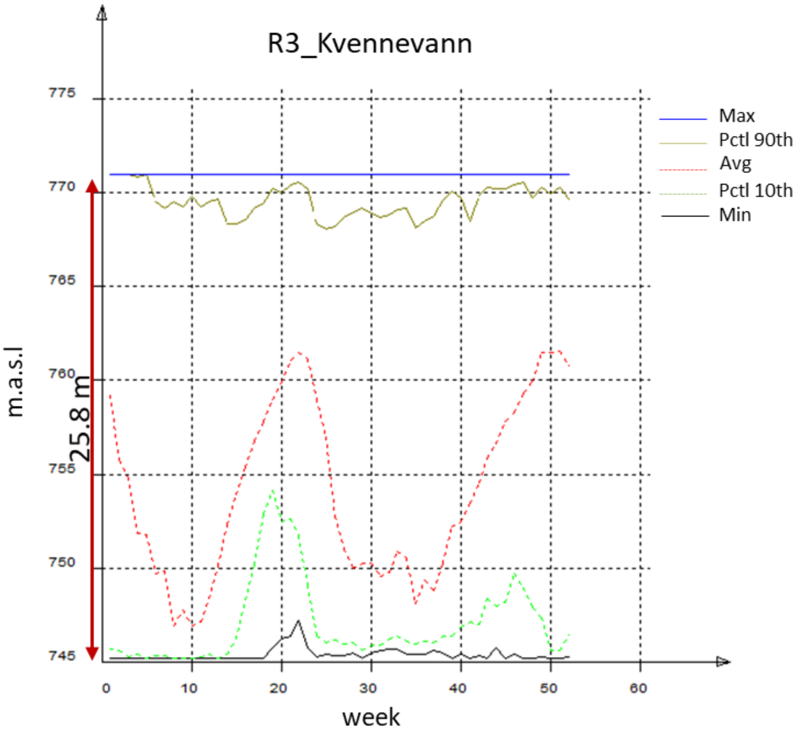


Figure 10. R3, Kvennevann reservoir curve and meters of regulation.

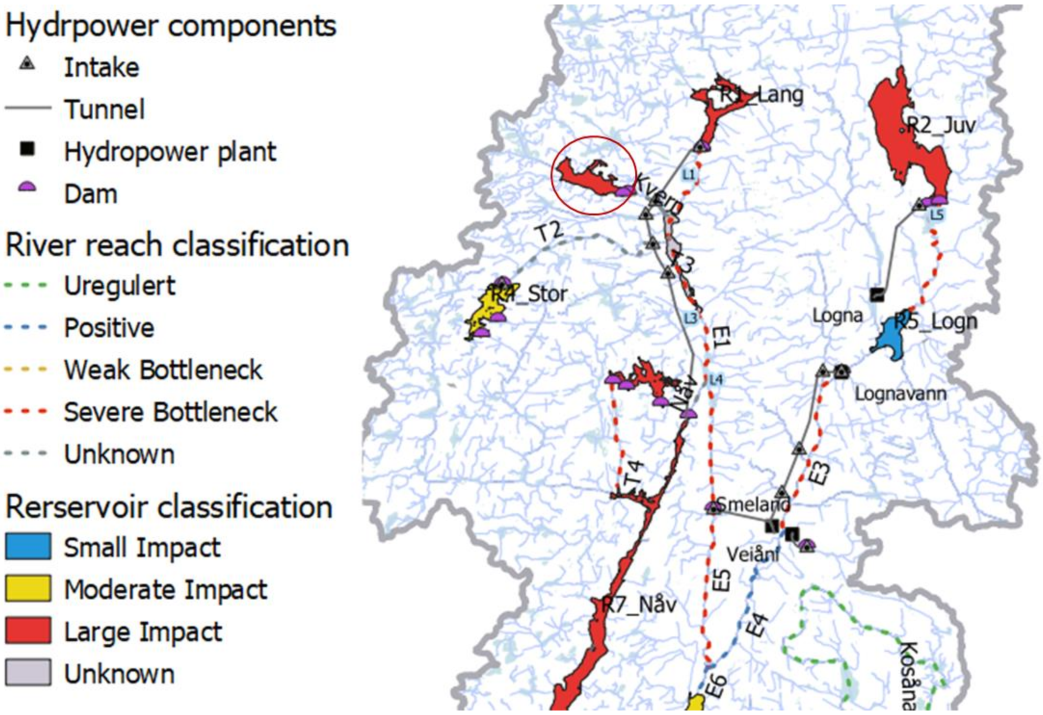


Figure 11. Hydrological classification for R3, Kvennevann (red circle).

3.3.2 Ecology and recreation

The brown trout population of Kvennevann has a CPUE of 1,9 which indicates low density and poor recruitment. The population has a poor ecological status (Figure 12) and the population consists of small fish and a medium density, with the average female size being 24cm, making 12 % of catch. This reservoir is stocked and hatchery reared fish are released annually. There is little to no natural recruitment in the reservoir and a probable cause is that it is difficult for fish to access spawning grounds.

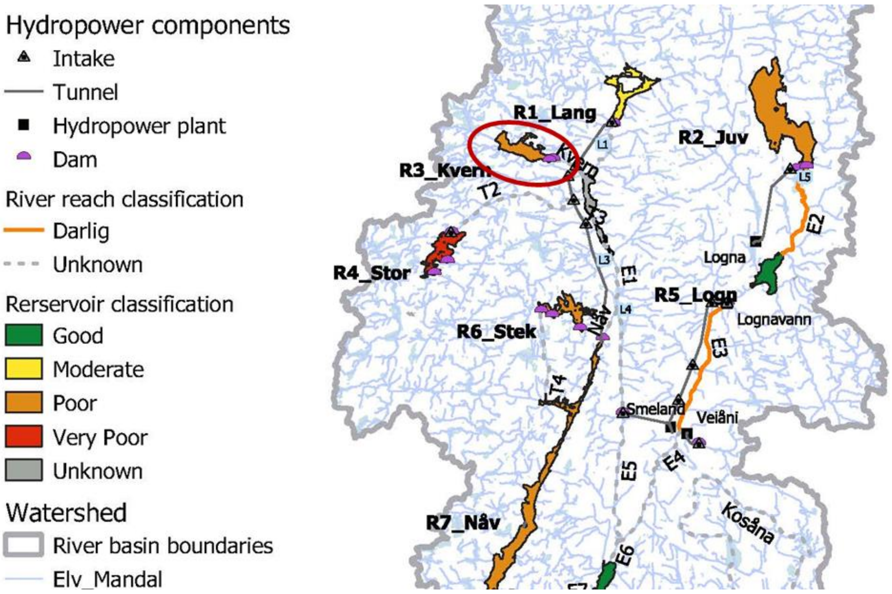


Figure 12. Ecological classification for R3, Kvennevann (red circle).

Kvennevann has high density of cabins and several hiking- and ski-tracks in the area. There are several tourist cabins in the area, such as Lakkenstova and Ljosland fjellstove.

3.3.3 Potential

There is a potential to increase abundance of naturally recruited brown trout in the area by facilitating natural recruitment of brown trout. This can be achieved by constructing cell structure weirs to secure access to two spawning streams and adding spawning gravel to stream Sandvassåna and Øyvassånæ. Another mitigation measure is to terminate cultivation brown trout in this reservoir.

There is a potential for increased recreational value as currently the access to the lake is made difficult because of a high regulation height. Avoiding a high regulation height will make it easier to use the reservoir for recreational purposes such as fishing, but also due to aesthetics.

3.4 R4 Storevann

3.4.1 Hydrology

Storevann reservoir is regulated 6 m and has no restriction (Figure 13). The LRV is 854 m.a.s.l and HRV is 860 m.a.s.l, and a volume of 10.9 Mill m^3. It is classified as moderately impacted by hydropower regulation (Figure 14).

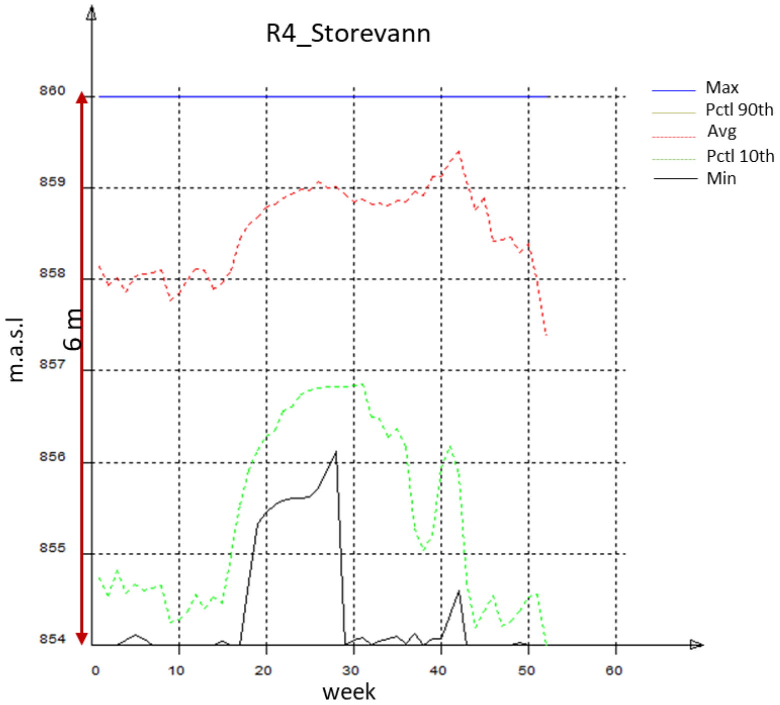


Figure 13. R4, Storevann reservoir curve and meters of regulation.

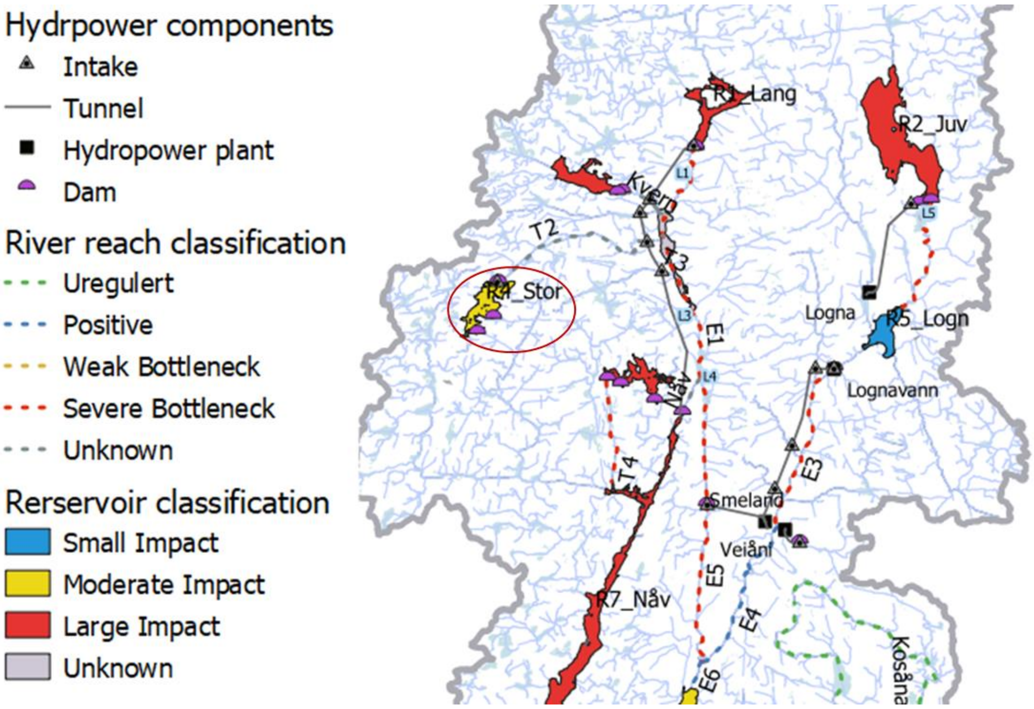


Figure 14. Hydrological classification for R4, Storevann (red circle).

3.4.2 Ecology and recreation

The brown trout population of Storevann has a CPUE of 0 which indicates an absence or very low numbers of fish in the reservoir. The ecological status of the lake is thus regarded as bad. Hatchery reared trout are stocked in this reservoir and the population is of medium density, with the average female size being 28cm, making up 36 % of catch.

There is no natural recruitment in the reservoir because of lack of admission for fish to streams with spawning and recruitment areas.

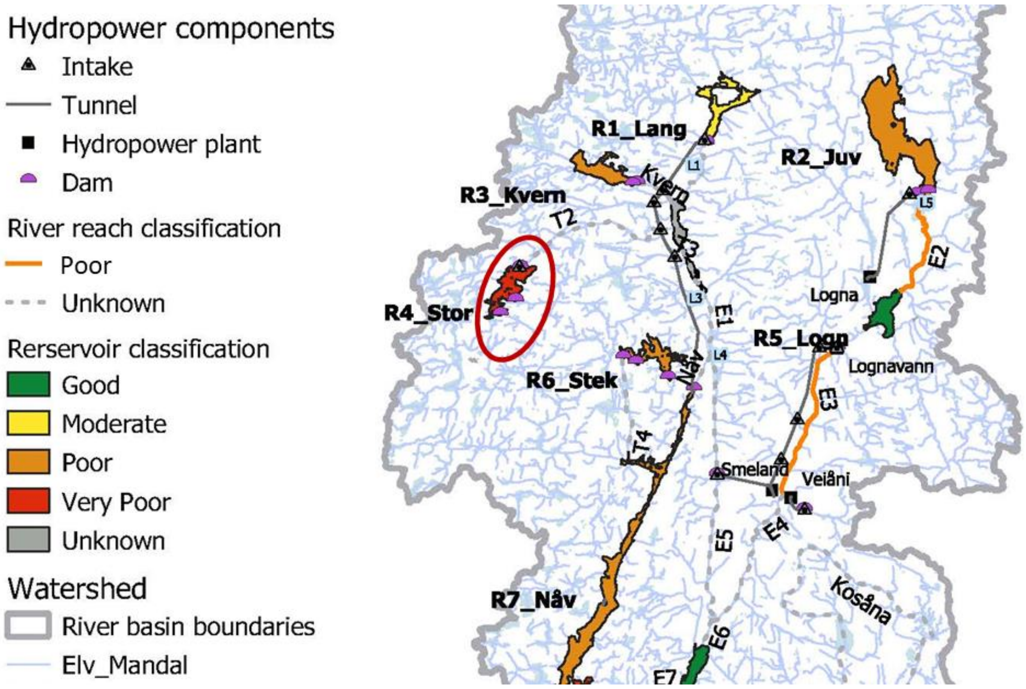


Figure 15. Ecological classification for R4, Storevann (red circle).

The area surrounding the reservoir has a very low density of cabins and few tracks and can be viewed as a pristine area.

3.4.3 Potential

There is a potential to increase abundance and to mitigate the lack of spawning streams. Currently such a stream does exist, however trout cannot access it. By constructing cell structure weirs, access to the spawning stream can be secured and facilitate natural recruitment. Increasing natural recruitment of brown trout will increase the recreational value of fishing.

3.5 R5 Logna

3.5.1 Hydrology

Logna reservoir is regulated 0.70 m, with no restrictions. The LRV is 357 and HRV is 357.7, and a total volume of 1.4 Mill m^3. It is classified as small impacted from hydropower regulation (Figure 16).

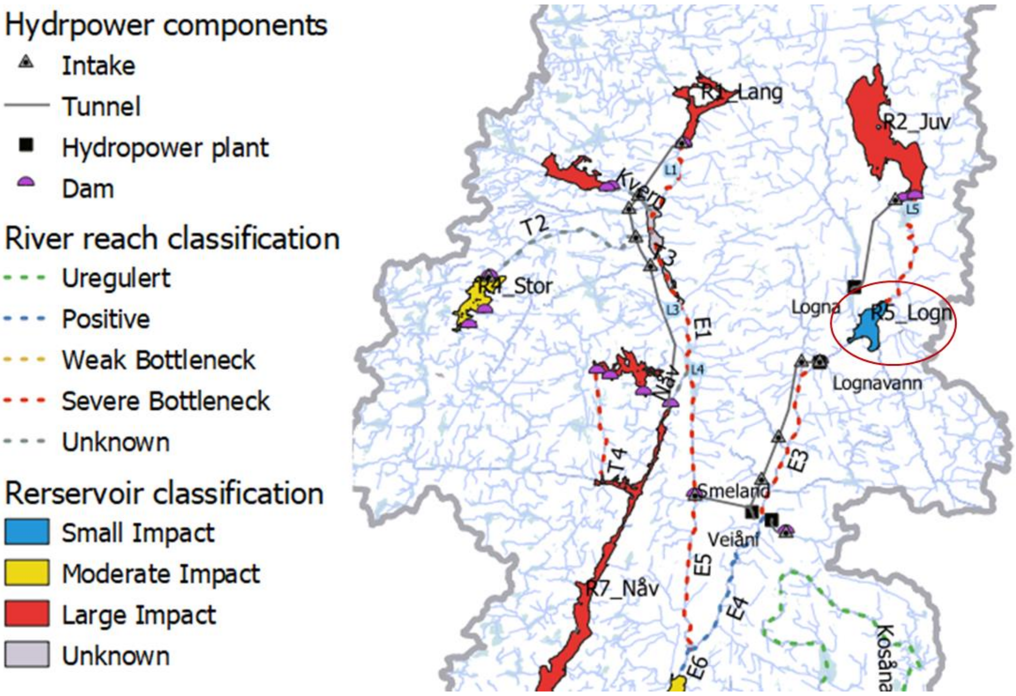


Figure 16. Hydrological classification for R5, Logna (red circle).

3.5.2 Ecology and recreation

The ecological status is assumed to be good in 2019 (Figure 17), but there is a lack of data from the reservoir. The most recent test-fishing was done in 2006 (Hesthagen and Haugland, 2007) and reported a poor condition of the brown trout population (females 25cm, 10 % of the catch). The conditions for recruitment are good. Local inhabitants have reported that population currently consists of a medium density of small fish and it is assumed that water quality has improved since 2006.

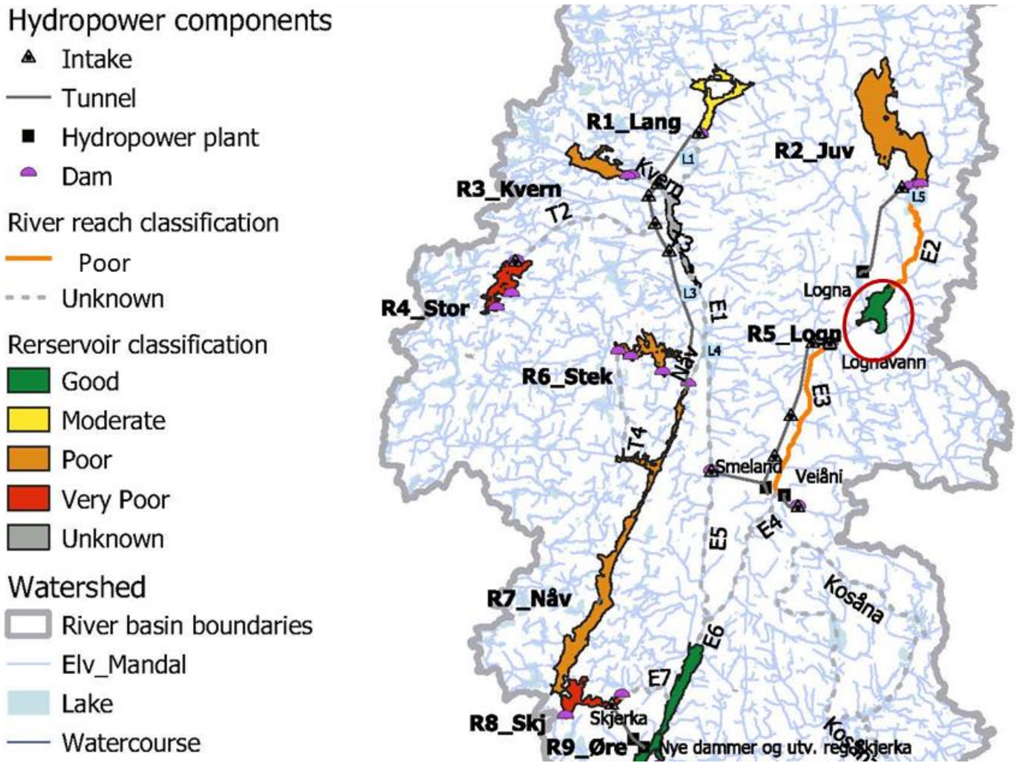


Figure 17. Ecological classification for R5, Logna (red circle).

There are tracks for hiking in the area and a road running along the lake. There are no cabins, but a few permanent residents.

3.5.3 Potential

For recreational value a high regulation can be avoided because of aesthetics. There are no other mitigation measures suggested for this reservoir.

3.6 R6 Stekil

3.6.1 Hydrology

Stekil is regulated 8 m (Figure 18), without any restriction. The LRV is 754 m.a.s.l and HRV is 762 m.a.s.l, and a volume of 10.9 Mill m^3. It is classified as high impacted from Vann-Net (Figure 19).

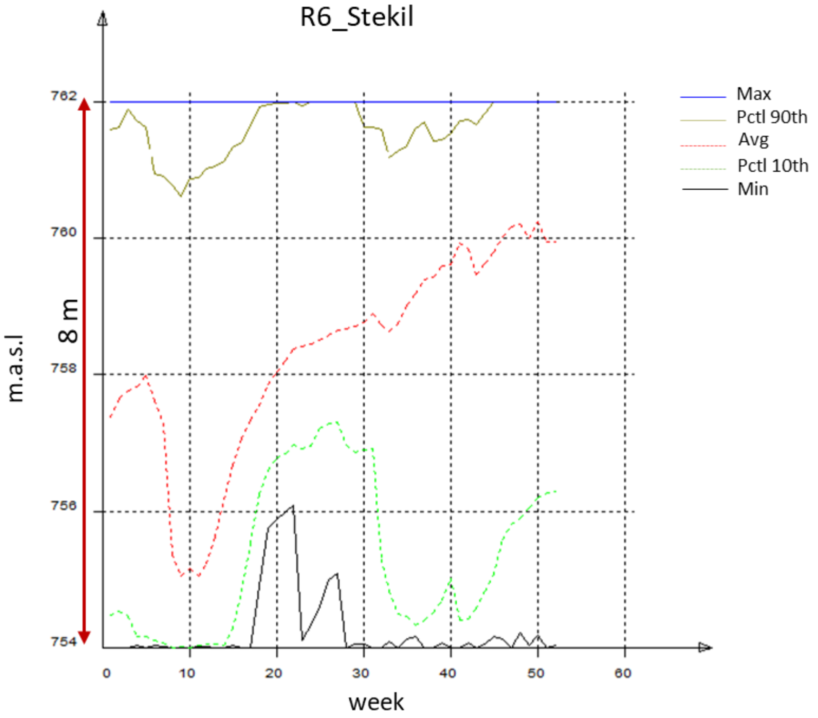


Figure 18. R6, Stekil reservoir curve and meters of regulation.

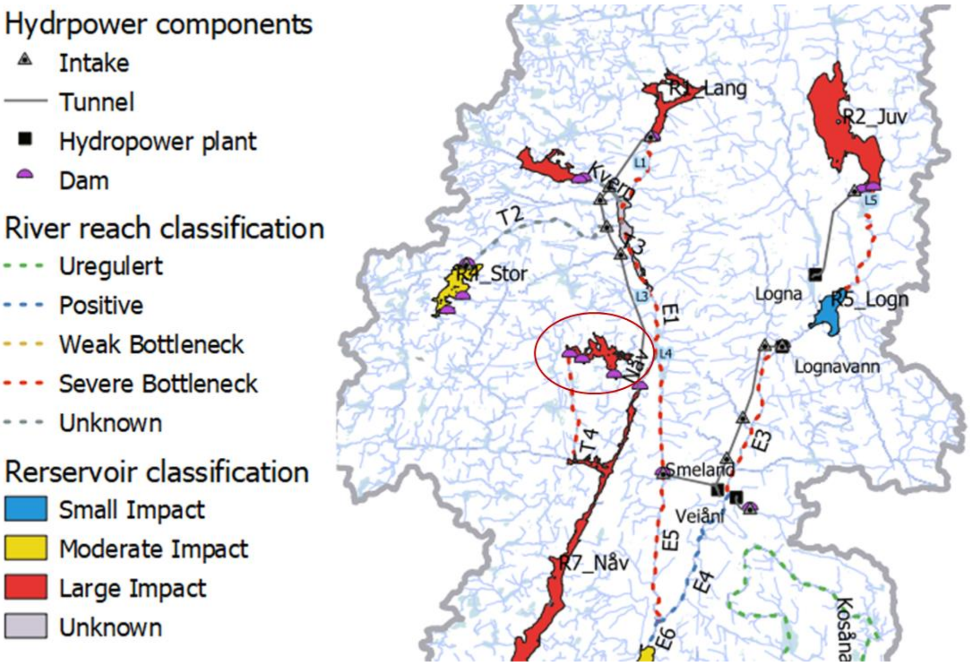


Figure 19. Hydrological classification for R6, Stekil (red circle).

3.6.2 Ecology and recreation

The brown trout population of Stekil has a CPUE of 0.2 which indicates very low numbers of fish in the reservoir. The population has thus a bad ecological status: Hatchery reared trout are stocked in this reservoir and have been caught in the gillnets with a CPUE of 3,1. Thus indicating a low density with medium sized females (28cm, making up 39 % of the catch). Stekil lacks spawning habitat and the regulation height of 6m will cause large areas to be above water periodically. There is no natural recruitment in the reservoir because of lack of admission to streams with spawning and recruitment possibility. The lake is nutrient poor.

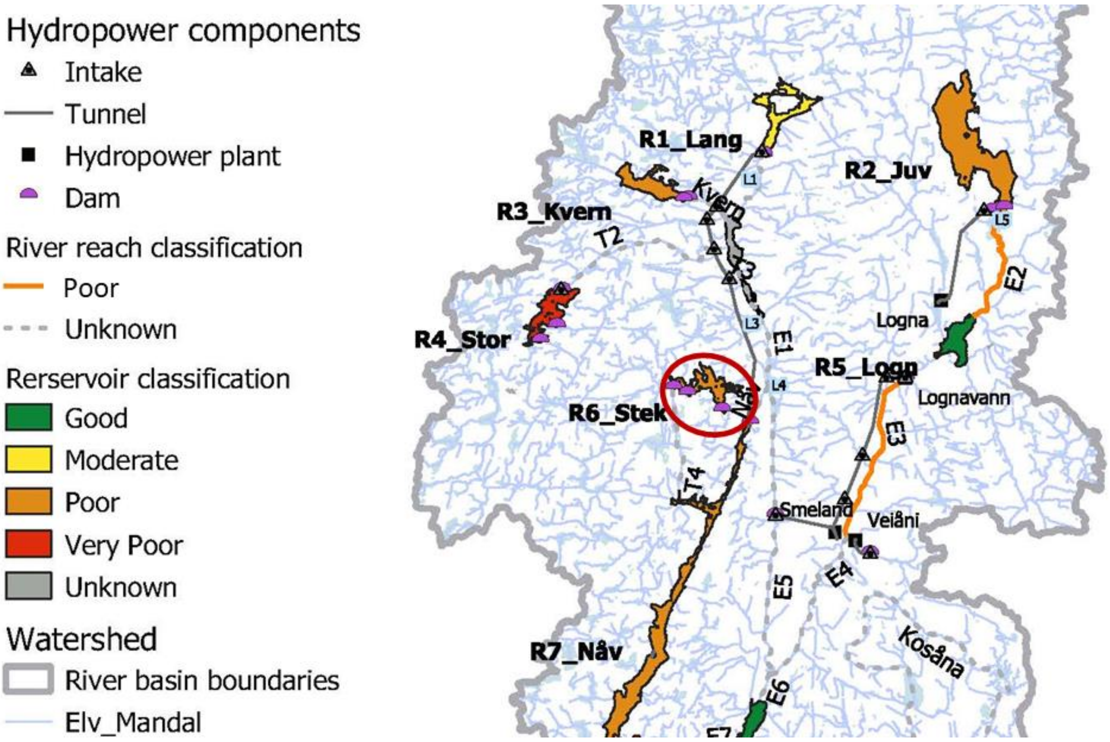


Figure 20. Ecological classification for R6, Stekil (red circle).

This area has little cabins, tracks, roads or permanent residents and it can be viewed as a pristine area, with little human influence.

3.6.3 Potential

There is a potential to increase abundance and to mitigate the lack of spawning streams. By constructing cell structure weirs, access to the two possible spawning stream can be secured and facilitate natural recruitment.

Avoiding large regulation height will secure a good recreational value due to aesthetics. Increasing natural recruitment and catch size of brown trout will increase the recreational value of fishing.

3.7 R7-8 Nåvann-Skjerka

3.7.1 Hydrology

Nåvann and Skjerka reservoirs has in total 37 m of regulation (Figure 21). The LRV in Nåvatn is 591.5 m.a.s.l and HRV is 628 m.a.s.l, and a volume of 124.2 Mill m^3 for Skjerka the LRV is 591 m.a.s.l and the HRV is 605 m.a.s.l with a volume of 19.6 Mill m$^{3.}$ It is classified as high impacted (Figure 22). There is an annual restriction of 5.2%

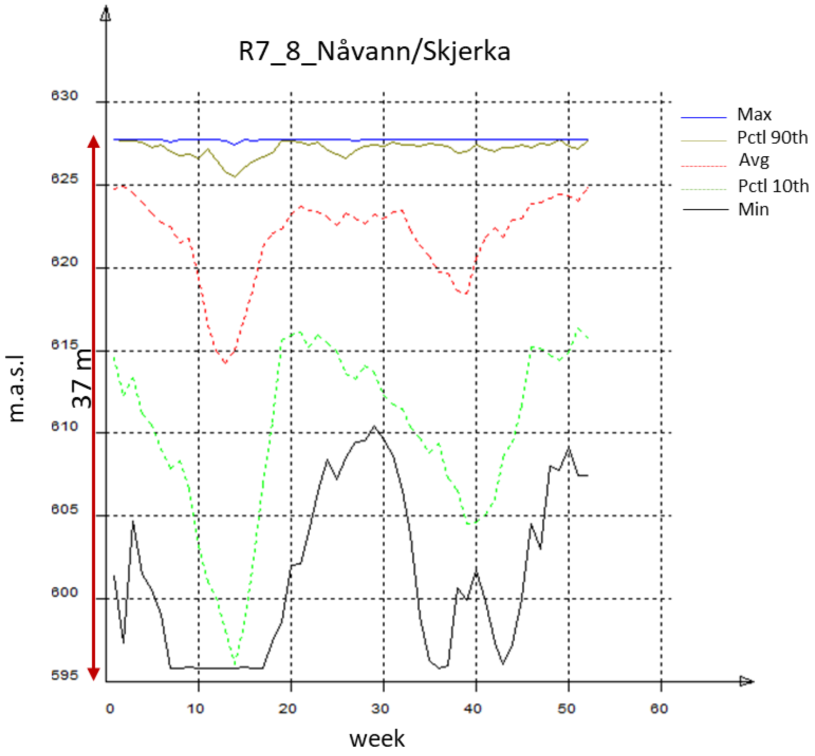


Figure 21. R7&8, Nåvann and Skjerka reservoirs curve and meters of regulation.

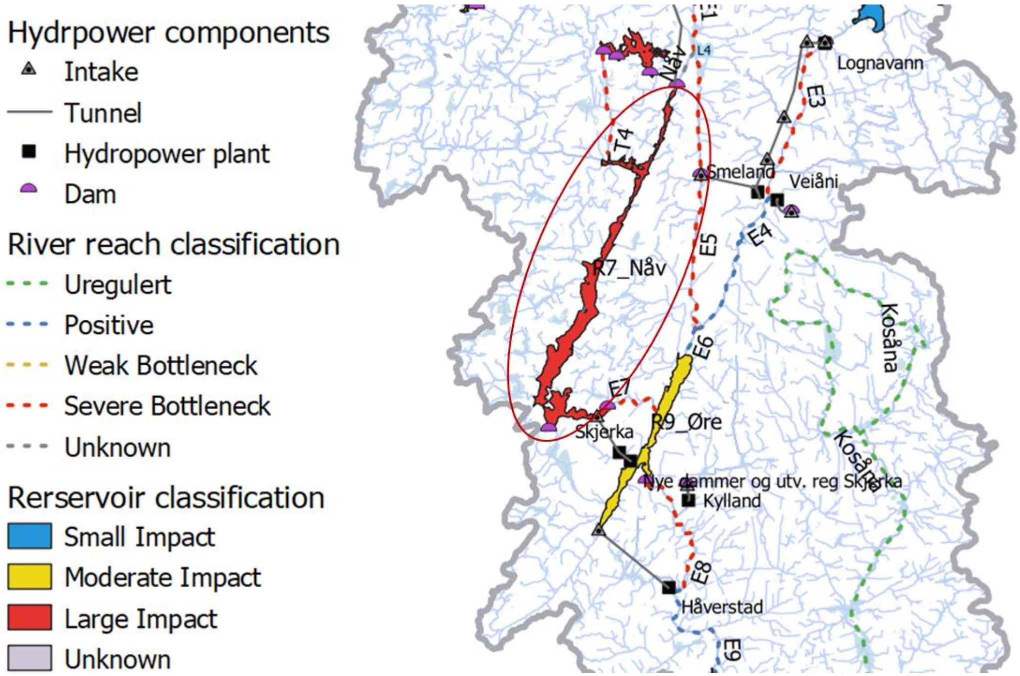


Figure 22. Hydrological classification for R7&8, Nåvann and Skjerka (red circle).

3.7.2 Ecology and recreation

The brown trout population of Nåvann/Skjerka has a CPUE of 0-1,8 which indicates low density and poor recruitment. Hatchery reared trout are stocked in this reservoir and have been caught in the gillnets with a CPUE of 1.9. The population consist of low density with medium sized females (28 cm, making up 33% of the catch). Nåvann-Skjerka has limited recruitment in southern part.

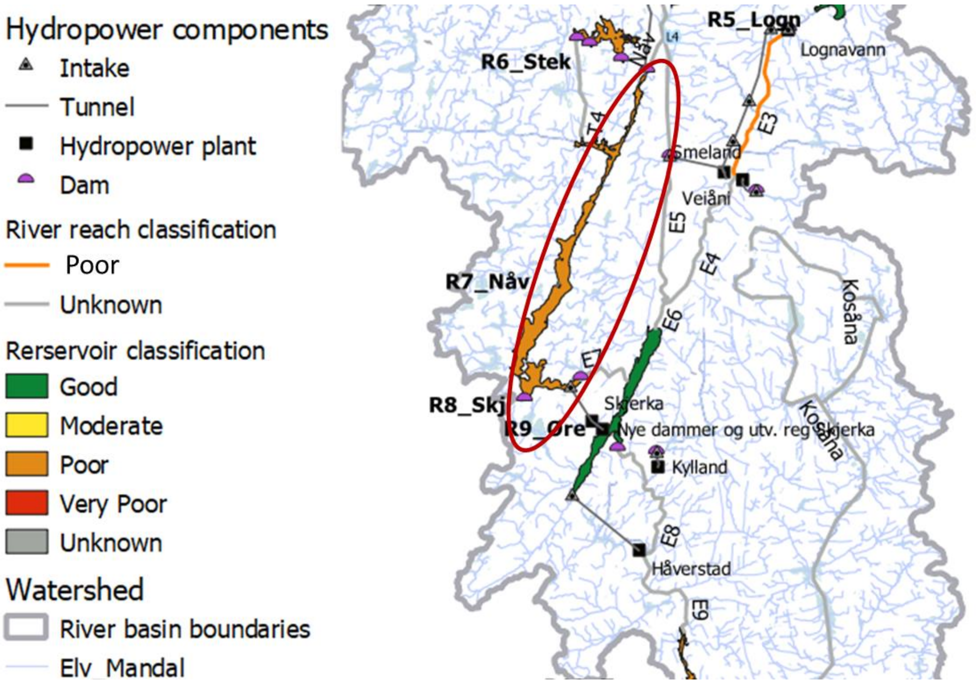


Figure 23. Ecological classification for R7&8, Nåvann and Skjerka (red circle).

There are some tracks in the area, but not in immediate closeness to the lake. A few kilometers south of the lake there is a dense cabin area with ski tracks. No permanent residents in the area. Accessing the lake is difficult because of a high regulation height.

3.7.3 Potential

There is a potential to increase abundance of the local brown trout population by improving spawning habitat in an inlet stream. Improve recruitment of brown trout by improving spawning habitat and water quality in an inlet stream; Uvdalsåni, by adding shell sand

3.8 R9 Øre

3.8.1 Hydrology

Ørevann is regulated 3.12 m (Figure 24), and it is classified as moderate impacted (Figure 25). The LRV is 256.08 m.a.s.l and HRV is 259.20 m.a.s.l, and a volume of 11.2 Mill m^3. The reservoir has an annual restriction of 52.50% as minimum reservoir volume.

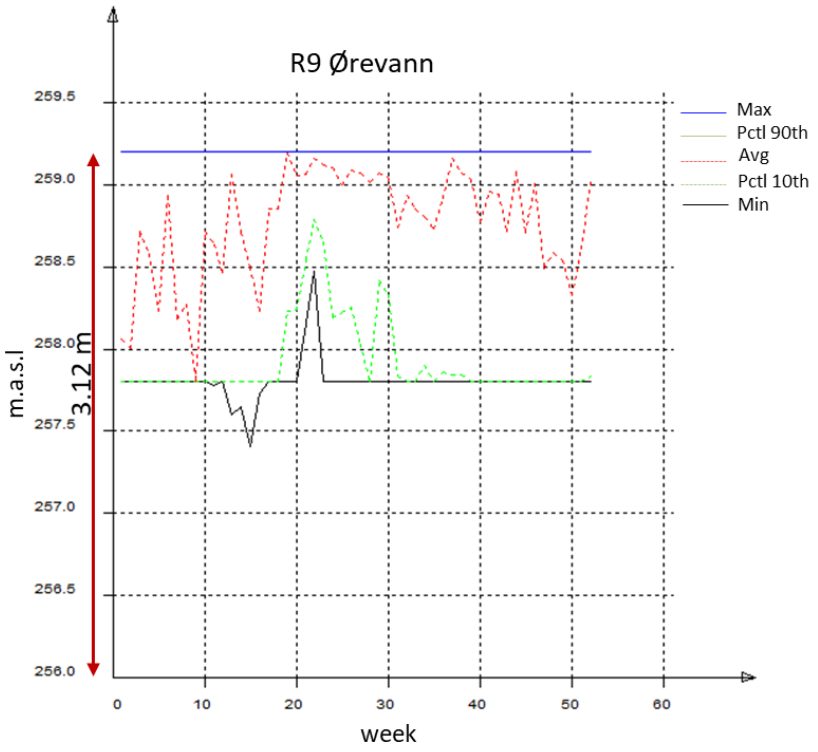


Figure 24. R9, Ørevann reservoir curve and meters of regulation.

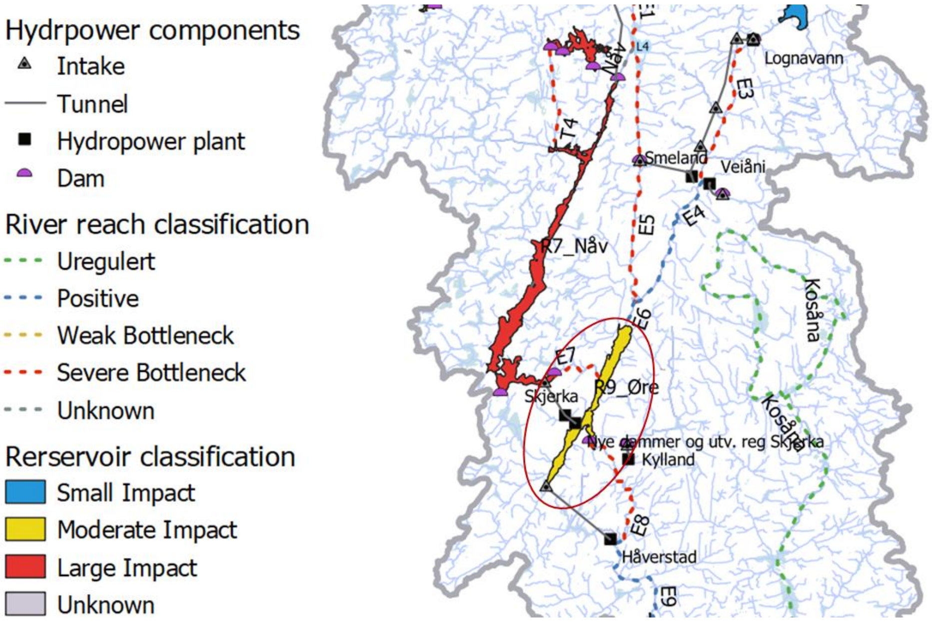


Figure 25. Hydrological classification for R9, Ørevann (red circle).

3.8.2 Ecology and recreation

The brown trout population of Ørevann has a CPUE of 15,8 which indicates high density and good recruitment. The ecological status of the wild populations is there for good (Figure 26). Hatchery reared trout are stocked in this reservoir and have been caught in the gillnets with a CPUE of 3.7

The average female size is female 23 cm and make up 44% of catch, this there is a medium density for the population with small sized females. Natural recruitment is not a problem in this reservoir, rather the contrary.

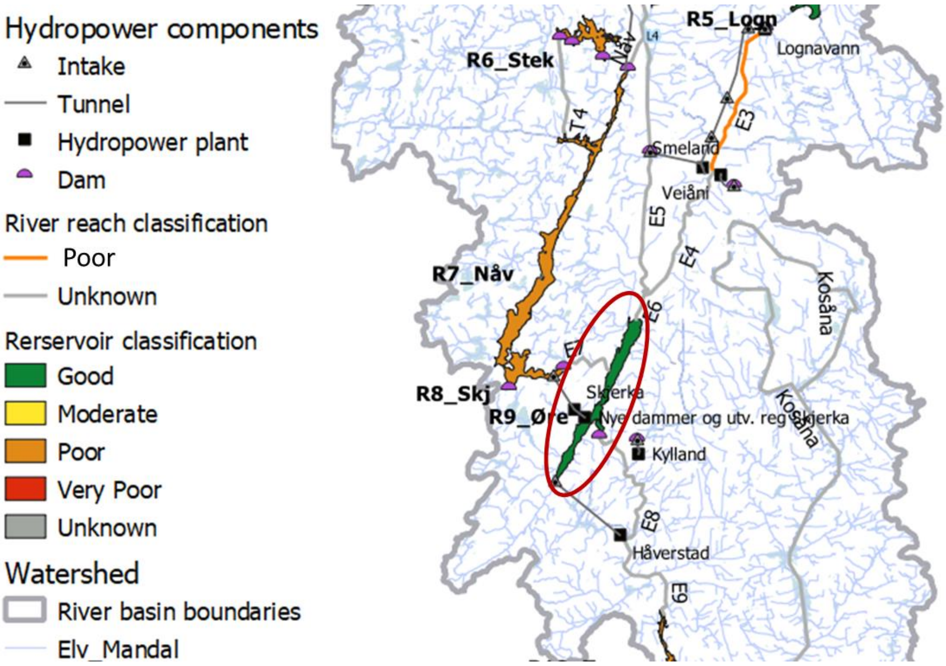


Figure 26. Ecological classification for R9, Ørevann (red circle).

There is a high density of cabins and hiking tracks in the nearby area; as well as an alpine resort. There are both hiking and skiing track in the area. During summer months the lake is used for swimming and paddling. The area can thus be regarded as of high value. The recreational fishing is not attractive in this lake because of the small sized brown trout.

3.8.3 Potential

There is a potential to increase the quality of the fish population by reducing abundance and reducing access to spawning areas to reduce recruitment. This can be achieved by blocking admission to spawning by putting in physical barriers to spawning streams. Further, thinning the population through fishing will decrease abundance, but increase average size.

If ecological mitigation measures are implemented and fish size is increased, it will increased value of recreational fishing

3.9 E1 Langevann_Monn

3.9.1 Hydrology

The river reach named E1 between Langevann and Mon intake (which is part of Smeland power plant system) is considered as a residual flow or bypass reach, it is affected by several intakes, starting from Langevann reservoir and continuing with intakes along the tributaries. There is not minimum flow required. However, it is planned to be implemented 0.4 m^3/s from May to September and 0.20 m^3/s from October to April. The river reach is classified as impacted by a severe bottleneck (Figure 28) according to the percentage of change in winter and summer 7-day low flow before and after regulation (Table 1.).

Table 1. Hydrological indices for E1 reach for Unregulated and Regulated period and the percentage of change in %.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	2.97	-83.69
Q95	1.02	0.00*	-100.00
Summer low flow	1.91	0.00*	-100.00
Winter low flow	0.89	0.00*	-100.00
Annual mean flood	171.84	68.11	-60.37
Ten-year flood	244.10	110.71	-54.65

*flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

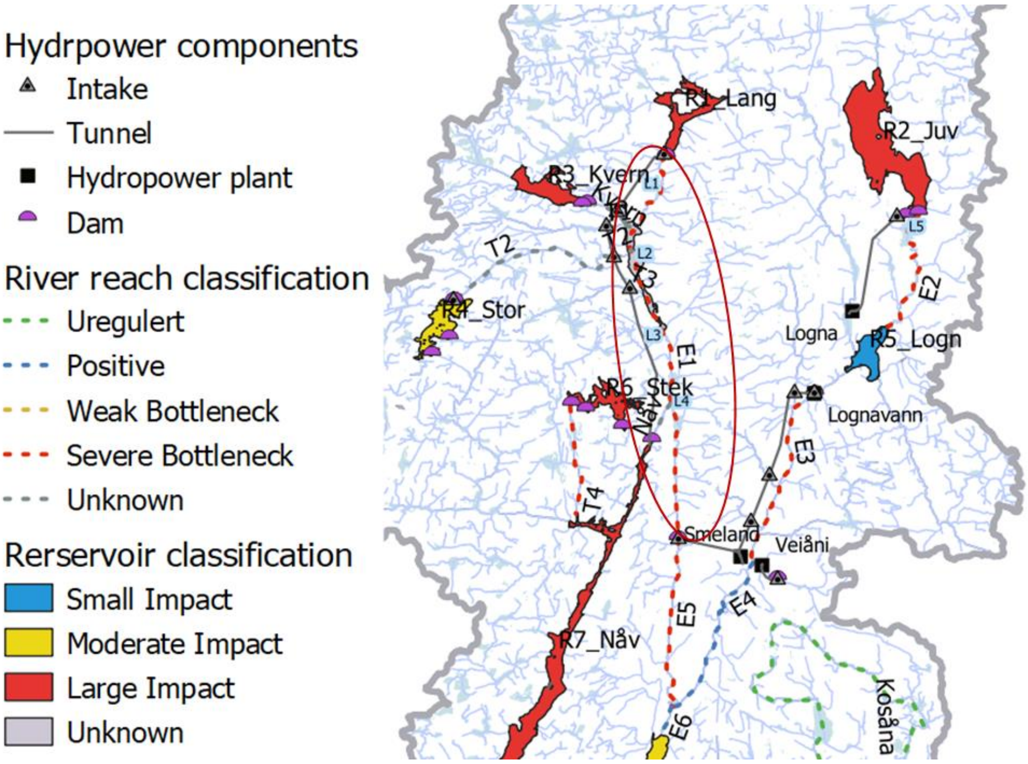


Figure 27. Hydrological classification for E1 reach, between Langevann and Mon intake (red circle).

3.9.2 Ecology and recreation

The status of the ecological status of the is river stretch is currently unknown as there is no data available. Thinning of the fish populations is currently done locally indicating a fish population with high density and small size. There is currently no minimum discharge applied. Recreational status is presently unknown.

3.9.3 Potential

Minimum discharge may increase available habitat for brown trout in effort to increase ecological status of the area.

3.10 E2 Logna (Juvatnet-Lognevatnet)

3.10.1 Hydrology

The river reach between Juvatn reservoir and Logna (E2) it is characterized as a residual flow reach or bypass section where water from Juvatn goes through the intake to the turbines and is released downstream. There is no minimum flow required in this reach, but the hydropower power does voluntarily release a residual flow in this reach that varies from 0.009 m^3/s to 0.013 m$^{3/}$s, depending on the reservoir volume. According to the change in winter and summer 7-day low flow before and after regulation (Table 2), the river reach is considered to have a severe hydrological bottleneck (Figure 28).

Table 2. Hydrological indices for E2 reach for Unregulated and Regulated period and the percentage of change in %.

Hydrological Indices	Unregulated (m^3/s)	Regulated (m^3/s)	Change (%)

Annual mean flow	9.79	0.63	-93.56
Q95	0.92	0.00*	-100.00
Summer low flow	0.89	0.00*	-100.00
Winter low flow	0.82	0.00*	-100.00
Annual mean flood	102.40	15.88	-84.49
Ten-year flood	148.10	45.12	-69.53

*flow might be slightly higher than 0 but still consider extremely low. In this case the voluntarily release is not considered in the hydropower model as environmental restriction, and therefore the output from the model is 0.

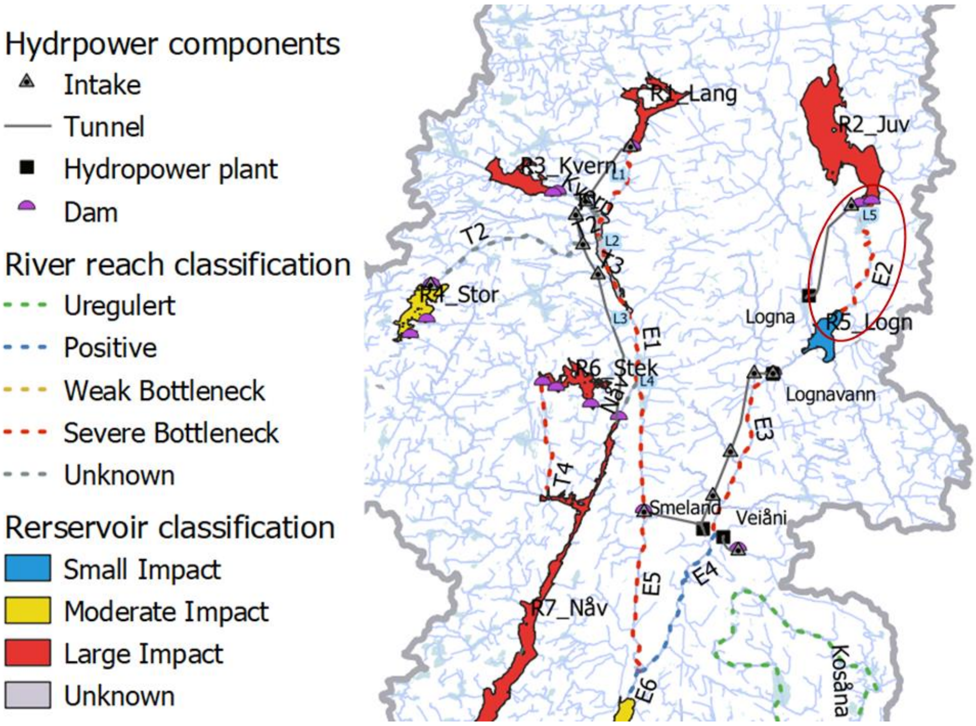


Figure 28. Hydrological classification for E2 reach, between Juvatn reservoir and Logna (red circle).

3.10.2 Ecology and recreation

There exists no data on the brown trout population and the ecological status in this stretch of the river. However, there is no minimum discharge indicating poor ecological status of the brown trout population (Figure 30).

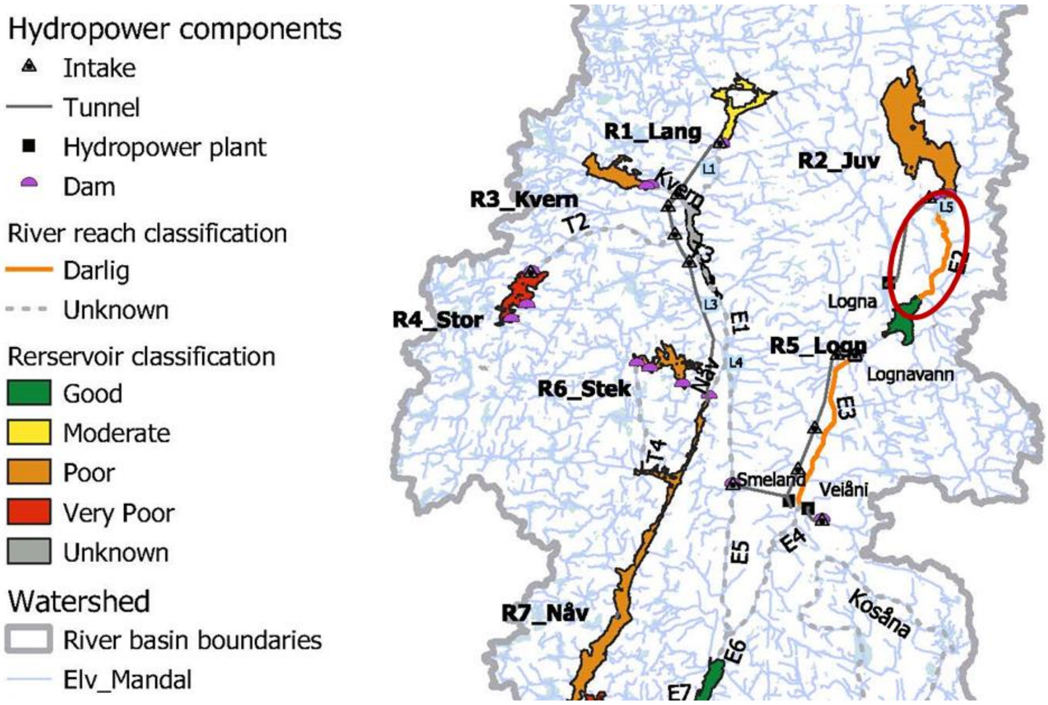


Figure 29. Ecological classification for E2 reach, between Langevann and Mon intake (red circle).

Recreational status is presently unknown.

3.10.3 Potential

Minimum discharge may increase recruitment and prevent stranding of juvenile brown trout. Winter survival may be increased by construction of deeper pools (cell structure weirs) in inlet to Lognevatnet

Establish hiking track close to river will increase recreation value of area

3.11 T4 Uvdalsåni (Stekil-Nåvatn)

3.11.1 Hydrology

The river reach between Stekil and Nåvatn named as T4 it is affected by the dams that regulate Stekil reservoir. This river reach it is classified as severe bottleneck (Figure 30) due to their differences between summer and winter low flow indices before and after regulation (Table 3). There is no minimum flow specified.

Table 3. Hydrological indices for T4 reach for Unregulated and Regulated period and the percentage of change in %.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	1.67	0.31	-81.45
Q95	0.24	0.00*	-100.00
Summer low flow	0.13	0.00*	-100.00
Winter low flow	0.18	0.00*	-100.00
Annual mean flood	16.50	56.59	242.97

Ten-year flood	23.60	99.93	323.43

*flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

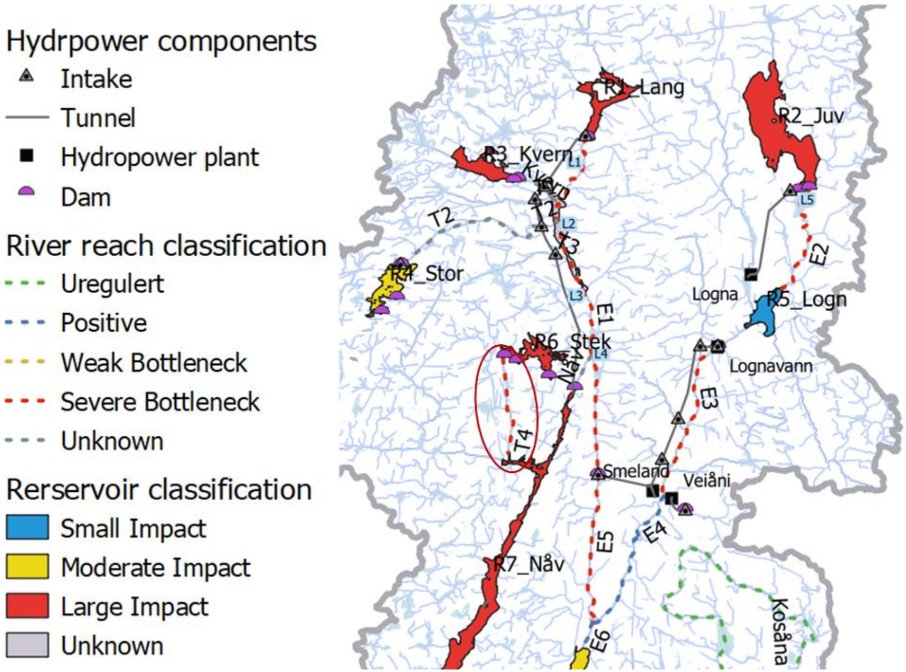


Figure 30. Hydrological classification for T4 reach, between Stekil and Nåvatn (red circle).

3.11.2 Ecology and recreation

There exists little data on the brown trout population, however water quality in the area has improved in recent years.

Recreational status is presently unknown, however there are few tracks and cabins in the area; it thus represents a pristine area with little human influence.

3.11.3 Potential

Potential spawning stream and recruitment area to lake Nåvatn can be created if minimum discharge is implemented (0.3m^3/sek) and spawning gravel is being added to the stream. Minimum discharge may increase recruitment and prevent stranding of juvenile brown trout

3.12 E10 Tungesjo-Kavfossen

3.12.1 Hydrology

This section of river reach names E10 is regulated by Bjelland hydropower plant, and it is affected by water going into the intake from Tungesjo reservoir, therefore this river reach is characterized as a bypass section, the river reach goes until kavfossen which is the last part of the anadromous reach and also where the unregulated tributary Kosåna flows into Mandalselva. According to the hydrological impact, it is classified as severe bottleneck (Figure 31) from the percentage of change in summer and winter low flows (Table 4).

Table 4. Hydrological indices for E10 reach for Unregulated and Regulated period and the percentage of change in %.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	6.56	-90.67
Q95	8.76	0.00*	-100.00
Summer low flow	8.90	0.00*	-100.00
Winter low flow	7.66	0.00*	-100.00
Annual mean flood	619.40	159.65	-74.23
Ten-year flood	888.00	306.72	-65.46

*flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

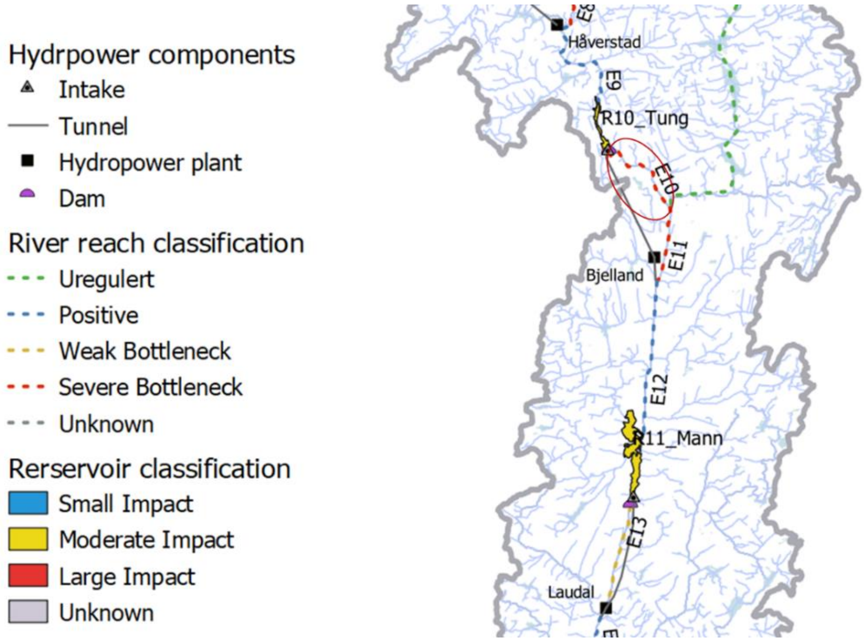


Figure 31. Hydrological classification for E10 reach, between Tungesjo intake and kavfossen (red circle).

3.12.1 Ecology and recreation

This stretch of river has been strongly influenced by hydropower and the river stretch has not had any restrictions on discharge and presently there are no minimum discharge regulations. The currents ecological status of the brown trout populations is there for assumed to be bad (Figure 32). This stretch of river is located right above the anadromous stretch, with a waterfall separating it from the anadromous stretch which Atlantic salmon cannot pass.

The anadromous stretch of river downstream of this area and the Atlantic salmon population is strongly influenced by hydropower regulation and the population would benefit from increasing the available anadromous habitat available.

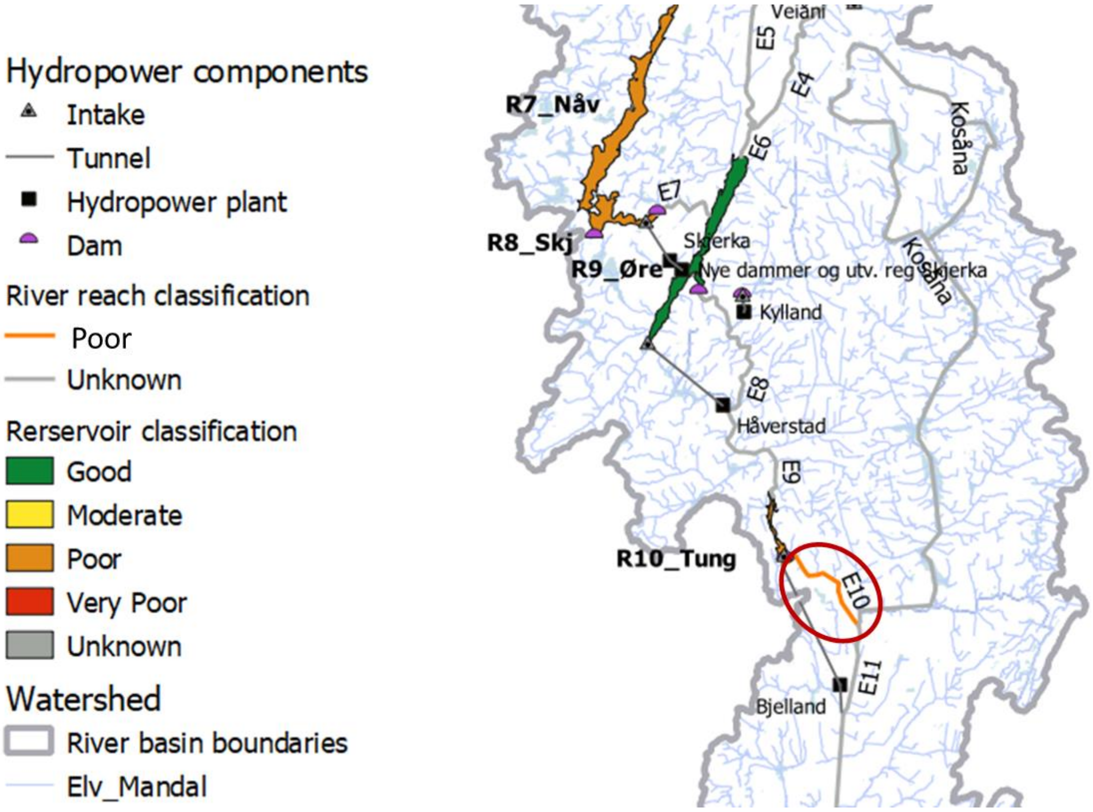


Figure 32. Ecological classification for E10 reach, between Tungesjo intake and kavfossen (red circle).

Currently the recreational value of the area is low, with little water running in the river and unknown status of the local brown trout population.

3.12.2 Potential

We propose to Increase anadromous stretch with 2.9 km, by constructing a salmon ladder and migratory fish way. This must be done in conjunction with implementation of minimum discharge for winter and summer periods.

Area will become more attractive for recreational fishing if Atlantic salmon are introduced to the river stretch. Minimum discharge is important for salmon production, but also for the esthetical impression of the river. The increased recreational value will be both for local inhabitants and tourists.

5. Annex

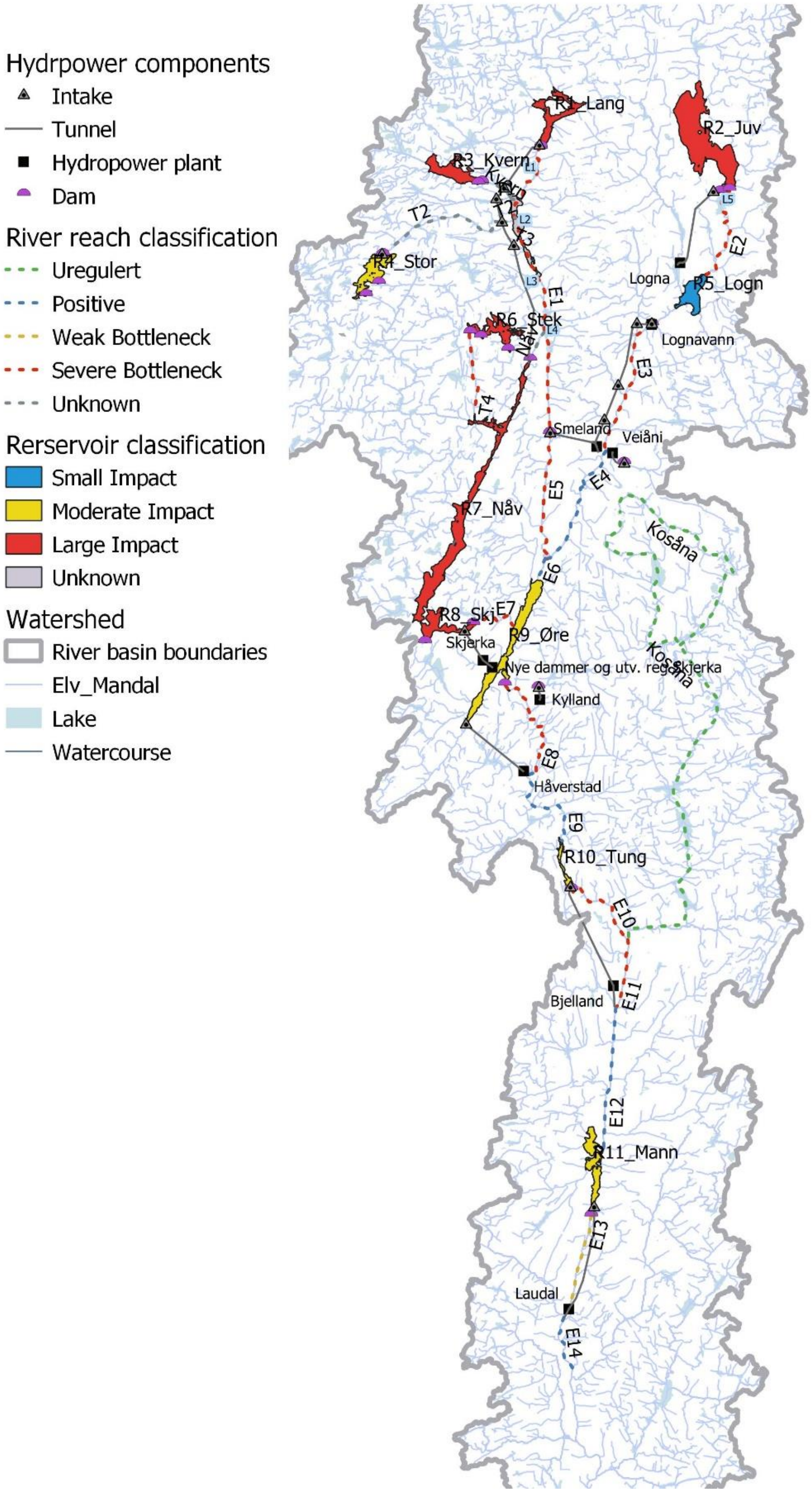


Figure 33. Hydrological classification for reservoirs based on Vann-Net classification and for river reaches based on potential hydrological bottlenecks from the environmental design handbook (Forseth and Harby, 2014).

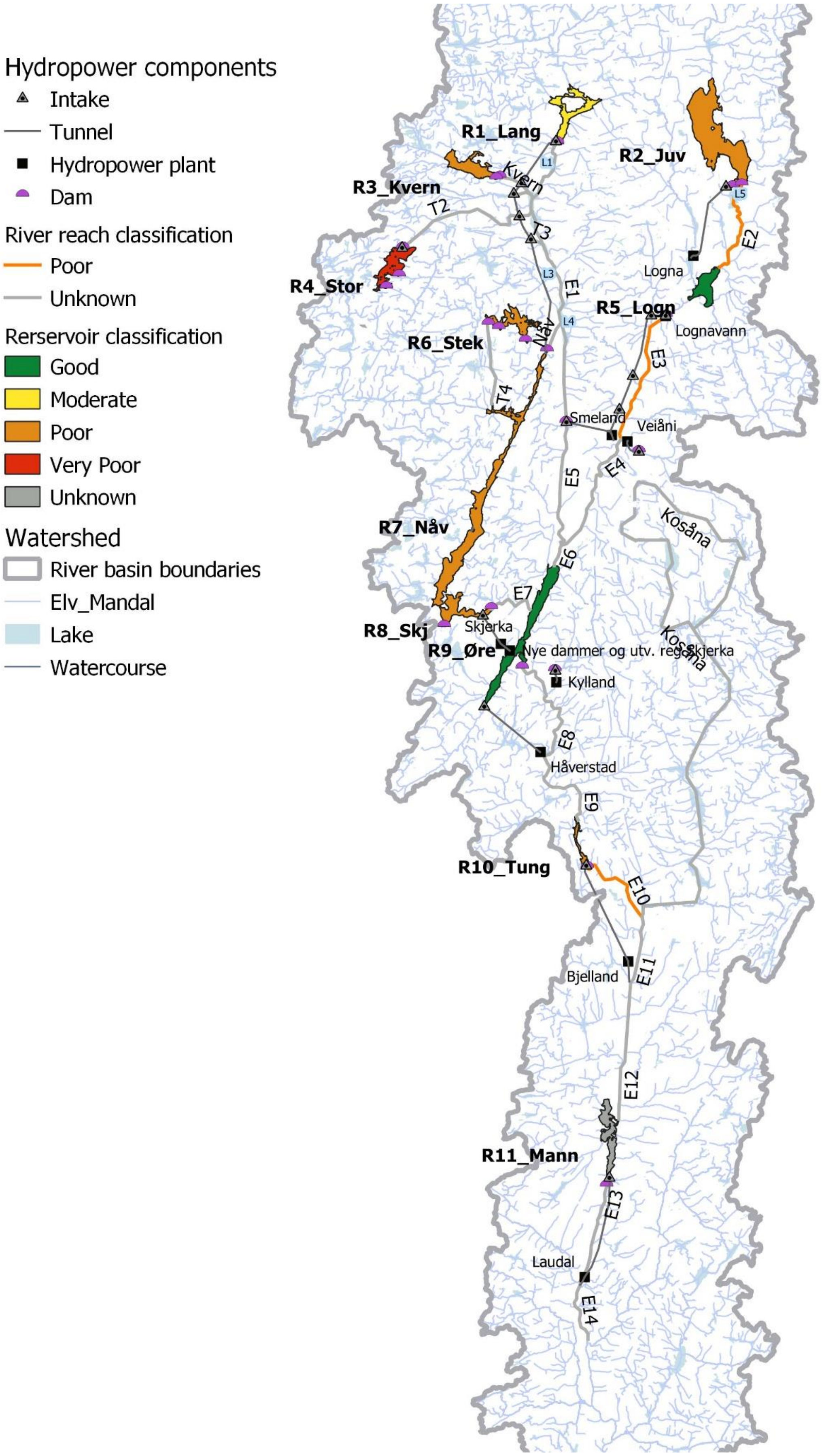


Figure 34. Ecological classification.

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AlternaFuture

A2: Hydropower Projects and Scenarios for Extreme Upgrading

Eirik Øvregård, Leif Lia, and Kaspar Vereide

2019-01-04

1 Introduction

This memo presents the screening and selection of hydropower projects for extreme upgrading of the Mandal hydropower system. To provoke new ideas and solutions, some challenging goals were introduced:

- The installed output from the system should be tripled [MW]
- The new scheme should include at least on large PSP
- The environmental conditions in the river should be improved

In parallel, researchers at NINA and SINTEF have been screening for potential environmental projects (Memo 3). By combining hydropower projects and environmental projects, three scenarios for extreme upgrading of the Mandal hydropower system with potentially positive environmental impact have been selected. The resulting scenarios are presented in this memo.

Two-page “hydropower cards” presenting each of the hydropower projects are given in Appendix 1. These hydropower cards present the key information, costs and evaluation of each project.

2 Method

AlternaFuture is a desk study project. Screening of projects were done by using maps, mainly NVE Atlas, and looking for suitable areas for new reservoirs and new power plants. All ideas with initial potential were moved to the next phase where dimensions, costs and productions were roughly estimated. In the end the most favourable projects were identified, and a hydropower card were made for each of them. A hydropower card is a two-page document displaying one project. Some of the ideas, e.g. B.3 Langevatn PSP, were initially proposed by Agder Energi. Also, many of the ideas came up during workshops where many participants from HydroCen attended. These ideas were then evaluated by the authors of this report.

In June 2018 the participants visited Åseral and visited the locations of the proposed projects. Further improvements were made to the hydropower cards. The proposed solutions have been distributed among all participants and the solutions have been iterated several times.

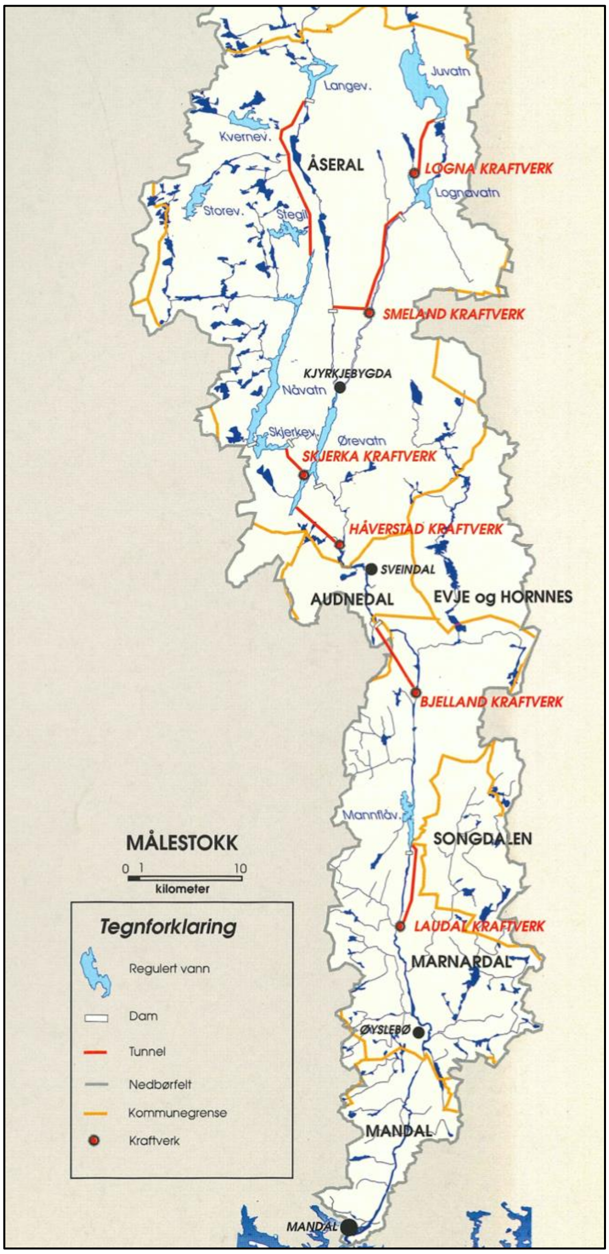


Figure 1: Mandalsvassdraget (from Fædrelandsvennen)

2.1 Assumptions and design criteria

Cost-benefit optimization of projects has not been carried out. This was seen to be too time consuming and not necessary for the scope of the project. The main parameters were set based on established rule-of-thumb to estimate acceptable dimensions of the power plants and hydropower structures. Obvious cost excessive solutions were avoided.

The criteria set for the powerplant design were:

- Water velocity in tunnels: 2 m/s
- Head loss due to friction: 1 m/km
- Turbine efficiency: 0,92
- Pump efficiency: 0,85
- Placement of tunnels by drawing straight lines, and modified if necessary, to ensure sufficient rock cover.

In addition, proposed alternatives should not touch upon protected nature, urban areas, infrastructure or areas protected from hydropower development. Potential reservoir volume where calculated by measuring the area at LRL and HRL. Assuming linear areal growth between LRL and HRL, the increased volume was calculated. Built-in tools in NVE Atlas were used.

All proposed new dams were assumed to be embankment dams, with 1:1.5 inclination of the slopes. Dam locations were decided based on an evaluation of increased reservoir volume versus dam volume. Only rough calculations where applied, so more suitable locations might exist. The height of the new dams was set as high as possible without exceeding the criteria set.

All pump storage plants were assumed to have reversible pump turbines, as this was a more cost-effective option than separating the pump and power plant. Upgrading of the electrical grid has not been taken into consideration.

2.2 Cost estimates

All costs are calculated based on information from “Kostnadsgrunnlag for vannkraftverk” (NVE, 2016). The major cost-intensive elements in power plants were the basis for the calculation:

- Turbines
- Generators
- Tunnels
- Power stations
- Dams

All cost includes all works, assembly and parts. For pump storage plants a 25 % cost increase is added to the turbine cost for a conventional power plant. In addition, an uncertainty factor of 1.3 were applied to all parts.

The costs of the dams and all dam related items were calculated by assuming 250 - 350 NOK per m^3 of dam body volume. These number were gathered from partly from “Kostnadsgrunnlag for vannkraftverk” and experience. Large dams have typically lower unit costs than smaller dams and this was considered when calculating the costs of the dams.

Cost of other infrastructure such as roads and upgrading of electrical grid has not been included.

3 Results: Screening

This chapter will present the outcome from the screening process. The reasoning behind choice of hydropower cards will also be presented. The results will serve as a reference when evaluating the simulated scenarios 1, 2 and 3. The hydropower cards are divided into four categories:

Category
A: Conventional power plants
B: Pump storage power plants
C: Flood power plants
D: Reservoirs

3.1 Hydropower cards

3.1.1 A - Parallel power plants

The easiest way to satisfy the specified target of triple installed capacity is to build four new power plants in parallel with the existing power plants. The new parallel power plants will have twice the capacity of the existing ones tripling the existing capacity. Table 1 provides a brief description of the proposed parallel power plants.

Power plants A.2 Nåvatn - Ørevatn and A.4 New Laudal are duplicates of the existing power-plants Skjerka and Laudal respectively, with twice the installed capacity. A.1 Juvatn – Smeland and A.3 Ørevatn – Bjelland bypasses the two existing powerplants and exploits the total head in one powerplant. A.1 bypasses Logna and Smeland powerplants and A.3 bypasses Håverstad and Bjelland. This is assumed to be a less costly option than building separate power plants.

The placement of the tunnels is chosen to avoid depressions in the topography and provide sufficient rock cover. The length and dimensions of the tunnels can be optimized by doing more accurate calculations.

Table 1: Selected projects and hydropower cards for category A – conventional power plants

	Power plant		**Tunnel**		**Electro-mechanical**			
Power plant	**P [MW]**	**H_0 [m]**	**L [m]**	**A [m^2]**	**Turbine**	**Unit / Freq. conv. [MVA]**	**Rev. / Speed-number**	**Cost [mill. NOK]**
A.1 Juvatn – Smeland	86	245	20	22	Vertical Francis	1 x 100 / 1 x 30	375 / 0,42	680
A.2 Nåvatn – Ørevatn	400	357	1,8	60	Vertical Francis	1 x 465 / 1 x 130	214,3 / 0,32	790
A.3 Ørevatn – Bjelland	206	180	18	65	Vertical Francis	1 x 240 / 1 x 67	200 / 0,52	1050
A.4 New Laudal	64	36	6	110	Vertical Francis	1 x 75 / 1 x 21	62,5 / 0,71	600

3.1.2 B – Pumped storage power plants

According to the AlternaFuture project description, a scenario with at least 500 MW pump-capacity should be included. Numerous different options were identified using existing reservoirs and proposed new reservoirs. All proposed storage power plants are assumed to have efficiency factors of 0,92 and 0,85 for production and pumping respectively. All PSP are chosen to be reversible pump turbines because of the reduced cost compared to separate turbines and pumps.

B.1 Storavatn PSP

The easiest way to incorporate 500 MW of pump-capacity is to place a PSP in parallel to Skjerka power plant exploiting the elevation difference between Skjerkevatn and Ørevatn, or between the proposed new reservoir D.1 Storavatn and Ørevatn. These are the locations with the highest fall in the Mandal river. The two alternatives are in many ways similar, but the total usable reservoir volume is larger by placing the intake in D.1 Storavatnet. This option is named B.1 Storavatn PSP.

B.2 Ørevatn PSP

Kosåna, a major tributary enters the main Mandal river just upstream from the outlet of Bjelland HPP. The water from Kosåna is now only exploited by the most downsteam power plant Laudal. A pump storage plant replacing A.3 Ørevatn – Bjelland would be able to pump this water, for storage and utilization in several additional power plants. The average flow from Kosåna is around 10 m^3/s, so a pump must be able to pump $2 \cdot Q_{mid}$, based on experience. This corresponds to a minimum installed capacity of 50 MW.

However, given the small reservoir volume of Ørevatn of 11 mill. m^3, a 50 MW power plant is not sufficient to equal the inflow and outflow of Ørevatn when all powerplants are running at full capacity. The Ørevatn PSP is therefore only useful if it is combined with the B.1 Storavatn PSP. If these two projects are combined, the Kosåna water can be pumped up to Storavatn for seasonal storage.

B.3 Langevatn PSP

There are four reservoirs at high elevation on top of the Mandal river in close vicinity of each other; Stekilvatn, Kvennevatn, Langevatn and Storevatn, ranging between 70 – 250 m above Nåvatn reservoir. Connected with a tunnel, they may be used as potential pump storage reservoirs. It was decided to investigate the possibility of a PSP with one unit to pump water to all reservoirs from Nåvatn. This would be a challenging engineering task, and for that reason the idea was examined further. The initial design criterion was that the PSP should be able to fill all four reservoirs within a 14-day period to follow the North Sea wind cycle. This however would require excessively large tunnels, so as a compromise the same design criterion was applied to roughly half the available reservoir volume. This would require a 60 MW PSP. The tunnel system consists of one long main tunnel from Nåvatn to Langevatn with tributary tunnels, which needs the ability to be closed off, to the other reservoirs.

B.4 Langevatn – Juvatn PSP

A possible PSP between Langevatn and Juvatn was identified. The two reservoirs can be connected by a 5 km long tunnel with a difference in elevation of 170 m. The design criterion was to fill Langvatn in 14 days to follow the North Sea wind cycle. This requires a 70 MW PSP.

Table 2: Selected projects and hydropower cards for category B - pump storage power plants

	PSP		**Tunnel**		**Electro-mechanical**			
PSP	**P [MW]**	**H_0 [m]**	**L [m]**	**A [m^2]**	**Turbine**	**Unit / Freq. conv. [MVA]**	**Rev. / Speed-number**	**Cost [mill. NOK]**
B.1 Storavatn PSP	500	357	1,5	80	Vertical pump turbine	2 x 290 / 2 x 290	187 / 0,33	940
B.2 Ørevatn PSP	120	180	18	40	Vertical pump turbine	1 x 120 / 1 x 120	250 / 0,52	820
B.3 Nåvatn – Stekilvatn Kvennevatn Langevatn Storevatn	60	70 - 250	5 - 19	65	Vertical pump turbine	1 x 180 / 1 x 180	100 – 300 / 0,72 – 0,45	930
B.4 Langvatn – Juvatn PSP	70	170	5	20	Vertical pump turbine	1 x 85 / 1 x 85	375 / 0,6	340

3.1.3 C - Flood power plants

The downstream section of Mandalselva have in recent years been subject to large flood events. From Øyslebø and further downstream to Mandal city in particular. To avoid this problem multiple flood power plants have been proposed to decrease a 200-year flood to a 20-year flood in Øyslebø. A flood power plant will run normally until a flood event occur, where the power plant disconnects itself and the tunnel diverts the excess water straight to the sea.

After the initial screening, two alternatives were considered, C.2 from Nåvatn to Fedafjorden and C.1 from Øyslebø to Try. The alternative from Nåvatn to Fedafjorden had the advantage of large head which reduces the required cross-sectional area of the tunnel system and increases potential power output. However, the distance between Nåvatn and Fedafjorden in a straight line is 40 km. A proposed tunnel would also have to traverse large depression valleys in the terrain. Another drawback of this option is that Nåvatn is high up in the catchment, so during a flow event the dampening effect from the reservoir will be modest. The power plant itself would also have limited production potential.

The option from Øyslebø to Try is considered more favourable. The distance between Øyslebø and Try is 12 km. The location is in the downstream end of the river just upstream the major urban areas. The tunnel would thus be able to divert flood water from a much larger catchment and protect the most valuable lands. One significant drawback is that the difference in elevation between Øyslebø and Try is only 30 m, which will require tunnels with a large cross-sectional area. A proposed outlet close to Mandal was also considered in an early phase but was dismissed because of longer tunnels, unfavourable topography, and construction works in an urban area.

With the arguments above in mind it was decided to set aside option C.2 Nåvatn to Fedafjorden and focus on option C.1 Øyslebø to Try.

The difference between a 200-year flood and a 20-year flood in Øyslebø is approx. 430 m^3/s. By using Mannings formula to estimate the head loss in the tunnel, and by assuming $M = 35 m^{1/3}/s$, the cross-sectional area must be 120 m^2 to divert the excess flood. The installed capacity of the powerplant was set to 20 MW and discharge capacity of 75 m^3/s based on discharge data from Øyslebø. This will generate 70 GWh of new energy annually.

Table 3: Selected projects and hydropower cards for category C – flood power plants

	Power plant			Tunnel		Electro-mechanical			
Power plant	**P [MW]**	**E [GWh]**	**H_0 [m]**	**L [m]**	**A [m^2]**	**Turbine**	**Unit/ Freq. conv. [MVA]**	**Rev./ Speed-number**	**Cost [mill. NOK]**
C.1 Øyslebø	20	70	30	12	120	Vertical Kaplan	1 x 25 / 1 x 5	93,75 / 0,71	800

3.1.4 D – Reservoirs

Several potential areas for reservoirs were found, but few were in the end topographically suitable to large reservoirs. In general, finding new reservoir sites proved difficult given the flat plateau-like topography of the region and population in the valleys. Criteria for finding reservoirs:

- Avoid large number of houses, cabins, structures etc.
- Environmental considerations. Avoid protected, conserved and sensitive areas.
- Avoid existing infrastructure.
- Reasonable dam cost versus reservoir volume.
- Avoid transferring water from one catchment to another.

Eptevatnet south-east of Ørevatn were examined as a potential reservoir for a PSP between Eptevatnet and Ørevatn. However, only a 10 m tall dam were feasible to construct, and the resulting storage volume would be to small to sustain flexible production. Dam heights above this would require several dams and a long dam length. As a consequence, the use of Eptevatnet was disregarded.

Several smaller reservoirs were investigated, e.g. Joruntjørn, Bustjørn and potential volumes of water around Monn and Logna. The reservoirs would have limited impact on the surrounding area, but the storage potential was also limited, and the reservoirs would require disproportionately large dams.

Eight km west of Nåvatn a potential large reservoir was identified. Placing a 60 m high dam across Faråna downstream of Kissvatn would create a reservoir three times the storage capacity of Nåvatn. This reservoir could also be connected to Nåvatn with a tunnel, eliminating the need for another power plant. However, this area is a protected nature area and was not included as a potential reservoir. The same arguments eliminated potential reservoirs north of Juvatn and Langvatn.

After screening the region only one new reservoir was identified. South of Nåvatn three small bodies of water are situated in a small valley with steep rock slopes. Placing a dam at the downstream end of Kråkelitjønna and raise the water level to Nåvatn`s HRL would create a storage volume of 280 mill. $m^3$. Connecting the new reservoir and Nåvatn at Nåvatn`s LRL would in principle create one large reservoir. Along the existing bodies of water there is half a dozen cabins, but it was considered acceptable to go forward with the reservoir. The new reservoir was named D.1 Storavatn.

Raising existing reservoirs were also considered. Nåvatn-Skjerkevatn, Ørevatn, Lognevatn, Stekilvatn, Storevatnet and Tungefoss were all deemed to be unsuitable for increased water levels due to topography restricting the potential gain in storage. There is also large numbers of buildings and public interest in and around Ørevatn. All reservoirs above was therefore set aside. The dam at Langevatn is currently under construction to increase its height and was also set aside.

The storage capacity of Kvennevatnet and Juvatn could both be significantly increased without too much negative impact. Kvennevatnet can be raised another 10 m without water release. This would increase the storage capacity from 38 mill. m^3 to 90 mill. m^3. This option would create little to no negative effects on the surrounding area and would only require a small dam. This alternative was given the name D.3 Raise Kvennevatnet.

Juvatn can be raised almost 30 m without impacting the main cabin areas on its west side. There are also limited societal interest in the potentially claimed areas, bar a few cabins on the eastern and northern shores. Given the large area of Juvatn this would create a large increase in storage capacity. Two separate dam locations were identified:

- Alternative 1: At the existing dam location
- Alternative 2: Two km downstream of the existing dams.

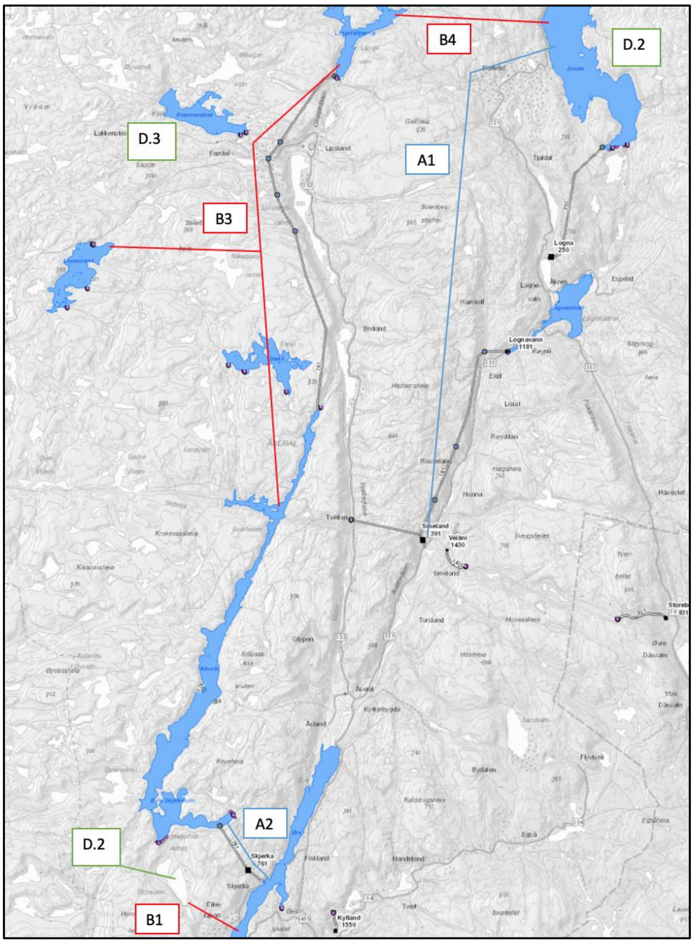
Alternative 2 would increase the area of Juvatn by another 2 km^2 and further increase the reservoir volume by 100 mill. m^3. However, the dam volume needed for alternative 2 would be four to five times larger than for Alternative 1. Alternative 1 was deemed the preferable alternative and was given the name D.2 Raise Juvatn.

Table 4: Selected projects and hydropower cards for category D – Reservoirs

	Reservoir				**Dam**		
Reservoir	**HRL [mas.]**	**A (HRL) [km^2]**	**H [m]**	**Volume [mill. m^3]**	**Length [m]**	**Volume [mill m^3]**	**Cost [mill. NOK]**
D.1 Storavatn	627	4,9	97	280	1150	6,6	1650
D.2 Raise Juvatn	540	14	51	520	950	1,2	300
D.3 Raise Kvennevatnet	780	2,4	35	90	400	0,15	50

3.1.5 Summary of results

The maps below show the locations of the hydropower cards.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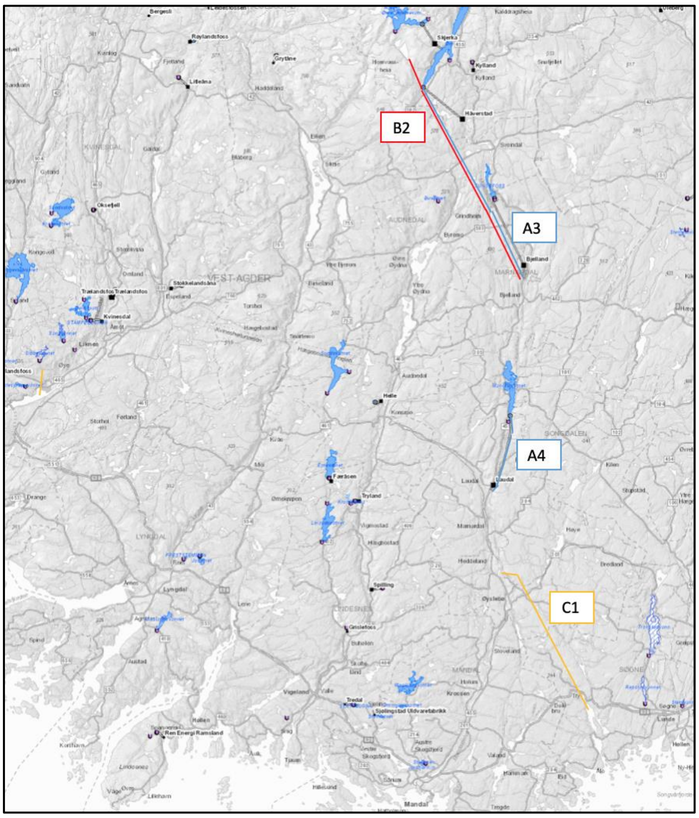
A1
B3
A2
D.2
B1


B2
A3
A4
C1

3.1.6 Screened and dismissed projects

Table 5 shows other ideas that were investigated but not included in the final selection of hydro power cards. These projects will not be mentioned again in this report.

Table 5: Dismissed ideas and projects

Project	Pros and cons	Conclusion
Power plant Myglevatn – Lauvfossen (Kosåna)	+ Exploit the elevation difference and water from Myglevatn. Now unexploited. – Misses out on water from Rolandsbekken, which drains water from a significant catchment. – Kosåna and its catchment is protected from hydropower development before it pours into Mandalselva.	Set aside because Kosåna is protected from hydropower development.
Flood power plant Nåvatn - Lygne	+ Large elevation difference + Relatively short tunnel and little to no visual impact. + Dams already in place – Lygne is protected – Moving of water from one catchment to another – Loss of hydraulic head compared to the total head exploited from Nåvatn to downstream of Laudal	Set aside because of unacceptable environmental impact and violation of protected nature.
Juvatn – Byglandsfjorden PSP	+ Large elevation difference + Juvatn and Byglandsfjorden are both large reservoirs ideal for PSP. + Dams already in place – Byglandsfjorden is partly protected because of Norway's only inland Salmon population – Moving of water from one catchment to another – Loss of hydraulic head compared to the total head exploited from Juvatn to downstream of Laudal	Set aside because of unacceptable environmental impact and violation of protected nature. Projects should be within the catchment.
Transfer water from Tveitevatnet in Kosåna catchement to Tungefoss.	+ The water from Kosåna will be exploited by Bjelland and Laudal, not just Laudal, providing an additional 0.2 kWh/m^3. – Kosåna catchment is protected from hydropower development	Set aside because Kosåna is protected from hydropower development.
Juvatn – Ørevatn PSP	– Long tunnels and large cost. – Inferior to similar projects, e.g. PSP from Nåvatn to Ørevatn.	Inferior alternative. Set aside in favour of better alternatives.

4 Results: The Selected Scenarios

Three different scenarios were proposed to fulfil the scope of the project:

Scenario	Description
1 – Triple installed capacity	- Triple current installed capacity in MW - Include at least one flood power plant
2 – Full flexibility	- Triple current installed capacity - At least 500 MW of pumping capacity
3 – Flood dampening	- At least 500 MW of pumping capacity - Include at least one flood power plant

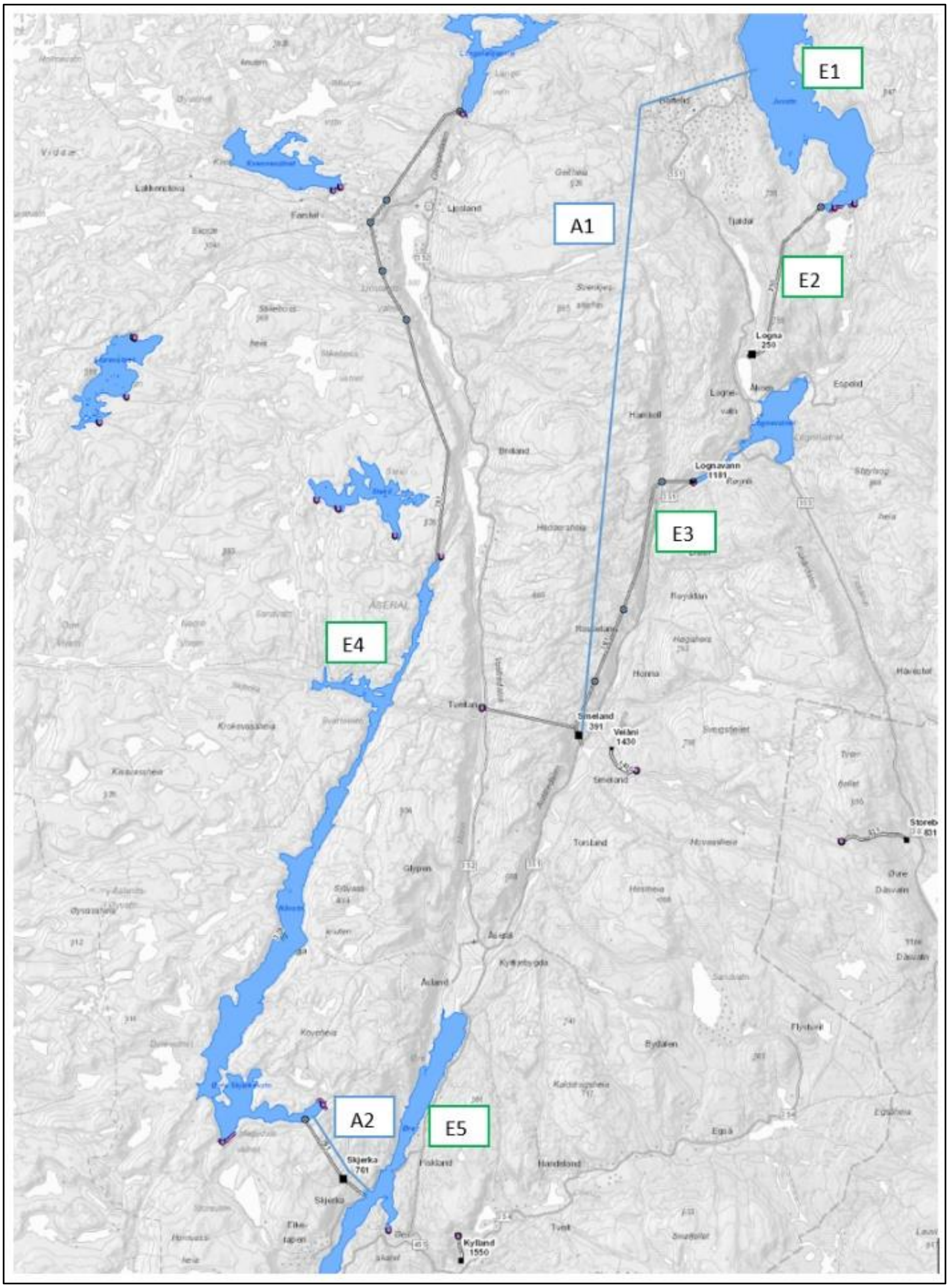
As one of the prerequisites for the project was improved ecological status in Mandalselva, researchers from NINA and NTNU met and decided on a quid pro quo basis which hydropower cards and environmental cards should be included in each scenario. Environmental cards are the environmental equivalent to the hydropower cards. Researchers from NINA identified several potential positive measures in Mandalselva. The measures with the most positive impact on the ecological status were presented as environmental cards. The combined positive impact from the environmental cards should outweigh the combined negative impact from the hydropower cards in each scenario.

4.1 Scenario 1: Triple installed capacity

Table 6 shows the chosen projects included in scenario 1 with calculated cost and installed capacity. The maps on the next pages show the location of the selected hydropower and environmental projects.

Table 6: Projects included in scenario 1

Hydropower Cards	**Cost [MNOK]**	**Installed capacity [MW]**	**Installed pump cap. [MW]**
Power plants			
0 Existing power plants		385	
A.1 Juvatn – Smeland	680	88	
A.2 Nåvatn – Ørevatn	790	400	
A.3 Ørevatn – Bjelland	1050	206	
A.4 Laudal II	590	32	
C.1 Øyslebø - Try	800	20	
Environmental cards			
E.1 Reservoir Juvatn			
E.2 River reach intake to outlet Logna HPP			
E.3 River reach Lognevann to outlet Smeland HPP			
E.4 Reservoir Nåvatn			
E.5 Reservoir Ørevatn			
E.6 River reach Tungefoss-Kavfossen	15		
E.7 River reach Mannflåvatn to outlet Laudal HPP			
E.8 River reach Øyslebø to the sea			
E.9 New reservoir Storavatn			
Sum	**3925**	**1130**	**0**


E1
A1
E2
Logna
250
Lognavann
1181
E3
E4
Smeland
391
Veisi
1430
Storeb
831
A2
E5
Skjerka
761
Kylland
1550
Ljosland
Lognevatn
Tveitan
Hunnedalsvatnet
Skjerka
Smeland
Tonland
Åseral
Fiskland
Handeland
Espeland
Åvin
Glypen
Holmevatn
Ljosland
Lakkerkvina
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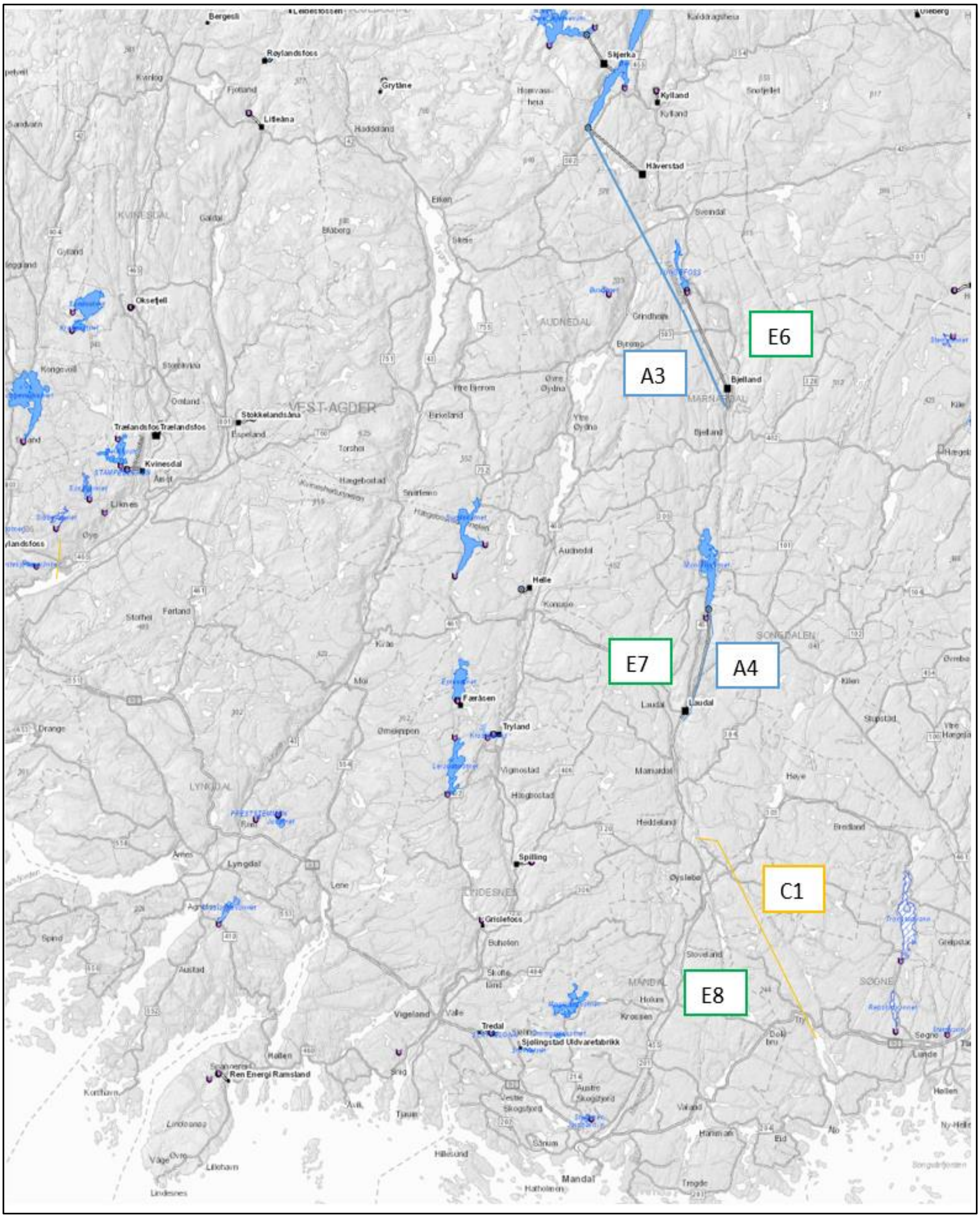
E6
A3
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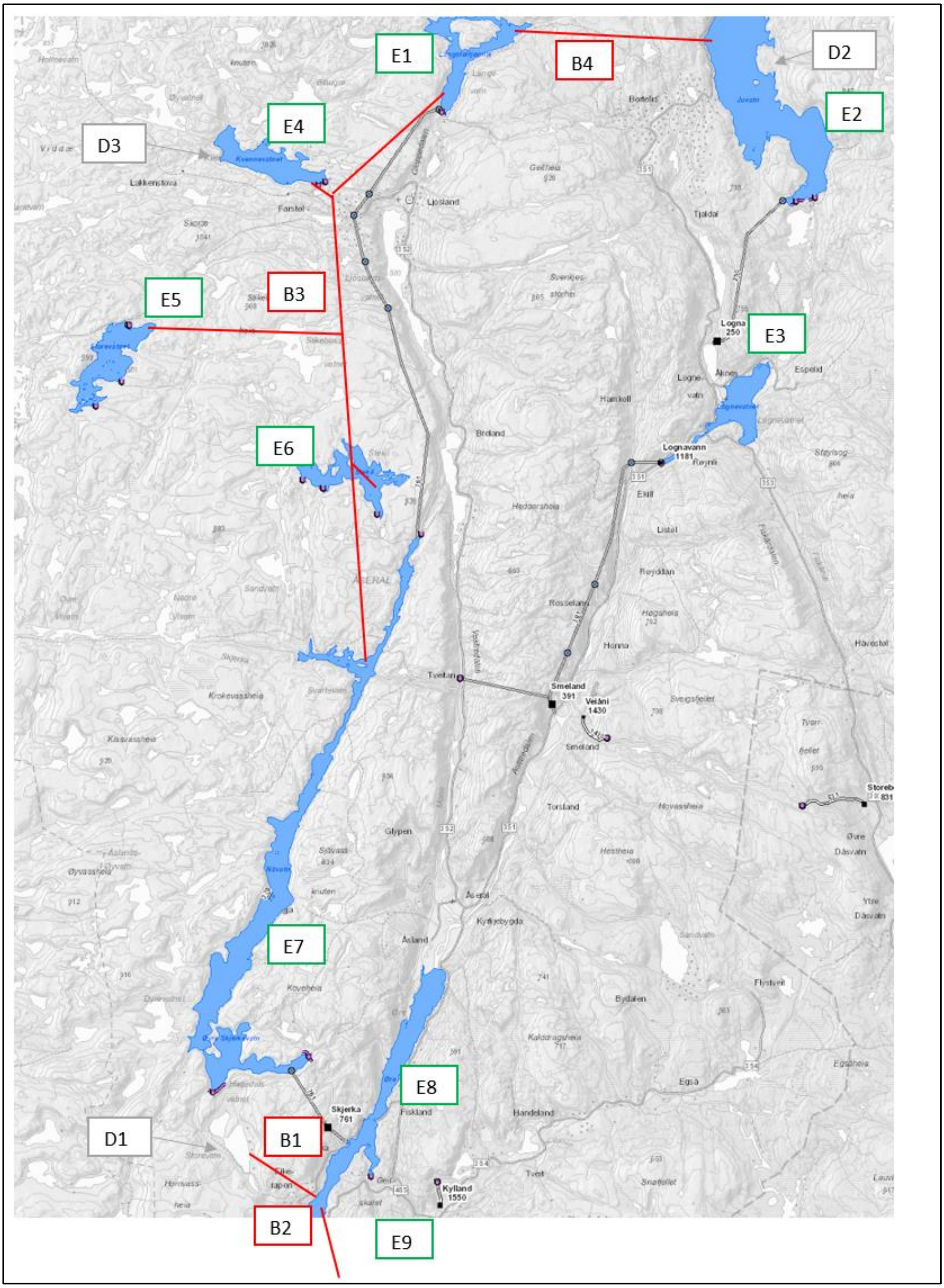
C1
E8
VEST-AGDER
KVINESDAL
AUDNEDAL
MARNARDAL
SONGDALEN
LYNGDAL
LINDESNES
MANDAL
SØGNE
Røylandsfoss
Grytåne
Litleåna
Skjerka
Kylland
Håverstad
Bjelland
Okseffell
Stokkelandsåna
Trælandsfos
Kvinesdal
Helle
Færåsen
Tryland
Laudal
Spilling
Grislefoss
Tredal
Sjølingstad Uldvarefabrikk
Ren Energi Ramsland
Mandal

4.2 Scenario 2: Maximum flexibility

Table 7 shows the chosen projects included in scenario 2 with calculated cost and installed capacity. The map on the next page shows the location of the selected hydropower and environmental projects.

Table 7: Projects included in senario 2

Hydropower Cards	**Cost [MNOK]**	**Installed capacity [MW]**	**Installed pump cap. [MW]**
Power plants			
0 Existing power plants		385	
B.1 Storavatn PSP	940	500	500
B.2 Ørevatn PSP	820	120	120
B.3 Langevatn PSP	930	60	60
B.4 Juvatn PSP	330	70	70
Reservoirs			
D1 Storavatnet	1650		
D.2 Raise Juvatn	400		
D.3 Raise Kvennevatn	50		
Environmental cards			
E.1 Reservoir Juvatn			
E.2 River reach intake to outlet Logna HPP			
E.3 River reach Lognevann to outlet Smeland HPP			
E.4 Reservoir Nåvatn			
E.5 Reservoir Ørevatn			
E.6 River reach Tungefoss-Kavfossen	15		
E.7 River reach Mannflåvatn to outlet Laudal HPP			
E.8 River reach Øyslebø to the sea			
E.9 New reservoir Storavatn			
Sum	**5135**	**1135**	**750**

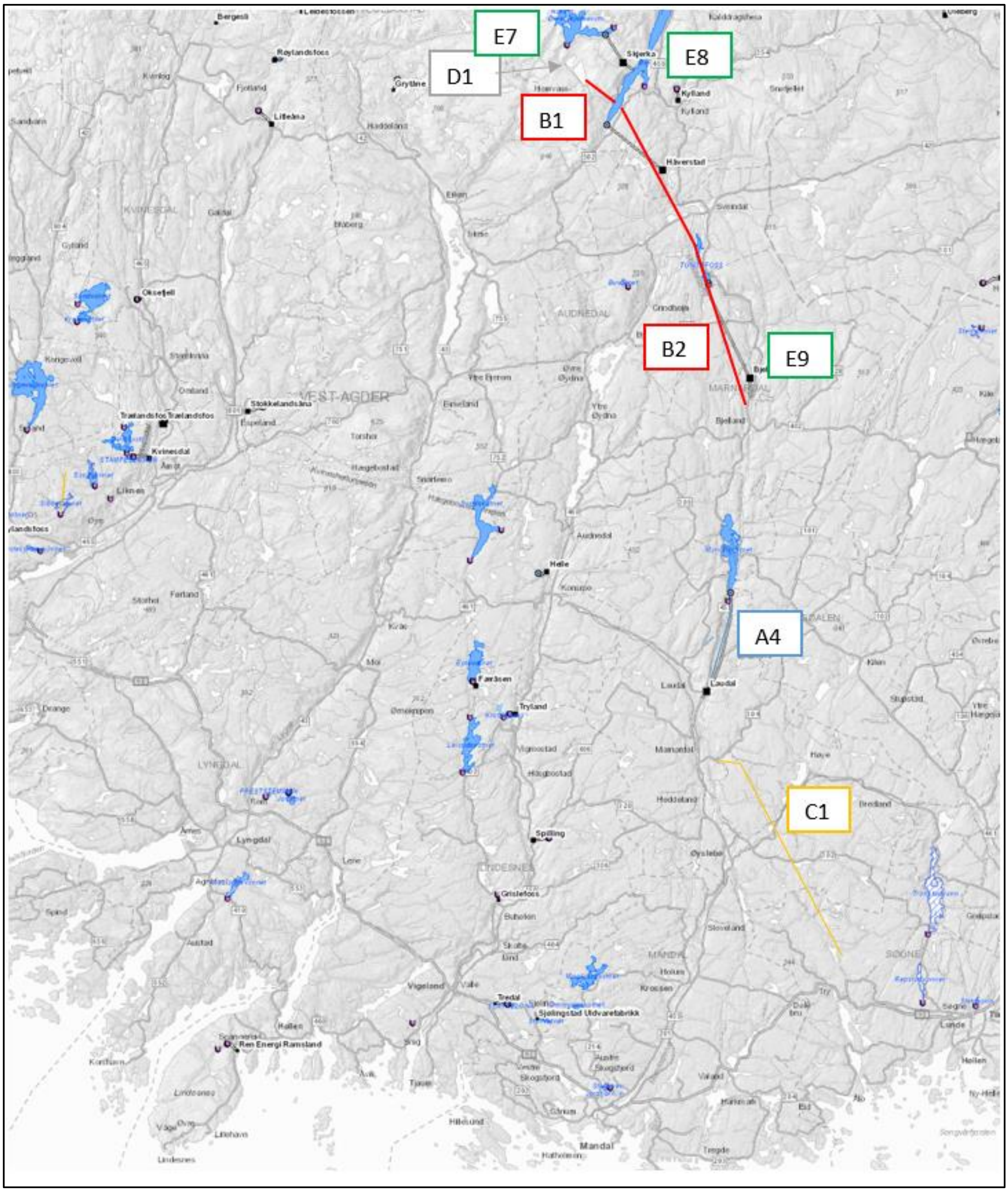

E1
B4
D2
E2
E4
D3
E5
B3
E3
E6
E7
E8
D1
B1
B2
E9
Lakkenstova
Farstøl
Ljosland
Bortelid
Tjaldal
Logna
250
Åknes
Espelid
Lognavann
1181
Røynli
Brokland
Heddersheia
Ekill
Listøl
Røyddan
Rosseland
Høgsheia
Honna
ÅSERAL
Tveitan
Smeland
391
Veiåni
1430
Smeland
Sveigsfjellet
Håvestøl
Krokevassheia
Kissvassheia
Torsland
Novassheia
Glypen
Øyvassheia
Åseral
Kyrkjebygda
Åsland
Bydalen
Flystveit
Øvre
Dåsvatn
Ytre
Dåsvatn
Storeb
831
Skjerka
761
Fiskland
Handeland
Egså
Kylland
1550
Tveit
Snøfjellet

4.3 Scenario 3: Flood protection

The table below shows the chosen projects included in scenario 3 with calculated cost and installed capacity. The maps on the next pages show the location of the selected hydropower and environmental projects.

Table 8: Projects included in scenario 3

Hydropower Cards	Cost [MNOK]	Installed capacity [MW]	Installed pump cap. [MW]
Power plants			
0 Existing power plants		385	
B.1 Storavatn PSP	940	500	500
B.2 Ørevatn PSP	820	120	120
A.4 Laudal II	390	32	
C.1 Øyslebø - Try	800	20	
Reservoirs			
D1 Storavatnet	1650		
Environmental cards			
E.7 River reach Mannflåvatn to outlet Laudal HPP			
E.8 River reach Øyslebø to the sea			
E.9 New reservoir Storavatn			
Sum	**4600**	**1060**	**620**


E7
E8
D1
B1
B2
E9
A4
C1
VEST-AGDER
AUDNEDAL
MARNARDAL
KVINESDAL
LYNGDAL
LINDESNES
MANDAL
SØGNE

5 Discussion and Conclusions

The methodology applied in this work is rough and with high uncertainty. Simple rule-of-thumb and design criteria based on experience have been used to design the hydropower projects, and no further optimization has been carried out. However, the method is considered appropriate to fulfil the scope of the AlternaFuture-project. The main purpose of the work is to consider how an existing hydropower system can be reconstructed with a significantly higher installed capacity and have a positive environmental impact. The scenarios developed in this work will reveal if this is possible and give indications to the economic cost and increased hydropower production.

The scenarios presented in this memo will be simulated with the optimization software ProdRisk (Memo 6). By using three different price forecasts, it will be possible to see if some of the scenarios are economically feasible. It is stressed that the optimization of the scenarios may be significantly improved. The resulting water use and hydropower operation found from the ProdRisk simulations will thereafter be evaluated by researchers at NINA and SINTEF to consider the environmental impact.

In hindsight, scenario 2, maximum flexibility, should have included both A.4 New Laudal and C1 Øyslebø - Try. The total discharge from Bjelland HPP and B.2 Ørevatn PSP exceeds the capacity of Laudal HPP. This means that in times with preferable electricity prices, all power plants can not operate at full capacity at the same time. This will lead to loss in income, or in another perspective, wasted investments. In addition, B.1 Storavatnet PSP should be around 380 MW and B2 Ørevatn PSP around 200 MW to make sure that all power plants connected to Ørevatn could operate at full capacity at the same time. In the current edition of scenario 2 the inflow to Ørevatn is significantly larger than the outflow.

6 References

NVE (2016). Kostnadsgrunnlag for vannkraftverk, report, available from: http://publikasjoner.nve.no/rapport/2016/rapport2016_46.pdf.

NVE (2019). NVE Atlas, online tool, available from: https://atlas.nve.no.

NVE (2019). NEVINA, online tool, available from: https://nevina.nve.no.

Appendix

Appendix 1: Hydropower Cards

AlternaFuture MEMO nr.5

AlternaFuture

A2: Innovation Cards and Research Project Cards

Kaspar Vereide, Leif Lia and Eirik Øvregård

2019-01-04

1 Introduction

This Memo presents the methodology and results from an evaluation of 16 innovations in HydroCen. The innovations have been tested and evaluated on case-studies in the Mandal hydropower system as a part of the AlternaFuture-project. The results are presented on 16 two-page “Innovation Cards”.

There is also presented 18 proposed research projects that are regarded as necessary to enable extreme upgrading of existing hydropower systems as investigated in AlternaFuture. These proposed research projects are presented on two-page “Research Project Cards”.

1.1 Innovations from HydroCen

This chapter presents an overview of the innovations produced in HydroCen. At the time of writing, a total of 16 innovations have been generated directly or indirectly as a part of the work in HydroCen. To gain an understanding and a benchmark of the innovations, they have been “stress-tested” on case-studies in the Mandal river. This has been done as a part of the AlternaFuture-project to provide insights to how new technology may enable extreme upgrading of hydropower systems in the future.

The table below presents an overview of the innovations generated directly or indirectly from the work in HydroCen. The table is colour coded based on the TRL grading provided by the authors. The innovation cards can be found in Appendix 1.

Table 1. Overview of the innovations

No.	Name	Type	TRL
1	Deck-of-Cards-Method	Scientific Method	8
2	SediSluicer for Brook Intakes	Sediment Handling	8
3	SHOP-ProdRisk Coupling	Production Optimization	6
4	OMGvanes	Mechanical Engineering	5
5	Flexible Sandtraps	Hydraulic Engineering	5
6	Tunnel Balloon Plug	Operation and Maintenance	5
7	Fault Detection in Generators	Electrical Engineering	5
8	Snorkel for Large Coanda Screen Intakes	Civil Engineering	5
9	Guideless Francis Turbine for Reduced Sediment Abrasion	Sediment Handling	5
10	Improved Design of ACSC	Civil Engineering	5
11	LeakReg	Mechanical Engineering	4
12	VarSpeed Pumping to Multiple Reservoirs	Electromechanical Design	4
13	Anti-Diving Sickness	Fish-Friendly Design	3
14	AcurLE	Hydropeaking Mitigation	3
15	AcurHE	Reservoir Optimization	3
16	Fish Friendly Hydropower Tunnels	Fish-Friendly Design	2

1.2 Proposed New Research Projects

This chapter presents an overview of new research projects proposed as further research after the AlternaFuture-project, to enable extreme upgrading of existing hydropower systems in the future. The table is sorted based on the authors subjective opinion to which projects should be prioritized based on cost-benefit. These proposals are generated based on ongoing work and discussions in HydroCen and a workshop conducted with participants from the industry, governmental agencies and other research institutions.

Table 2. Overview of the Research Project Cards

No.	Name	Discipline	Type	Funding (MNOK)	Period (years)
1	The Value of Hydropower Flexibility	Multi	KPN	20	4
2	Flood Power Plants	Multi	KPN	20	4
3	Fish Friendly Intakes for Pumping	Fish/Hydraulic	PhD	5	4
4	Fish Friendly Intakes for Flood Power Plants	Fish/Hydraulic	PhD	5	4
5	Generator Capability	Electro	PhD	5	4
6	Temperature-Controlled Water Release	Eco/Hydraulic	PhD	5	4
7	Draught Period Water Release	Eco/Hydraulic	KPN	20	4
8	Cell Weirs in Reservoir	Fish/Hydraulic	PhD	5	4
9	Thermic Inertia for Reactive Power	Electro	PhD	5	4
10	Heat Energy in Hydropower Plants	Electro/Mech.	IPN	20	4
11	Fish Friendly Hydropower Tunnels	Fish/Hydraulic	PhD	10	4
12	Tunnels as Reservoirs	Hydraulic	PhD	5	4
13	Cost Reduction 50% for Hydropower	Multi	IPN	20	4
14	Virtual Inertia	Electro/Mech.	PhD	5	4
15	Digital Twin Turbine Governor	Mech.	IPN	20	4
16	Social Acceptance for Hydropower	Social	IPN	20	4
17	Pumped Storage with Multiple Upper Reservoirs	Electro/Mech.	PhD	5	4
18	Underground Pumped Storage Plants	Multi	KPN	20	4

The research projects are presented on two-page “Research Project Cards” that can be found in the appendix. The research project proposals are not evaluated with the same methodology as the innovations and will not be discussed in the next chapters of this memo.

2 Methodology

2.1 Innovation Cards

The 16 innovations are evaluated on relevant case-studies in the Mandal hydropower system. The case-studies are selected based on where the innovations are assumed to provide the highest benefit compared to the costs. One case-study per innovation has been considered.

The costs presented for each innovation are the estimated construction costs and does not include the development costs to commercialize the innovations. The intention is to evaluate the cost-benefit of the innovations once they are available and ready for commercial use. The costs are primarily based on the NVE cost curves for hydropower (NVE, 2016). Some specific costs not given in the NVE costs estimates are either derived from similar technological components or have in some cases been provided by various suppliers.

The possible income presented for each innovation has been estimated by the authors. This has been the most challenging and uncertain part of the work. For all NPV-calculations a 7% discount rate is used. The expected lifetime is estimated for each innovation separately.

A limitation in this approach is that the optimal case-study may not have been found, giving unjustified differences in the cost-benefit for benchmarking of the innovations. In addition, the selection of case-studies is limited to the Mandal river, where the conditions or situation for which the innovations are meant for may not be present. It is also pointed out that none of these innovations have currently been developed and implemented in a hydropower system yet, and the possible costs and benefits are therefore highly uncertain and based on assumptions and simplifications. However, the results are intended as a rough comparison and to gain an overview of the potential of the innovations, and for these purposes, the approach and results are regarded as suitable.

3 Results

This chapter presents the evaluation of each innovation. The results are also presented as “Innovations Cards” on a standardized two-page format found in Appendix 1.

3.1 Deck-of-Cards-Method (I.1)

3.1.1 Description

The Deck-of-Cards-Method has been developed in the AlternaFuture-project. The method has been used to facilitate the selection of combinations of hydropower cards and environmental cards to generate scenarios with extreme upgrading of an existing hydropower system, where the environmental consequences shall in sum be positive.

Other methods to evaluate and select scenarios based on multi-purpose criteria exist (Trossat 2019; GWP and INBO 2009; DFID 2016; MRC, ADB and WWF, 2016), however, none of these are intended for upgrading of already existing hydropower systems. For the use in a desk-study, there is also need for a simple and fast method. As such, the Deck-of-Cards Method was proposed by Prof. Leif Lia and has been a valuable tool in the AlternaFuture-project. The method is described in the following.

Select design criteria
In the current study, the existing hydropower system is to be upgraded adhering the following conditions:

- Minimum triple the installed capacity, including large-scale pumped storage.
- In sum, a positive impact on the environmental condition of the river basin.
- Existing environment protection shall be respected.
- Water use and the interests of the local municipalities shall be upheld.

Selection of scenarios

1. Identify all possible hydropower projects in the river reach (upgrades, new power plants, new reservoirs).
2. Discard impossible projects based on the conditions above.
3. Identify all possible environmental projects (fish habitat, land use, recreation, increased environmental flow).
4. Find possible combinations of hydropower projects and environmental projects that satisfy the conditions above.
5. Conduct production simulations to determine energy production, revenue and water use.
6. Evaluate the result and select the best alternatives.

The name “Deck-of-Cards-Methods” derives from the approach used, where all the potential hydropower projects and environmental projects on two-page cards and grouped together to find the scenarios that may satisfy the design criteria. The use of the method and preliminary results are presented in Vereide et al. (2019). The technology readiness level is considered to be 8 as the method has been tested and is ready for use but may still be further developed. One possible development is to give each card a rating and develop a “game” with the purpose of maximizing the total score.

3.1.2 Case-study

The AlternaFuture-project has been the case-study from this innovation. The main benefit of the method has been the reduced effort to compare and select different scenarios for extreme reconstruction of the Mandal river hydropower system. The cost-benefit of this innovation has not been assessed.

3.2 SediSluicer for Brook Intakes (I.2)

3.2.1 Description

The SediSluicer for brook intakes is a concept presented by Tom Jacobsen in SediCon. The SediSluicer is a proven technology for sandtraps internationally and has been installed in several hydropower projects around the world (Jacobsen and Pedersen 2014). The use of the SediSluicer for brook intakes is a new application of the same equipment.

The SediSluicer consists of slotted pipes and valves that, when installed correctly, flush sediments and deposited debris with only gravitational forces. The purpose of the SeduSluicer in brook intakes is to remove sand, gravel and stones from the river that has been deposited in the intake. Such material threatens to block the intake and cause water losses. An advantage of the SediSluicer is the efficient flushing of deposited material with a limited water consumption.

3.2.2 Case-study

The existing Stekil brook intake is selected as a case-study for the SediSluicer in brook intakes. There are no brook intakes in the Mandal river that have challenges with transport of sand and gravel. For this case-study there is assumed a problematic gravel transport in Stekil.

A SediSluicer for the Stekil brook intake will require about 30 m of pipes with diameter 0.3 m. The pipes will be bolted to the concrete of the intake and the outlet including a control valve is mounted downstream the dam. The costs of a SediSluicer system for Stekil is assumed to be about 1 MNOK, and the construction time two weeks. The lifetime is assumed to be 20 years. The income is generated by reduced water losses owing to clogging of the intake. In this case-study, it is assumed a 0.1 MNOK/year increase of income owing to the SediSluicer.

The net present value of the installation of a SediSluicer in this case-study will be 0.2 MNOK over a 20-year lifetime. However, the NPV for such an installation is site-specific. The number used in this case-study shows that the concept is promising. As the concept is already commissioned for sand traps the technology is assessed to be TRL 8.

The SediSluicer may have a negative effect on the environment, if the amount of flushed sediments is high compared with the environmental flow. It has been documented from several rivers that to high concentration of sediments during flushing may cause fish-death and harm water organisms (Bilotta and Brazier 2008, Crosa et al. 2010, Baoligao et. al 2016). An assessment of the effect of the flushing should be carried out before installation of the SediSluicer. However, the volume of sediments deposited at a brook intake is limited and only minor consequences are expected.

3.3 SHOP-ProdRisk Simulator (I.3)

3.3.1 Description

The SHOP-ProdRisk simulator is a new tool adapted for analysis of future hydropower production for investment decisions. The tool combines the long-term simulation tool ProdRisk (SINTEF 2019a) with the short-term optimization tool SHOP (SINTEF 2019b). The tool is currently under development in HydroCen. The tool may be used by consultants or by the power companies directly to simulate the future power production from the potential hydropower project. The tool is used to compare various alternatives and find the most profitable.

3.3.2 Case-study

The New Skjerka HPP is used as a case-study. It is assumed that the SHOP-ProdRisk Simulator can increase the profitability from the project by 1% owing to better decision support to select the optimum project. It is assumed that the profit from applying the SHOP-ProdRisk Simulator is equal to 8 MNOK. The costs of the tool are assumed to be 0.5 MNOK for installation and training of personnel. The NPV of using the tool is thus 7.5 MNOK. The benefits of using the tools is very project-specific and depends on the accuracy and skill with existing tools and methods for decision making.

3.4 OMGvanes (I.4)

3.4.1 Description

The OMG vanes is hydraulic foils, vanes and blades with a new shape of the outlet edge. The inspiration for the innovation is the wings of owls which enable silent flight. The shape of the outlet edge mitigate turbulence that develops when the fluid is leaving the surface. For hydraulic equipment this technology will enable less vibrations, less energy losses and higher efficiency for hydropower turbines (Tengs et al. 2019).

3.4.2 Case-study

The existing Skjerka HPP is selected as a case-study. This power plant produces 600 GWh/year, and it is assumed that the power plant is about to change its runners, guide vanes and stay vanes.

It is assumed that the OMGvanes gives a 0.1% increase of the turbine efficiency. This generates an annual increased power production of 0.6 GWh/year. With a power price of 0.3 NOK/kWh and 20 years lifetime, this gives a net present value of the income of about 2 MNOK. The extra production costs of the runners are assumed to be 1 MNOK, giving an NPV of 1 MNOK for the selection of the turbine components with OMGvanes.

3.5 Flexible Sandtraps (I.5)

3.5.1 Description

The Flexible Sandtraps innovation consists of several possible solutions enabling optimal reconstruction and upgrading of existing sandtraps for more flexible operation and/or upgrading of hydropower plants. The design criteria are time-efficient and cost-efficient measures to limit outage for the reconstruction, while offering a high benefit. Several measures are proposed and are under testing in the NTNU hydraulic laboratory (Richter et al. 2017, Vereide et al 2016). These measures include flow conditioners, lowering of the invert in combination with shear plates, shear plates to avoid backflow, heightening of downstream weirs and installation of sediment flushing arrangements.

3.5.2 Case-study

The existing Skjerka HPP is selected as a case-study. It is assumed that the improved sandtrap will reduce the wear on the turbine and reduce necessary outage for maintenance and emptying of the sandtrap. The value of this is assumed to be 0.1 MNOK/year. The costs of the sandtrap upgrade is assumed to be 4 MNOK. The resulting NPV from this upgrade is negative 3 MNOK.

The above case-study shows that upgrading of the sandtrap is not profitable for most hydropower plants. However, if there are plans to upgrade the installed capacity of an existing hydropower plant, the upgrading of the sandtrap will often be necessary. The solutions developed for the Flexible Sandtraps will then be feasible and profitable.

3.6 Tunnel Balloon Plug (I.6)

3.6.1 Description

The tunnel balloon plug is a device to close and dewater hydropower tunnels and pipes without use of gates and valves. The advantages of the tunnel balloon plug are as follows:

- Independent for existing gates
- Reduced costs
- Flexible positioning
- One balloon can serve several closing purposes
- Easier maintenance

The main argument is the possibility to select more freely where to close the waterway. Instead of dewatering the whole tunnel and reservoir, limited dewatering is sufficient. The tunnel balloon plug may also replace the need for new gates and valves. The maintenance is more convenient as the balloon can always be repaired and maintained in workshops instead of on-site. One balloon may also serve as both intake gate, sandtrap gate, draft tube gate and more.

Previous solutions exist, such as delivered by the supplier PlugCo (PlugCo 2019) for pipes. A tunnel balloon plug has also been developed and tested in the New York subway (CNN 2012). Also, there have been used similar concepts for closing of mine shafts in Norway at the Fosdalen Gruver in Trøndelag. The novelty in the innovation presented here is to use such concepts for hydropower tunnels, which are larger and requires a different design to ensure safety and different methods for placement and inflation. A special challenge is that most Norwegian hydropower tunnels are unlined.

It is currently proposed a research project in HydroCen to further develop the concept of tunnel balloon plugs for hydropower plants. The technology readiness level is considered to be 5 as the concept has previously been proved viable for pipes, subway tunnels and mine shafts. Additional development is necessary to make it feasible also for unlined large hydropower tunnels.

3.6.2 Case-study

The new Ørevatn PSP has been selected as a case-study for the tunnel balloon plug. The cost-benefit is assessed by comparing the costs savings if a tunnel balloon may be used instead of an intake gate. Only the material and direct construction work costs are calculated. Engineering, project management, operation and maintenance costs are not included. The new Ørevatn PSP has a maximum turbine discharge of 82 m^3/s. The headrace tunnel is 40 m^2, and the intake gate will be 7x5 m (height x width). The cost of a standard intake gate is described in the table below. The sum is found to be about 14 MNOK.

The cost of a tunnel balloon plug is based on the news article from the NY subway. Here it is stated that the costs are in the range of 4 MNOK for a D = 5 m plug. For this case a plug with D = 7 m is needed and the costs are assumed to be 8 million MNOK. The table below presents the estimated costs for the tunnel plug.

Conventional gate		Tunnel balloon plug	
Element	Costs [MNOK]	Element	Costs [MNOK]
Roller gate with hydraulic control	9.0	Concrete foundation	0.5
Gate house	1.5	Tunnel balloon plug	8.0
Shaft	2.5	Compressor and control system	1.0
Concrete works	1.0		
Sum	14	Sum	10

The cost savings are estimated to 4 MNOK, which is equal to a 30% cost reduction. Operation costs may be assumed to be higher for a tunnel balloon plug compared with a conventional gate, as there is more work during the inflation of the balloon. However, the maintenance costs are assumed to be lower as the balloon can be maintained in a workshop instead of on-site.

It is stressed that this case-study assumes that the tunnel balloon plug is technically feasible. There is a still significant amount of development required before the tunnel balloon plug can become a real alternative to the conventional gates. But overall, this case-study shows that it is a promising technology.

3.7 Fault Detection in Generators (I.7)

3.7.1 Description

This innovation provides technology for early stage detection of faults in generators. It includes development and testing of new sensors, and new data processing tools to detect faults with new or already existing sensors. Development of new sensors focus on non-intrusive sensors that can be installed without dismantling of the generator. Some of the research work has been presented in Valavi (2018).

3.7.2 Case-study

The existing Skjerka HPP is used as a case-study. The costs of installing the new sensors are assumed to be 2 MNOK. It is assumed that the new equipment results in early detection of a fault after 5 years of operation and avoiding 6 months outage of one unit. There are two units of 100 MW in the existing Skjerka HPP and the 6 months outage is assumed to equal an income loss of 10 MNOK. The present value of the avoided outage is 7 MNOK, giving an NPV of 5 MNOK for the installation of the new monitoring equipment.

The case-study shows potential profitability for the application of new methods for fault detection in generators. The actual profitability depends on many factors and especially the age and type of the generator. Older generators nearing the end of its technical lifetime will have larger benefit from installing the fault detection equipment.

3.8 Snorkel for Large Coanda Screen Intakes (I.8)

3.8.1 Description

The snorkel for large Coanda screen intakes reduces the water losses caused by icing on the intakes. The innovation presented is a modification of an existing concept. The snorkel allows water from a deeper part of the intake pond to flow into the intake. This water has a slightly higher temperature and will result in more rapid melting of snow and ice on the intake trash-rack. The snorkel is removable and is mounted during winter and can be removed during the summer. It is made primarily from PE-materials.

3.8.2 Case-study

There are no Coanda screen intakes in the Mandal river yet. For this case-study it is assumed that the Stekil brook intake has a Coanda screen intake. The costs of the snorkel is assumed to be 0.2 MNOK and the annual reduced water loss is assumed to be worth 0.05 MNOK. The NPV of the snorkel is then 0.3 MNOK. The Snorkel is a small but sensible innovation for Coanda screen intakes in cold regions. The costs are limited compared to the positive effect and potential reduction of water spill.

3.9 Guideless Francis Turbines for Reduced Sediment Abrasion (I.9)

3.9.1 Description

The innovation is design of Francis turbines without guidevanes to reduce sediment abrasion. The guidevanes are one of the components of a Francis turbine that is most exposed to sediment abrasion. In addition, operation of the Francis turbine outside of the best-point of operation generates turbulence and unbeneficial flow through the turbine that increases sediment abrasion. By removing the guidevanes and optimizing the turbine for a single operation point, the Francis turbine may gain a higher best-point efficiency.

3.9.2 Case-study

There are no reports of problematic sediment abrasion in the power plants in the Mandal river. However, the New Skjerka HPP is used as a case study. The installation of one 400 MW Francis turbine with normal guidevanes is compared with the installation of three guideless Francis turbines of 50 MW, 100 MW and 250 MW. The cost of the one large unit is calculated to 360 MNOK, while the three smaller ones are calculated to 410 MNOK (includes a 25% cost reduction owing to no guide vanes). The extra civil costs for the power plants for three units is calculated to 50 MNOK. The cost difference amounts to 100 MNOK.

In the case of the New Skjerka HPP, the Existing Skjerka with 2x100 MW Francis units with guidevanes will still be operational. In combination, the Existing and New Skjerka will have a higher efficiency over the total plant operation range. The increased efficiency is assumed to be 0.2% equalling 1.2 GWh/year for the normal annual production of 600 GWh. The present value of the extra income is 14 MNOK. For the case of Skjerka HPP, the NPV of installing guideless Francis turbines is negative 86 MNOK.

This case study demonstrates that there must be sediment problems or other challenges before multiple units without guidevanes might become more economical than ordinary units with guidevanes. Another possible case is a reservoir power plant, where it is only possible to run on best-point without any part load or overload operation. In such a case one unit without guidevanes will be less expensive and have a better turbine efficiency.

3.10 Improved Design of Air Cushion Surge Tanks (I.10)

3.10.1 Description

Air cushion surge tanks (ACSC) have several advantages and disadvantages compared with conventional surge tanks. The advantages include (1) the possibility of a more direct tunnel alignment and the possibility to avoid the expensive pressure shaft, (2) enabling of faster load changes with significantly reduced water hammer and improved governor stability. And (3) reduced environmental impact. The main disadvantages are the risk of air leakage and time-consuming air filling and air emptying.

This innovation includes several improvements to the design of ACSC to mitigate these disadvantages. The design improvements are described in Ødegård and Vereide (2018). Pregrouting and optimized cross-section profile will reduce the risk of excessive air leakages. A new type of closing device will allow dewatering of the main tunnel without emptying and refilling the air into the ACSC thus solving the challenge of longer outage for HPP with ACSCs.

3.10.2 Case-study

The new Bjelland PSP is used as a case study. The construction costs for (a) tunnel system design with a conventional surge tank, low head headrace tunnel and a pressure shaft, is compared with (b) a tunnel system with direct inclined tunnel and ACSC. The tunnel system with the conventional surge tank requires a surface access, while the system with ACSC does not. By going with an inclined direct tunnel, the total length of the headrace tunnel is 10% less. However, the ACSC is five times larger than the conventional surge tank in volume. In sum the total excavation is reduced by 5% if the tunnel system with ACSC is selected. As the pressure shaft is also avoided the total costs savings for the tunnel system with ACSC is calculated to 20 MNOK. If it is assumed that the innovation of improved design of ACSC was the trigger that enabled this solution to be chosen, the NPV of the innovation is 20 MNOK.

For a case-study with calculation of the NPV of retrofitting an existing ACSC with a closing device such as presented above, see Ødegaard and Vereide (2018). For that case-study, retrofitting the existing ACSC at the 1240 MW Kvilldal HPP was found to be marginally profitable.

3.11 LeakReg (I.11)

Confidential.

3.12 VarSpeed Pumping to Multiple Reservoirs (I.12)

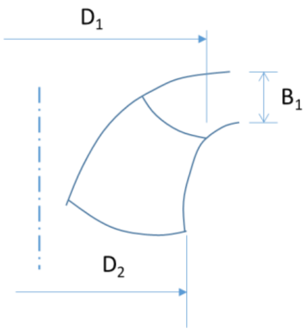
3.12.1 Description

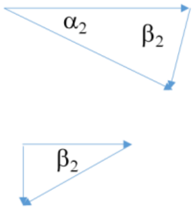
This innovation is the application of variable speed units to enable pumping to reservoirs at different heights. A full-size frequency converter is necessary to reach the full potential for variable lifting heights. A special unit is necessary with either one runner with a highly variable operational range, or two units with different design head sharing the same generator/motor. The innovation can save constructions costs since the number of generator/motors and turbines can be reduced, as the same units can be used to pump and generate power from significantly variable head.

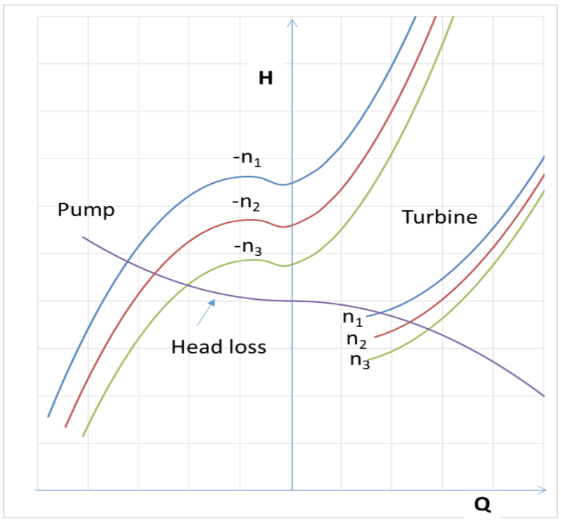
3.12.2 Case-study

The new Langavatn PSP is used as a case-study. This pumped storage plant shall utilize four existing reservoirs with a head ranging from 70 m to 250 m, as described in the table below. The design of one runner for different heads requires; (1) approximate the same main dimensions, (2) approximate the same speed number, and (3) approximate the same runner angles. The turbine main dimensions are calculated, selecting a speed of rotation for the different heads that meet the requirements. The resulting design and operation parameters for a single variable speed unit is given in the table below.

Upper reservoir	Kvennevatn	Storevatn	Stekil	Langevatn
Head, H_n [m]	144	233	135	56
Flow, Q_n [m^3/s]	61.7	60.7	50.9	124.8
Speed of rotation [rpm]	333	375	300	200
Speed number	0.7	0.6	0.6	1.2
Power, turbin [MW]	83.8	133.3	64.8	65.9
Power, pump [MW]	96.9	154.3	75.0	76.3
Inlet runner diameter D1 [m]	2.2	2.4	2.3	2.2
Inlet runner diameter D2 [m]	2.4	2.5	2.5	2.4
Inlet runner width B1 [m]	0.7	0.7	0.8	0.7
Alfa1 (a_1) [deg]	18.9	13.8	14.6	48.4
Beta1 (b_1) [deg]	82.7	80.0	80.5	87.8
Beta2 (b_2) [deg]	17.9	14.2	14.0	48.1
Submergency [m]	7.12	5.34	7.3	8.88

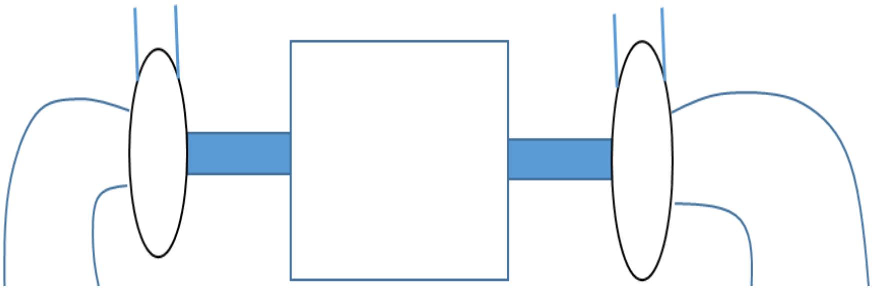






At given speed-of-rotation, the N_{ed}-Q_{ed} characteristic can be presented in flow-head characteristics, which is more common for pump systems. The figure below shows the characteristics for three speed-of-rotations. The pump mode is obtained by reversing the speed-of-rotation, i.e. the generator is running as a motor driving the pump. In pumping mode, static head plus the head loss must be overcome.

Observing the main dimensions D1, D2 and B1 and the inlet and outlet runner angle, it seems to be feasible to have one turbine for utilizing Kvennevatn, Storevatn and Stekil reservoir. The Langevatn reservoir is too different regarding head and flow and requires a different runner. With one generator/motor and two runners, the aggregate must be mounted horizontal. The generator can be arranged with the shaft sticking out on each end, and the two turbines attached on each end. The resulting unit is presented in the figure below.



A cost estimate for the proposed concept has not been completed as a part of the AlternaFuture-project. For future work it will be interesting to compare the cost of this solution with four conventional synchronous RPT-units.

3.13 Anti-diving sickness (I.13)

3.13.1 Description

I.13 is an application of ultrasound to avoid supersaturated water from hydropower turbines. Supersaturated water can kill fish and other aquatic organisms, and this innovation will have a positive environmental impact. Supersaturated water from turbines is rare, but some examples are reported, and they may have positive effects from this innovation. This innovation is primarily an environmental improvement without significant economical motives. However, if the supersaturated water has resulted in operational restrictions, the innovation may also result in economical profit if the restrictions can be removed.

3.13.2 Case-study

There is no power plant with problems from supersaturated water in the Mandal river. The innovation is at a very early stage and it has not been possible to estimate costs and effects for a case-study.

3.14 AcurLE (I.14)

3.14.1 Description

A new technology to mitigate hydropeaking in rivers and allow hydropower plants to operate without operational restrictions is proposed. By constructing an underground rock cavern in connection with the tailrace tunnel, and use compressed air to control the water level, an intermediate water reservoir is created. This water reservoir can be used to control the water discharge out into the downstream river, while the power plant can be allowed to operate freely. The innovation is described by Storli and Lundstrøm (2019).

3.14.2 Case-study

No environmental restrictions in the Mandal river limits how fast the hydropower plants ramp up or down. To assess the AcurLE it is assumed that Håverstad HPP is subjected to the same restrictions as Brattsberg HPP in Nidelva. This power plant has an operational restriction on ramp down from full load in minimum 60 minutes. This gives a profit loss as the power plant operation will not be optimized with the power market.

If it is assumed that the profit from the power plant can be increased by 5% by installing an AcurLE that enables the power plant to operate freely without any restrictions. For Håverstad HPP this equals about 5 MNOK/year. The costs of installing an AcurLE is estimated to 55 MNOK, resulting in an NPV of 5 MNOK. The AcurLE is considered to be a possible solution for hydropower plants with outlet to rivers, where environmental restrictions results in income losses.

It has also been discussed if it is possible to make a similar concept without the compressed air system, which amounts to almost half the total investment costs in the previous example. This may be possible by controlling the water level in the underground reservoir with a gate instead of compressed air.

3.15 AcurHE (I.15)

3.15.1 Description

AcurHE is a new technology to increase the size of existing reservoir. By installing air balloons in the dead storage (below the intake level) in reservoirs, an additional water volume can be utilized. The air volume in the balloons are controlled with compressors, and some of the energy required can be regained by generating electricity from the air flowing in and out of the system. The innovation is described by Storli and Lundstrøm (2019).

3.15.2 Case-study

The Ørevatn reservoir is used as a case-study for the AcurHE. Ørevatn has a small reservoir volume compared with the inflow, and the added volume that can be provided will be valuable. The volume of air balloons is selected to provide 2 m of regulation height, equal to 7 Mm^3 in Ørevatn. The air balloons are placed in the dead storage, below the intake level and thereby increases the total storage capacity of Ørevatn by 7 Mm^3. The air balloons are of the same type as warm-air balloons and has each a volume of 750 m^3. The compressor size is selected to provide an air volume equal to 2/3 of the turbine discharge capacity in Håverstad HPP (2/3 of 75 m^3/s). The costs of the compressor system and the air balloons are calculated to be over 1000 MNOK and the AcurHE is thus not considered economical feasible for this case-study.

3.16 Fish Friendly Hydropower Tunnels (I.16)

3.16.1 Description

This innovation is on the use of hydropower tunnels as habitat for fish and other aquatic organisms. Hydropower plants reduces the quality of natural fish habitats as they remove most of the water from the natural river. To compensate, it is possible to adapt hydropower tunnels to become new alternative habitats. In Norway, over 4000 km of hydropower tunnels exist and are mainly constructed as unlined drill and blast tunnels where gravel is left on the invert as a driving road. The water velocity is normally in the range from 0 to 2 m/s. Both headrace tunnels and tailrace tunnels may be adapted. Measures to make the tunnels habitable include installation of lights, resting areas, spawning gravel and very fine fish screens at the end of the tunnel towards the turbine to stop the fish from going into the turbines. Lighting can simulate day-night and the seasons.

3.16.2 Case-study

The New Bjelland PSP is used as a case-study. This PSP will be constructed with an 18 km long tunnel system. The outlet of the power plant is in the anadromous region of the river while the intake is above the natural migration barrier.

In the Mandal river at Bjelland it is considered to construct a fish ladder bypassing the natural migration barrier, to increase the habitat and spawning area for Atlantic salmon. The cost of such a fish ladder has been calculated to 10-15 MNOK and will introduce about 3 km of new river habitat for the fish.

As a comparison, it may be possible to adapt 16 km of hydropower tunnel in the Bjelland PSP. The tunnel system may be designed so that the powerhouse is placed 2 km downstream the inlet. The long tailrace tunnel may be adapted for fish habitat by installing lighting with seasonal and daily variation, installing a very fine trash rack (12 mm opening, horizontal bars) close to the draft tube, making rest areas, and introducing spawning gravel. The costs of such facilities are estimated to 5 MNOK. Maintenance costs have not been considered. If the adaptation is successful, the result will be a longer stretch of new habitat for a lower cost. If successful, retrofitting of many existing hydropower tunnels may also be possible, significantly increasing the habitat and spawning area of Atlantic salmon and other species.

It is stressed that this concept has never been tested and may prove to be impossible. Laboratory testing and studies on how it may be possible to adapt hydropower tunnels is necessary.

4 Discussion and Conclusions

The evaluation of the innovations presented in the previous chapter must be considered as very rough estimates. They are intended to provide understanding of the concepts and indications to the economic feasibility. All these innovations are presently under development, and the costs and effects of the final technology are unknown. The details provided for each innovation is highly variable depending on how far the innovations have been developed and amount of information that has been provided from the innovators.

It is concluded that there are several promising innovations that have resulted directly or indirectly from the work in HydroCen. This document has presented an overview and an evaluation of the innovations. Two-page innovation cards with a summary is provided in Appendix 1.

This memo includes a list of potential research projects to prepare for and enable extreme upgrading of existing hydropower systems in the future. Two-page descriptions of each research project is provided in Appendix 2.

Two of the innovations have resulted directly from the work in AlternaFuture, namely I.1 Deck-of-Cards-Method, and I.16 Fish Friendly Hydropower Tunnels. Seven research project suggestions have resulted directly from the work in AlternaFuture, namely RP.2 Flood Power Plants, RP.3 Fish Friendly Intakes for Pumping, RP.4 Fish Friendly Intakes for Flood Power Platns, RP.7 Draught Period Water Release, RP.8 Cell Weirs in Reservoir, RP.11 Fish Friendly Hydropower Tunnels, RP.17 Pumped Storage with Multiple Upper Reservoirs.

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6 Appendix

Appendix 1 – Innovations Cards
Appendix 2 – Research Project Cards

AlternaFuture MEMO nr.6

AlternaFuture

Simulation results from scenario 1, 2 and 3

Linn Emelie Schäffer

2019-11-12

This memo presents simulation results for development scenario 1,2 and 3 of the Mandal hydropower system using the ProdRisk model. The implementation of the scenarios (the changes made in the model of the Mandal system) and simulation results using three different price series are described in this memo.

Hydropower operations of the Mandal hydro system given scenario 1, 2 and 3 have been simulated using ProdRisk. Only required modifications to the operational dataset of the Mandal hydro system provided by Agder Energi have been done to model the different scenarios. The simulation results are compared to simulations of the current system to evaluate the impact of the scenario on the economic results and environmental conditions in the system.

We refer to separate descriptions of the development scenarios for more details. This memo will consider the changes made in the modelling of the system and results from the simulation. Environmental considerations are discussed in another memo.

Operations of the existing Mandal hydro system have been simulated using ProdRisk, an optimisation model for mid-term hydropower scheduling. It is important to understand how the system will be operated under different price scenarios, since the development of the European power system and the impact on power prices in Norway are highly uncertain. Therefore, the system is simulated for three different price series.

The original system consists of several intakes, reservoirs and power stations. In total there are six power stations in the existing Mandal system: Skjerka, Logna, Smeland, Haaverstad, Bjelland and Laudal. Skjerka is by far the largest power station in the system with a maximum power output of around 200 MW. The two biggest reservoirs are Skjerkevann and Juvann with approximately 188 Mm3 and 142 Mm3 storage volume.

Contents

1 Scenario 1: Triple Installed Capacity

1.1 Implementation

In scenario 1, the installed capacity is to be tripled. This has been done by building four new power stations in parallel to the existing power stations:

1. Juvann/Logna power station
2. Skjerka power station
3. Bjelland and Haaverstad power stations
4. Laudal power station

In addition, a flood power plant has been added downstream of Laudal power station.

There are no changes to the reservoirs in the system, but there are included some additional environmental constraints on operation. Note that the overall water balance in the system remains the same, as no new inflow is added by the changes to the system. For further details on the added power stations see memos describing the development scenarios.

1.1.1 New Skjerka power station

The new Skjerka power station is added in parallel to the existing Skjerka station, as illustrated in Figure 1-1. The stations have the same head, but different flow capacities and turbine characteristics. Bypass is used to direct water to the new station instead of to the old station (the model chooses optimal use of water).

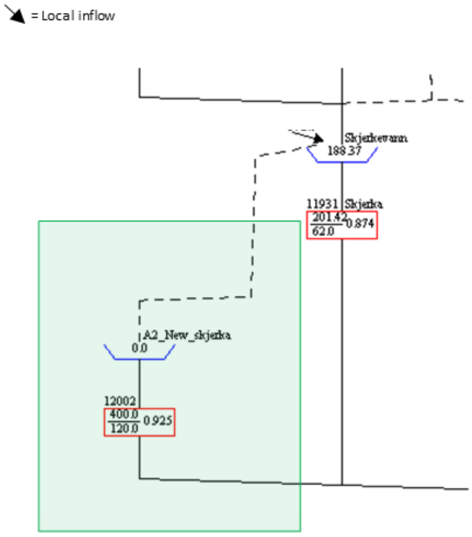

***Figure 1-1**. Illustration of the new Skjerka power station, marked with green, added in parallel to the old Skjerka station. The stations get water from the same outlet in Skjerkevann and can produce at the same time.*

1.1.2 New Juvann/Logna power station

The new Logna power station is added in parallel to the existing Logna station, as illustrated in Figure 1-2. The stations have the same head, but different flow capacities and turbine characteristics. Bypass is used to direct water to the old station from the new station if the old station is producing (the model chooses optimal use of water). The Juvann reservoir has not changed, but it has been connected to the new Logna power station with bypass to the old station (instead of opposite) to maintain the modelling of bypass restrictions around the old Logna and Smeland power stations.

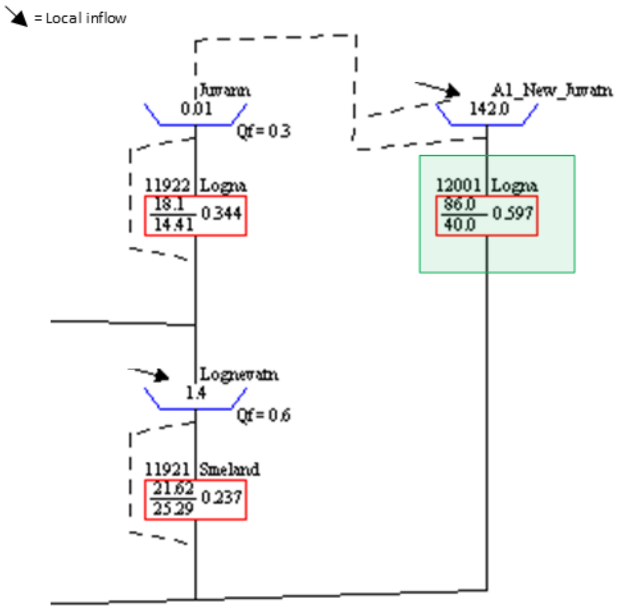

Figure 1-2. *Illustration of the new Logna power station, marked with green, added in parallel to the old Logna station. The stations get water from the same outlet in Juvann and can produce at the same time.*

1.1.3 New Bjelland power station and Laudal power station

The new Bjelland and new Laudal power stations are added in parallel to the existing stations, as illustrated in Figure 1-3. The parallel stations have the same head as the original ones, but different flow capacities and turbine characteristics. Bypass is used to direct water to the new stations instead of to the old stations (the model chooses optimal use of water).

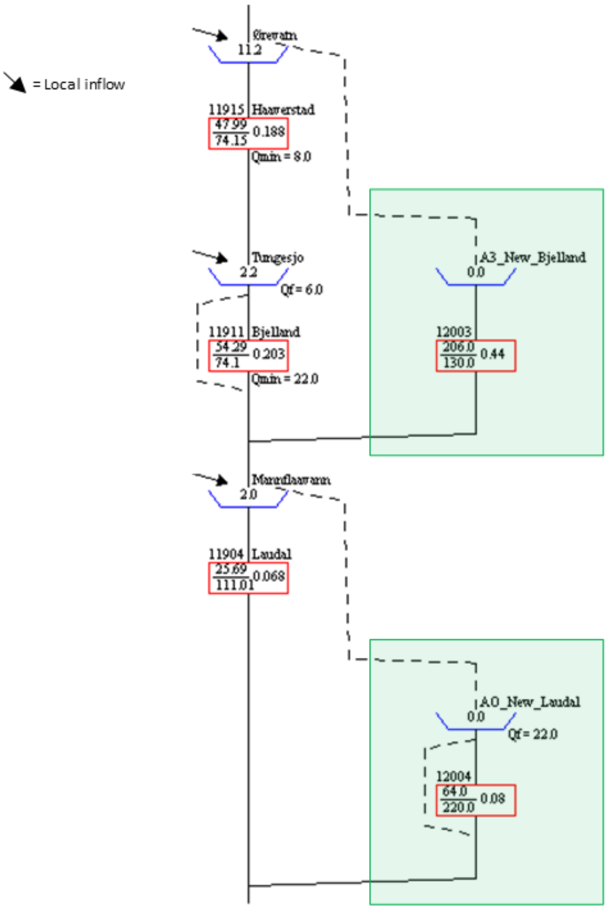

Figure 1-3. *Illustration of the new Bjelland and the new Laudal power stations, marked with green. The new Bjelland power station is added in parallel to the old Haaverstad and Bjelland power stations, while new Laudal is added in parallel to the old Laudal power station. The stations get water from the same outlet in Ørevatn and can produce at the same*

1.1.4 New flood power plant

A new flood power plant has been added downstream of the Laudal power station, as illustrated in Figure 1-4.

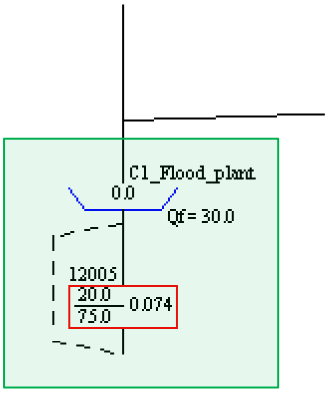

Figure 1-4. *Illustration of the new flood power plant, marked with green, added in parallel downstream of new and old Laudal power station.*

1.2 Results

This chapter present some results from the simulated operation of scenario 1.

1.2.1 Skjerkevann

Figure 1-5 shows simulated reservoir operation for Skjerkevann simulated for 60 different inflow years, given the different assumptions for power price. We see a seasonal difference between the 2015 price and the two 2030 prices, where the 2015 simulation seems to keep a higher reservoir filling throughout the summer and fall. In the 2030 simulations the reservoir level is drawn down a bit more during summer and is also drawn lower down in the winter before the spring flood than in the 2015 simulation. Furthermore, we see that the 2030 price with increased variability (2030 price scaled) seems to keep a slightly lower reservoir filling in general compared to the two other simulations.

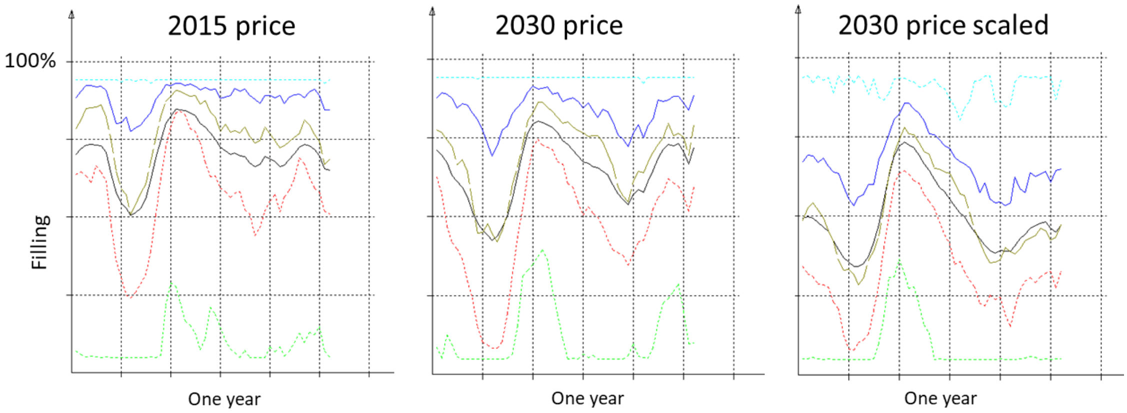

__Figure 1-5__. Percentile plot of the reservoir development in Skjerkevann over one year (simulation results over 60 years), given the different input prices. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.

1.2.2 Production new and old Skjerka

Figure 1-6 shows the duration curve of the power production in the new and old Skjerka power stations for the three different price simulations. In addition, the duration curve for the total production from the two stations is plotted in the figure. The new power station is either operated on maximum or not operated in most hours. The old station is operated at different production levels, and from the sum production we can see that the old station is operated in some hours when the new station is not operated. This is because of the different plant characteristics. The new plants are modelled with constant plant efficiency and no head dependency. In total the power stations are only operated up to about 30% of the hours. The change in operation from time step to time step for the new Skjerka power station is illustrated in figure 1-7. This figure also shows that the station is ramped directly from zero to maximum or from maximum to zero when operation is changed.

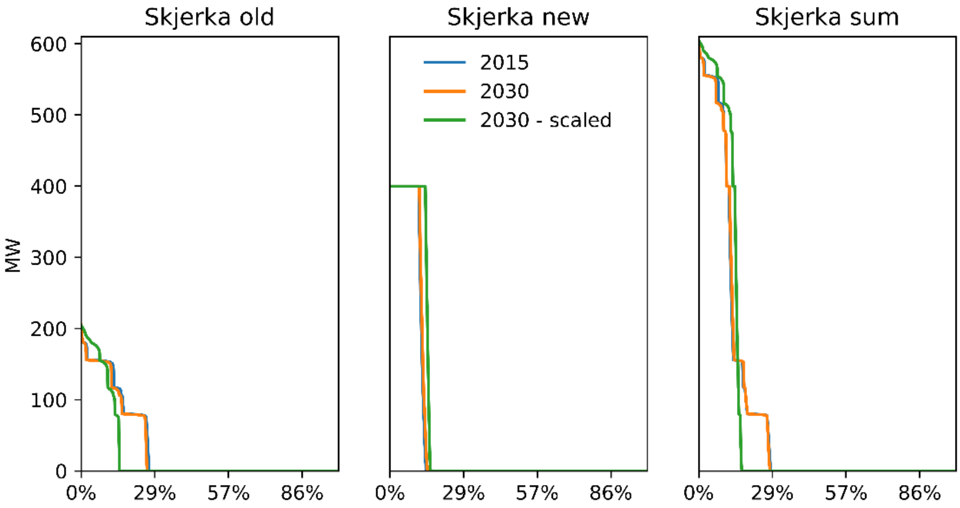

__Figure 1-6.__ Duration curve of the power production per time step for the old Skjerka power station (left), the new Skjerka power station (middle) and the duration curve for the total production from the two power stations (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). The 2015 and 2030 results are similar, and the blue curve is therefore hiding behind the orange curve.

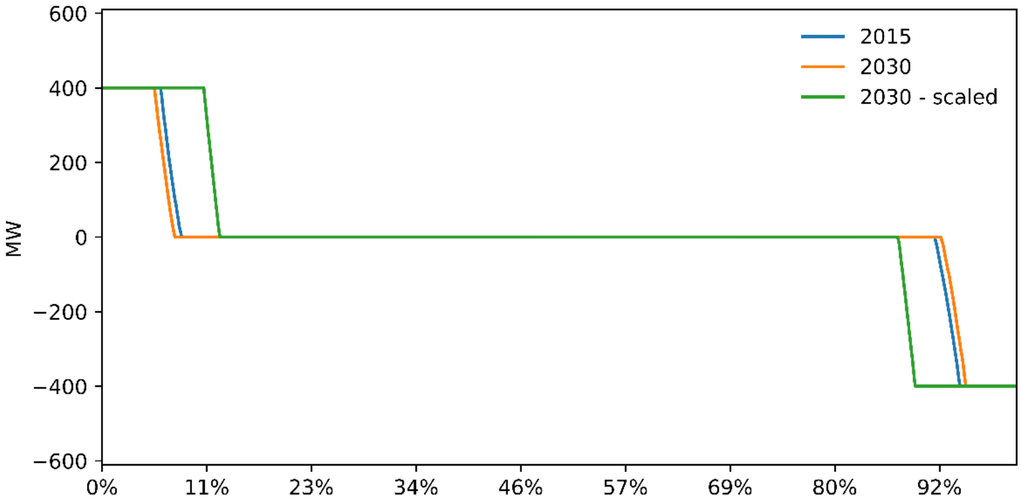

__Figure 1-7.__ Duration curve of the change in power production (ramping) per time step from the new Skjerka power station. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).

1.2.3 Juvann

Figure 1-8 shows simulated reservoir operations for Juvann for 60 years of weather data. Comparing the results based on different price assumptions, we see some smaller differences in the reservoir curves. The most distinct differences are for the 2030 price scaled simulation, where the reservoir level is drawn down lower in the winter and also is drawn down slightly more during summer and fall than in the two other simulations.

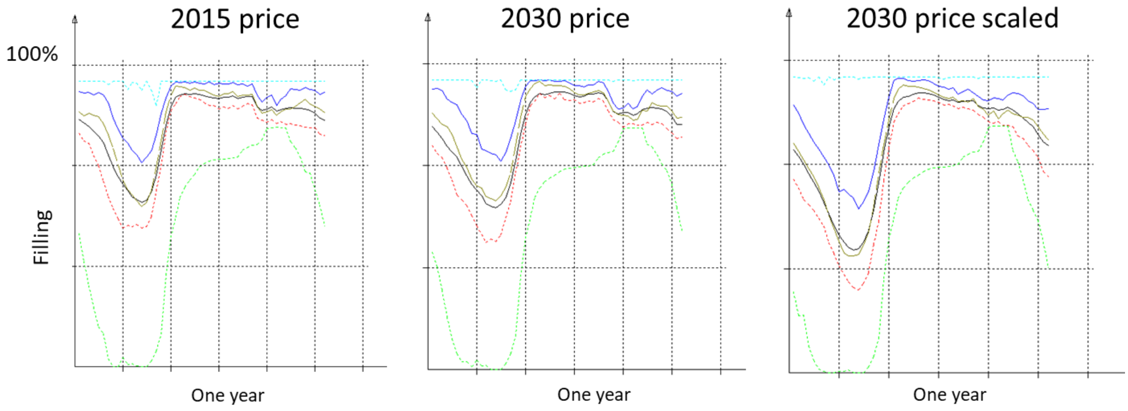

Figure 1-8. *Percentile plot of the reservoir development in Juvann over one year (simulation results over 60 years), given the different input prices. The plots show the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.*

1.2.4 Production new and old Logna

The duration curve for the power production from the new and old Logna power stations are given in Figure 1-9. If producing, the power stations are mostly operated at maximum. From the duration curve of the total production we see that the old Logna power station only is producing when the new station is producing at maximum. The new power station is operated about 30% of the hours, while the old station only is producing in less than 15% of the hours. Figure 1-10 illustrates the change in production from time step to time step for the new station.

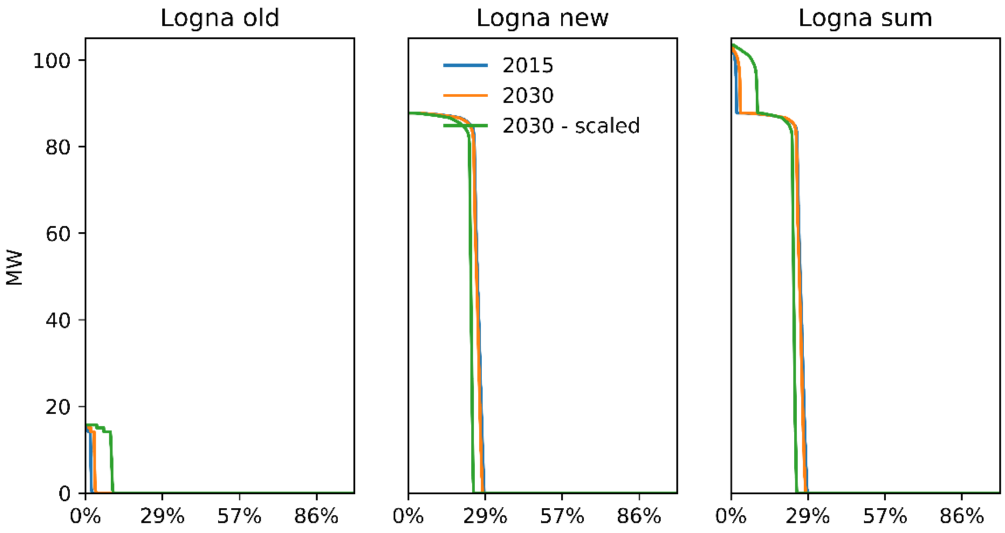

Figure 1-9. *Duration curve of the power production per time step for the old Logna power station (left), the new Logna power station (middle) and the duration curve for the total production from the two power stations (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

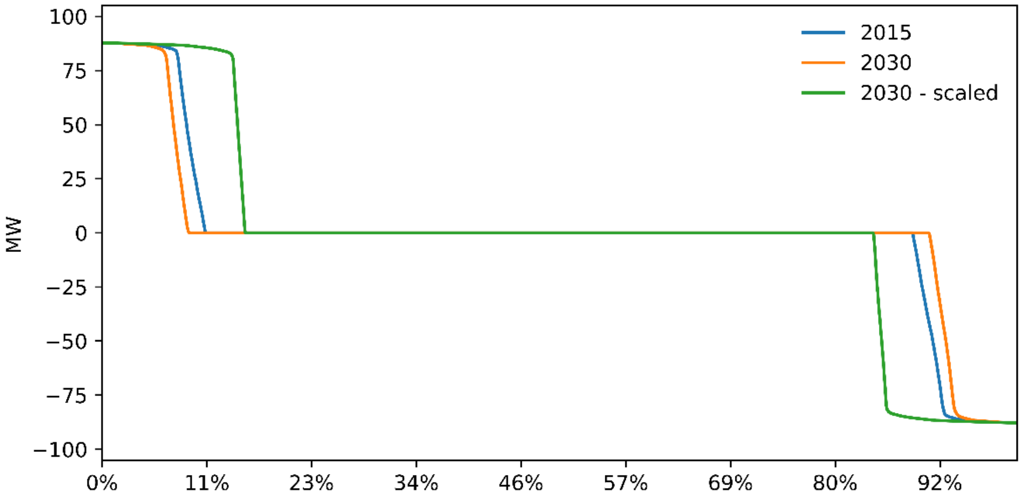

Figure 1-10. *The duration curve of the change in power production (ramping) per time step from the new Logna power station. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

1.2.5 Production new and old Bjelland and Laudal

Duration curves for simulated production from the new and old Bjelland power stations and the new and old Laudal power stations are plotted in figure 1-11 and 1-12 respectively. The duration curve for the change in production per time step for the new stations are plotted in figure 1-13 and 1-14. The new Bjelland power station is mostly producing at maximum when producing, while the new Laudal power station is operated at different production levels because of the modelled efficiency description. The new Bjelland power station operated around 30% of the hours, while the new Laudal power station produce 40-50% of the hours.

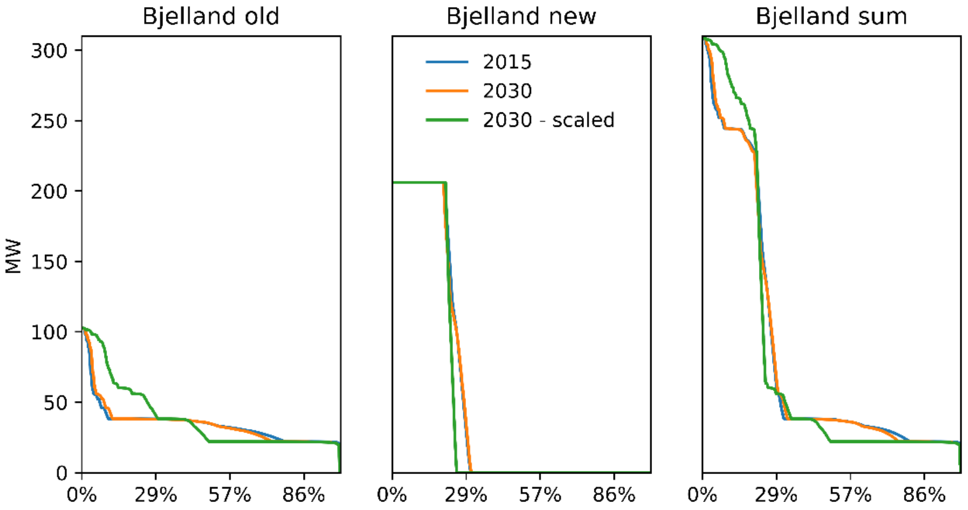

Figure 1-11. *Duration curve of the power production per time step for the old Bjelland power station (left), the new Bjelland power station (middle) and the duration curve for the total production from the power stations (right). The plot for the old Bjelland power station includes the production from both the old Bjelland power station and Haaverstad power station. The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

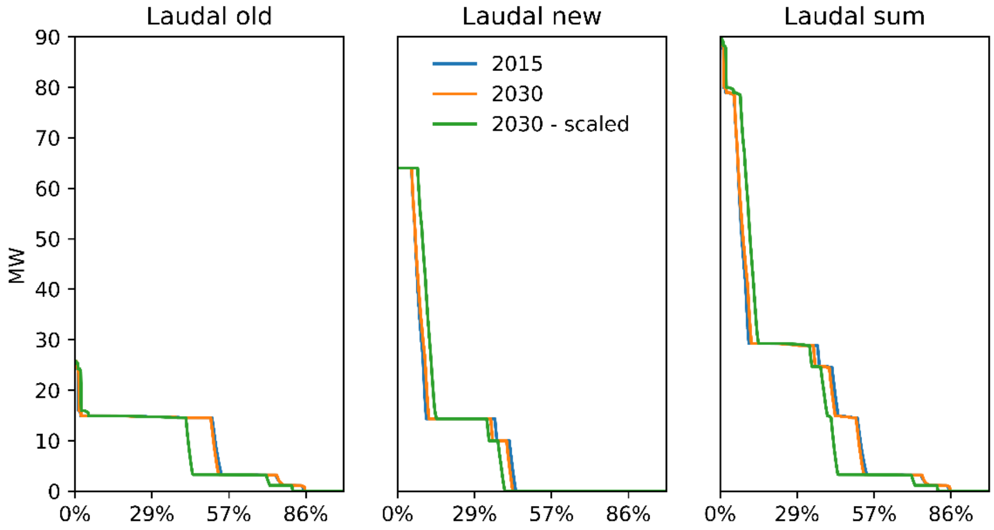

Figure 1-12. *Duration curve of the power production per time step for the old Laudal power station (left), the new Laudal power station (middle) and the duration curve for the total production from the power stations (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

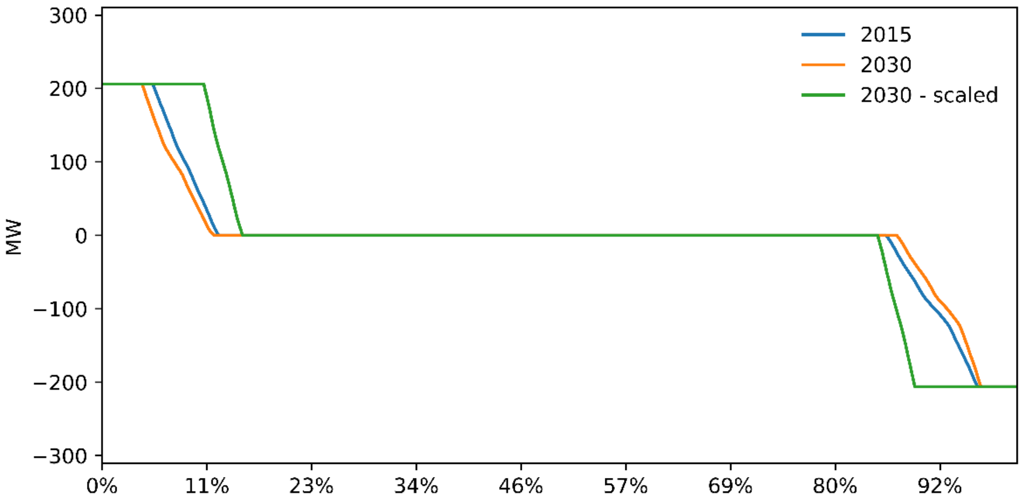

Figure 1-13. *The duration curve of the change in power production (ramping) per time step from the new Bjelland power station. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

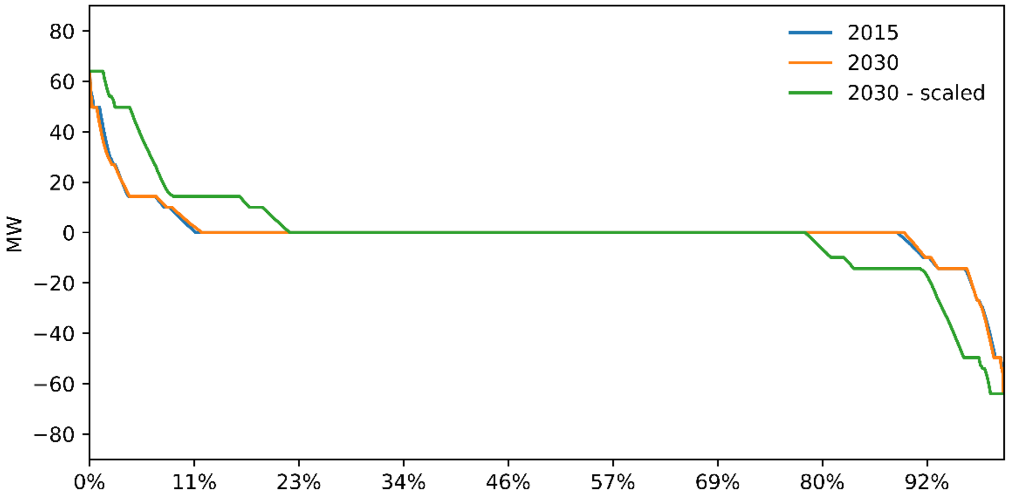

Figure 1-14. *The duration curve of the change in power production (ramping) per time step from the new Laudal power station. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

1.2.6 Production new flood power plant

Duration curve for simulated production and change in production per time step for the new flood power plant are shown in figure 1-15 and 1-16 respectively. The power plant is operated 35-50% of the hours and is mostly operated at maximum.

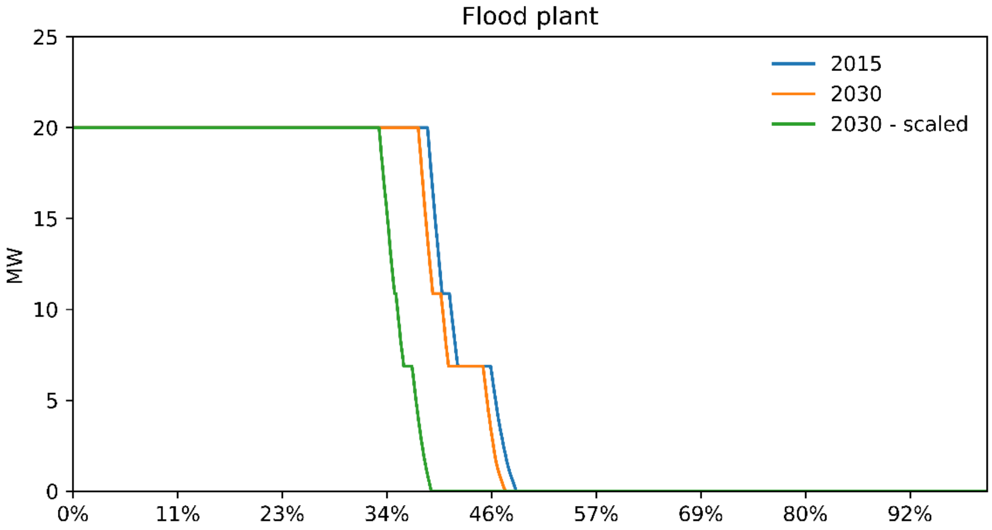

Figure 1-15. *Duration curve of the power production per time step from the new flood power plant. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

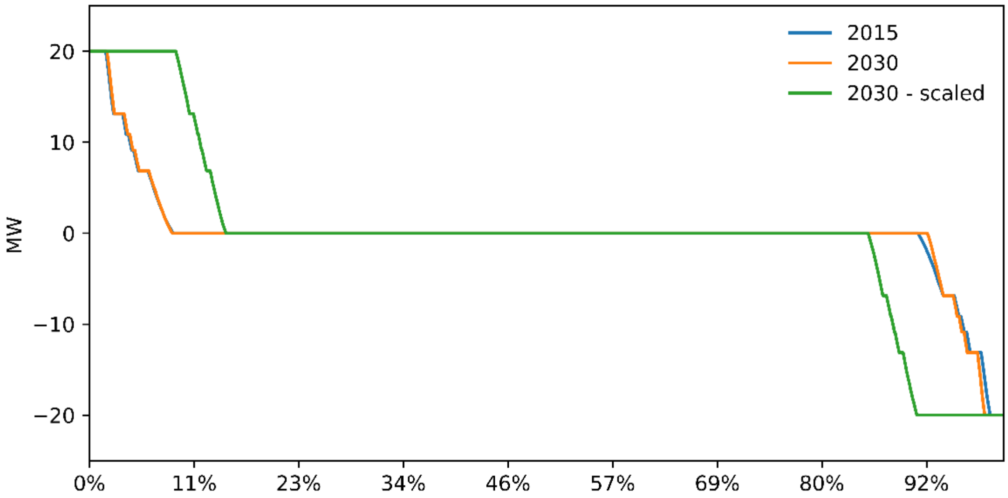

Figure 1-16. The duration curve of the change in power production (ramping) per time step from the new flood power plant. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).

1.2.7 The overall system

Total production, income and achieved power price are given in table 1-1 for the overall system. Results are provided for scenario 1 (S1) and the current system (today) given all three price scenarios. Comparing the results, we see that both total production and income increase in scenario 1 compared to the current system for all price scenarios. Furthermore, the achieved power price is higher for scenario 1 meaning that a higher price is realised per unit of energy sold even though more energy is sold (total production is increased). In total, yearly income in scenario 1 compared to the current system increase with 8.7 million EUR assuming the 2015 price, 14.7 million EUR assuming the 2030 price and 28.8 million EUR assuming the 2030 price with increased variability (2030 - scaled).

Table 1-1. Yearly power production and economic results for the overall system for scenario 1 (S1) and today (current system), given all three price scenarios. The results in scenario 1 are compared to the results from the current system.

		Power production [GWh]	Net Income [MEUR]	Achieved price [EUR/MWh]
2015	Today	1731.9	51.4	29.7
	S1	1960	60.1	30.7
	Increase S1	228.1	8.7	1.0
		13 %	17 %	3 %
2030	Today	1742.3	72.5	41.6
	S1	1956.6	87.2	44.6
	Increase S1	214.3	14.7	3.0
		12 %	20 %	7 %
2030 - scaled	Today	1705.8	81.1	47.5
	S1	1931.2	109.9	56.9
	Increase S1	225.4	28.8	9.4
		13 %	36 %	20 %

2 Scenario 2: Maximum Flexibility

2.1 Implementation

In scenario 2, the flexibility of the system is increased by installing several pumped storage hydropower plants and by expanding the storage capacity in the system. To increase the storage capacity:

1) A new reservoir is created, impounding the natural lake Storavatn. The new reservoir is connected to the Skjerkevann reservoir.
2) The Juvann reservoir is expanded.
3) The Kvennevann reservoir is expanded.

Furthermore, four new pumped storage plants (PSPs) are built:

1) Storavatn PSP is built in parallel to the Skjerka power station. The plant pumps from Ørevatn to Storavatn (connected to Skjerkevann).
2) Ørevatn PSP is built in parallel to the Haaverstad and the Bjelland power stations. The plant pumps from downstream Bjelland (river intake) to Ørevatn.
3) Langevann PSP is built between Skjerkevann and the upper reservoirs. The station pumps from Skjerkevann to four smaller reservoirs: Langevann, Stegilvann, Kvennevann and Storevann.
4) Juvann PSP is built to connect Juvann with the "Skjerkevann part of the system". The station pumps from Juvann to Langevann making it possible to move inflow from the Juvann part of the system to the Skjerkevann part of the system.

In addition, operation is constrained by some new environmental constraints. Note that the overall water balance in the system remains the same, as no new inflow is added. For further details on the added power stations and constraints see memos describing the development scenarios.

2.1.1 New Storavatn reservoir

The natural lake, Storavatn, is impounded to create a new reservoir and connected to the Skjerkevann reservoir. Since the two reservoirs are connected, allowing water to flow between, the two reservoirs are in the model described by one larger reservoir. The description of the Skjerkevann reservoir has been modified to describe this larger reservoir as illustrated in figure 2-1, i.e. the storage volume, highest regulated water level, lowest regulated water level and reservoir curve have been adjusted. No new inflow is added to the model.

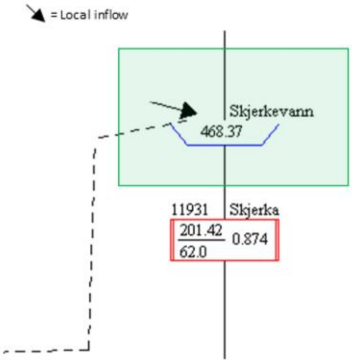

Figure 2-1. *Illustration of the adjusted Skjerkevann reservoir, in green, describing the characteristics of the "large reservoir" consisting of Skjerkevann and Storavatn reservoirs.*

2.1.2 Expanding the Juvann reservoir

The Juvann reservoir is expanded, as shown in figure 2-2, by making a new and higher dam. This increase the highest regulated water level and hence also the total storage volume.

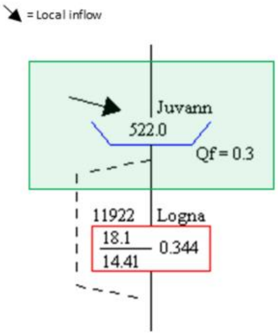

Figure 2-2. Illustration of the expanded Juvann reservoir, in green. The volume and higher regulated water level of the reservoir have been increased.

2.1.3 Expanding the Kvennevann reservoir

The highest regulated water level and storage volume in Kvennevann reservoir is increased by the building of a new and higher dam. This has been included in the model; however, this reservoir is in the model merged with three other reservoirs to enable modelling of the Langevann PSP. This is explained further down.

2.1.4 Storavatn PSP

The new Storavatn PSP is constructed in parallel to the old Skjerka power station, as illustrated in figure 2-3. The PSP can produce in parallel to the old station and can also pump water back up into the Skjerkevann reservoir.

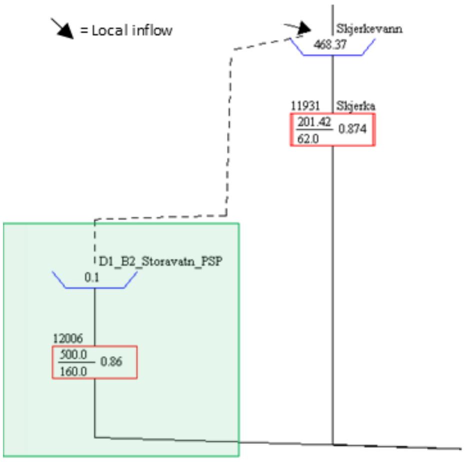

Figure 2-3. Illustration of the new Storavatn PSP, marked with green. The PSP is added in parallel to the old Skjerka station. The PSP pump water from Ørevatn to Skjerkevann and get water for production from Skjerkevann. The PSP and the old Skjerka power station can produce at the same time.

2.1.5 Ørevatn PSP

The new Ørevatn PSP is added in parallel to the existing Haaverstad and Bjelland power stations as shown in figure 2-4. The PSP pumps from a river intake downstream of Bjelland to Ørevatn reservoir. The river intake has been modelled by including a dummy module with a very small reservoir downstream of the Bjelland power station.

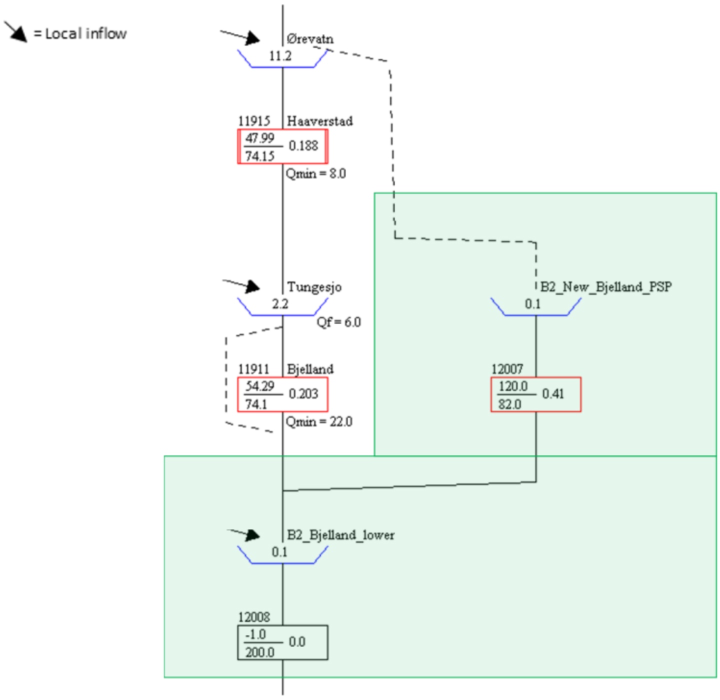

Figure 2-4. *Illustration of the new Ørevatn PSP (in the figure named New Bjelland PSP), marked with green. The PSP is added in parallel to the old Haaverstad and Bjelland power stations. The PSP pumps water from a river intake downstream of Bjelland - modelled using a dummy module with a small reservoir - up to Ørevatn reservoir. The PSP gets water for production from Ørevatn.*

2.1.6 Langevann PSP

The Langevann PSP pumps from Skjerkevann up to four smaller reservoirs. In ProdRisk it is not possible to use the same pump to pump to several reservoirs with different head. To model this it has been necessary to merge the four reservoirs into one large reservoir. The new Langevann reservoir therefore includes all the upper reservoirs of Langevann PSP: Langevann, Stegilvann, Kvennevann and Storevann. The Langevann PSP pumps from Skjerkevann reservoir up to the new Langevann reservoir. The modelling of Langevann PSP and Langevann reservoir is illustrated in figure 2-5.

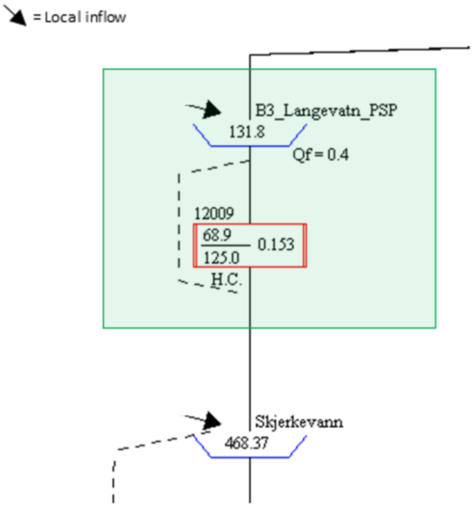

Figure 2-5*. Illustration of the modelling of the new Langevann PSP and the new Langevann reservoir, marked with green. The new reservoir represents (and replace) four reservoirs in the real system. The PSP pumps water from the Skjerkevann reservoir up to the new Langevann reservoir (representing Langevann, Stegilvann, Kvennevann and Storevann).*

2.1.7 Juvann PSP

The Juvann PSP pumps from Juvann to Langevann. Since Langevann is one of the reservoirs merged into the new Langevann reservoir, the Juvann reservoir pumps to the new Langevann reservoir – the same reservoir as the Langevann PSP pumps to. In the model this is represented by setting Juvann PSP to pump to a small dummy reservoir with a hydraulic coupling to the new Langevann reservoir. This allows water to flow freely between the new Langevann reservoir and the small Juvann dummy reservoir. In this way water can be pumped from Skjerkevann using Langevann PSP and from Juvann using Juvann PSP to the new Langevann reservoir. Water from this reservoir can then be used for power production in Langevann PSP or Juvann PSP, and further down the system. The modelling of the Juvann PSP is illustrated in figure 2-6. A weakness with this approach is that the Juvann PSP is modelled with a larger upper reservoir than intended. The Juvann PSP is set to pump to the new Langevann reservoir, which in the model includes not only the old Langevann reservoir, but also three other reservoirs.

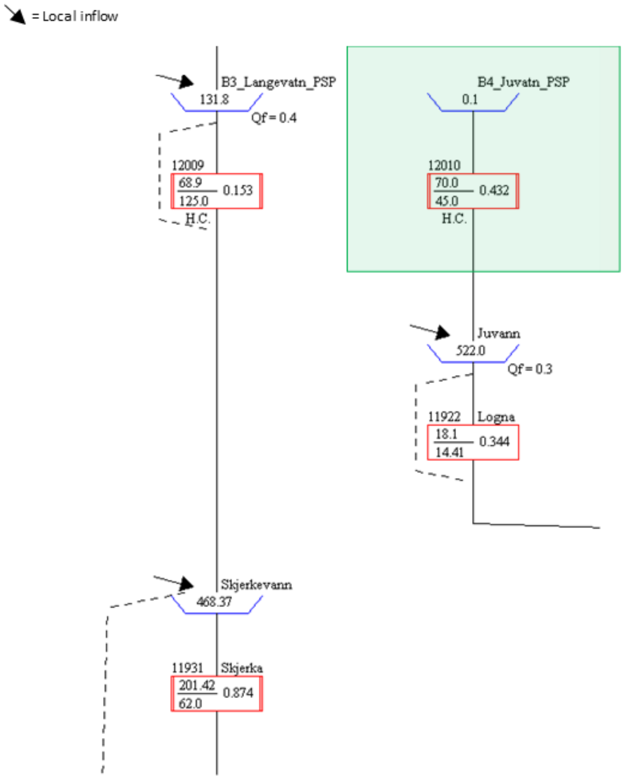

Figure 2-6. *Illustration of the new Juvann PSP, marked with green. The PSP pumps from the Juvann reservoir to a small dummy reservoir coupled to the new Langevann reservoir by a hydraulic coupling. This allows water to flow freely between the new Langevann reservoir and the small dummy reservoir, making the two reservoirs as one. The Juvann PSP use water from the new Langevann reservoir for power production.*

2.2 Results

This chapter present some results from the simulated operation of scenario 2.

2.2.1 Skjerkevann

Figure 2-7 shows simulated reservoir operation for Skjerkevann for 60 different inflow years, given the different assumptions on power price. We see a difference in the seasonal profile between the different simulations. In the 2015 simulations the reservoir level is drawn down during winter and then increase during spring and summer. In the 2030 simulation the curve is similar, but the filling seems slightly slower during spring and summer (the curve is a bit flatter). This tendency is even more distinct in the 2030 – scaled simulation, where the seasonal curve is much flatter and the reservoir level in general is kept lower throughout the year.

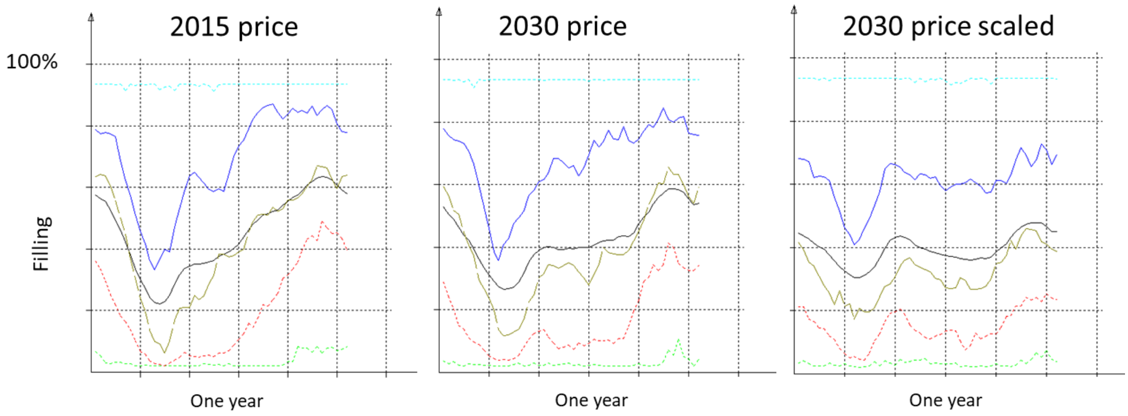

***Figure 2-7**. Percentile plot of the reservoir development in Skjerkevann over one year (simulation results over 60 years), given the different input prices. The plots show the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.*

2.2.2 Production Skjerka and Storavatn PSP

The Skjerka power plant and the Storavatn pumped storage plant are located in parallel. Figure 2-8 shows the duration curve of the production and pumping in the two stations and the total production and pumping. The Storavatn PSP is operated both in production and pumping mode. For the 2030 scaled price scenario the plant is used considerably more than in the two other simulations, and it seems that the plant is producing and pumping approximately the same number of hours. Notice that the two plants not always produce at the same time (seen by the sum curve). In some hours, only the old Skjerka station produce and not the PSP. Figure 2-9 shows the change in production from time step to time step. In the 2015 and 2030 simulation the plant is mostly operated at constant level, while the operation mode is changed much more often in the 2030 scaled price scenario. Most of the times when the production is changed it seems to either go from maximum production to no operation or to maximum pumping, or from maximum pumping to no operation or maximum production.

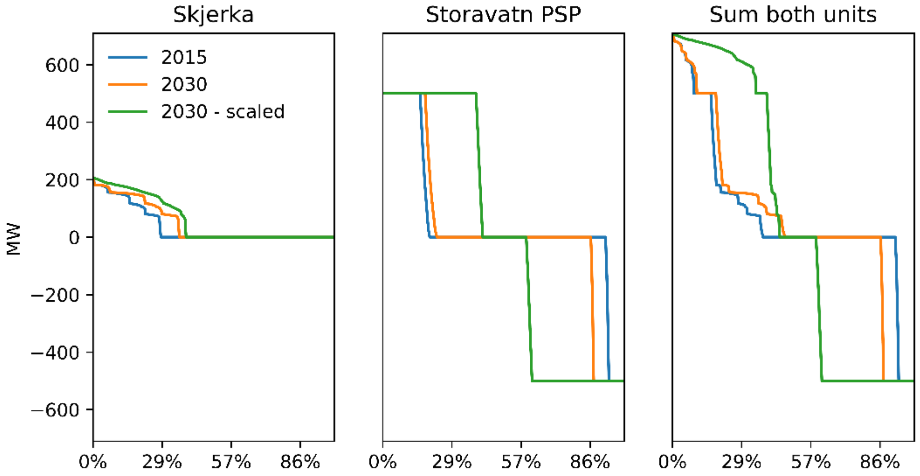

***Figure 2-8.** Duration curve of the power production per time step for the Skjerka power station (left), the new Skjerka PSP (middle) and the duration curve for the total production from the two plants (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.*

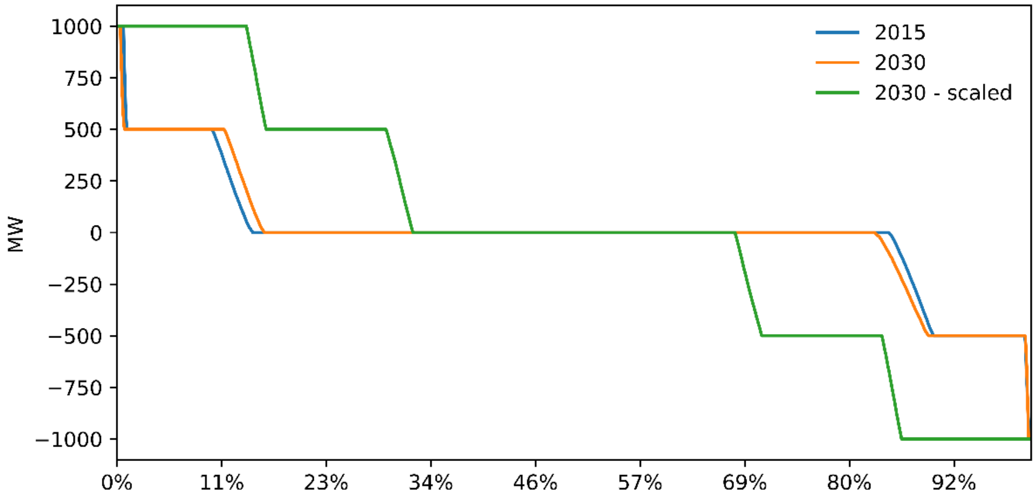

Figure 9. *Duration curve of the change in power production and pumping (ramping) per time step from Storavatn PSP. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

2.2.3 Langevann

Figure 2-10 shows simulated reservoir operation for Skjerkevann, simulated for 60 different inflow years, given the different assumptions on power price. We see a difference in the seasonal profile between the different simulations. In the 2015 simulations the reservoir level is kept at a high level for almost all weather years, except for the winter and spring. In the 2030 simulation the curve is similar, but the reservoir is only drawn down for a shorter period before spring. This tendency is even more distinct for the 2030 scaled price case, where the reservoir is drawn down both in the winter/before spring and in summer. In this simulation the percentiles are also more spread implying that there are larger differences in the reservoir operation depending on the weather year.

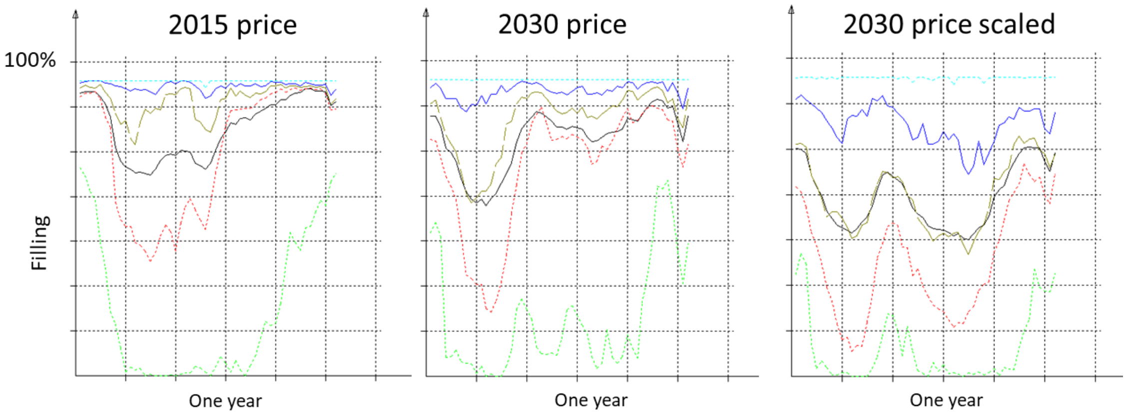

Figure 2-10*. Percentile plots of the reservoir development in New Langevann reservoir over one year (simulation results over 60 years), given the different input prices. The plots show the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.*

2.2.4 Production Langevann PSP

Figure 2-11 and 2-12 show the duration curve for simulated power production/pumping and change in production/pumping per time step for Langevann PSP. The plant pumps up to 10% of the hours and produces up to about 20% of the hours. Most of the time the plant is not used.

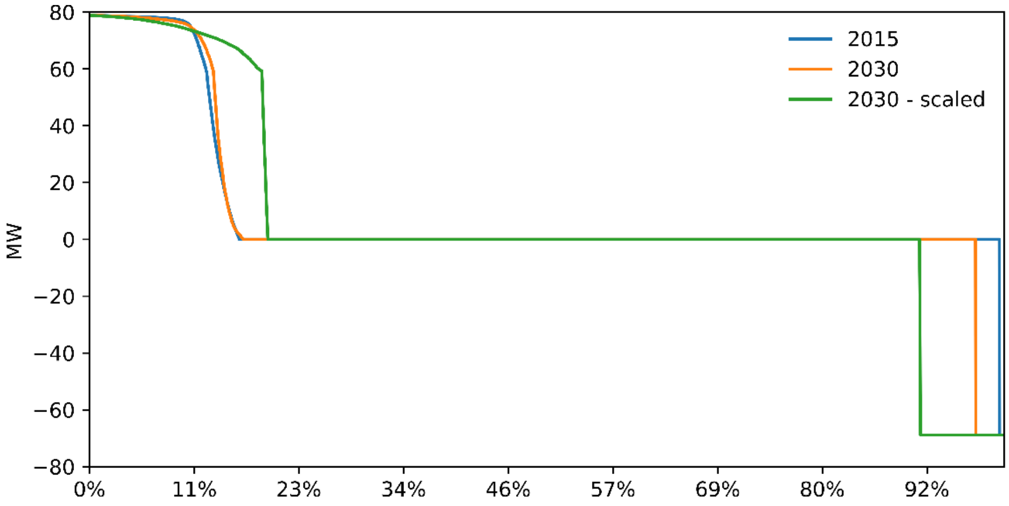

Figure 2-11. *Duration curve of the power production (ramping) per time step for the Skjerka power station (left), the new Skjerka PSP (middle) and the duration curve for the total production from the two plants (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.*

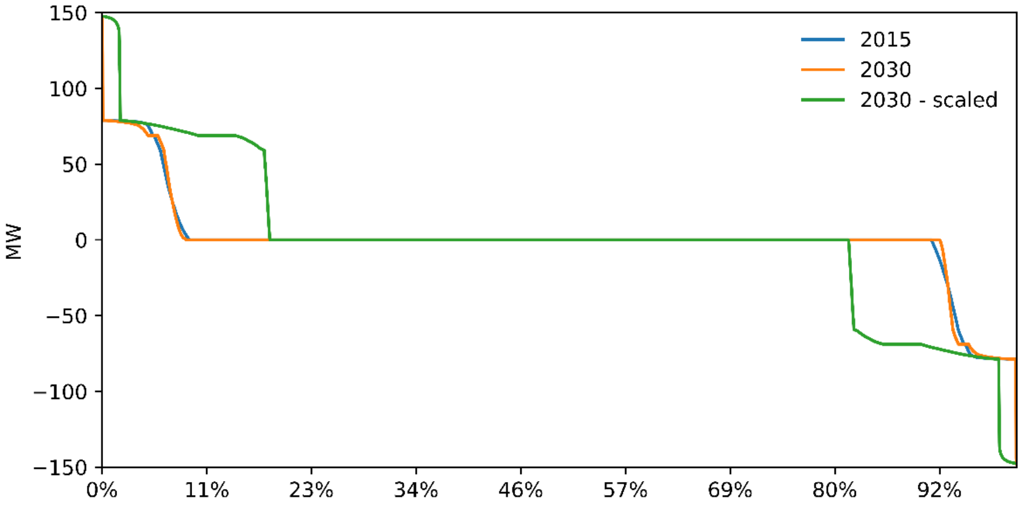

Figure 2-12. *Duration curve of the change in power production and pumping (ramping) per time step in new Langevann PSP. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

2.2.5 Juvann

Figure 2-13 shows simulated reservoir operation for Juvann based on simulations for 60 years weather data. Comparing the results from the simulations based on different price assumptions, there are only some smaller differences in the reservoir curves. The most distinct differences are in the lowest percentile (light green line) that is kept higher in the 2030 simulations than in the 2015 simulation.

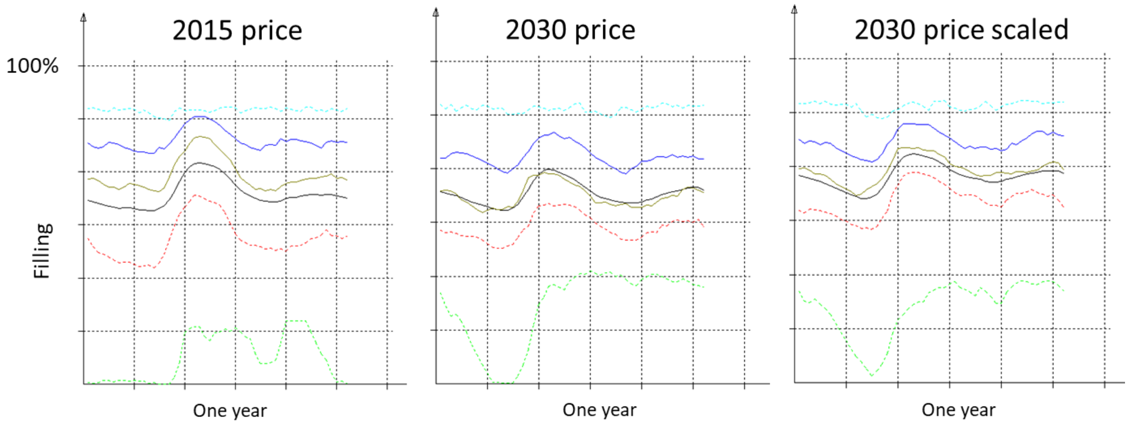

Figure 2-13. Percentile plots of the reservoir development in Juvann over one year (simulation results over 60 years), given the different input prices. The plots show the 0-, 25-, 50-, 75- and 100% percentiles as well as the average power price.

2.2.6 Production Juvann PSP

Figure 2-14 shows the duration curve for power production and pumping in Juvann PSP. In the 2015 and 2030 simulations the plant pumps between 15- 20% of the hours and produce in 10% of the hours. In the 2030 scaled simulation the plant is operating more often and is pumping around 50% of the hours and producing around 30% of the hours. The plant pumps more than it produce which implies that some of the water that is pumped by Juvann PSP is used for production in Langevann PSP. The duration curve of the change in production from time step to time step is shown in figure 2-15.

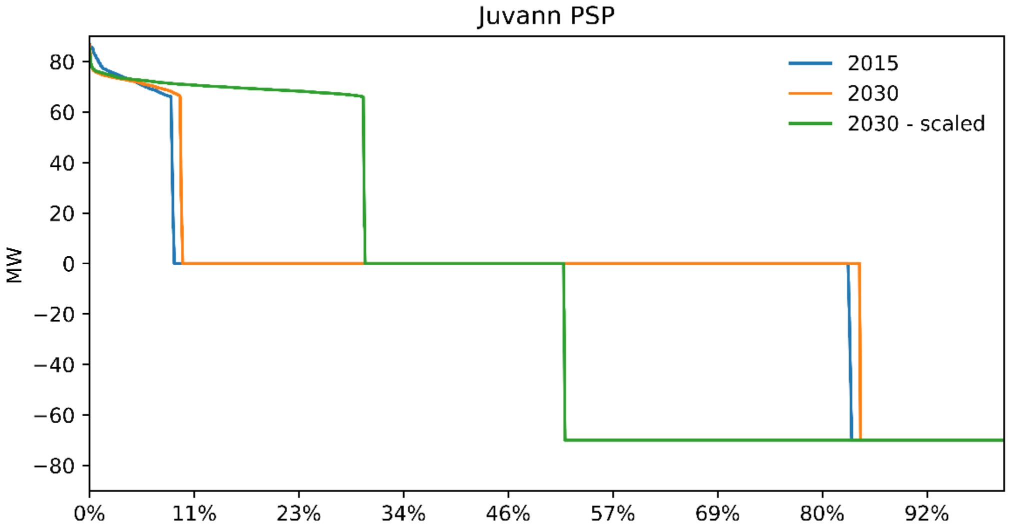

Figure 2-14. Duration curve of the power production and pumping per time step from Juvann PSP. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.

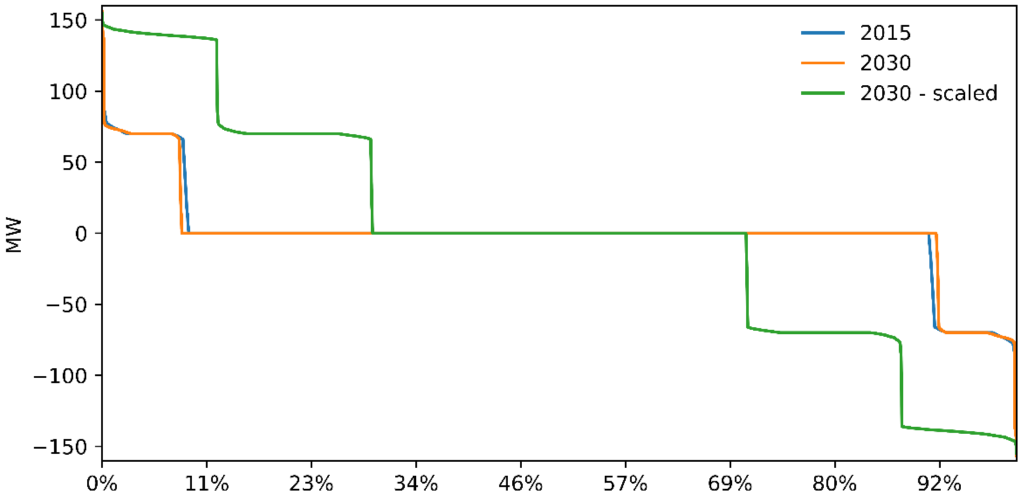

Figure 2-15. *Duration curve of the change in power production and pumping (ramping) per time step from Juvann PSP. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

2.2.7 Production Logna power station

Figure 2-16 shows the duration curve for simulated power production in the Logna power station. The plant is producing more than 50% of the time and produce more in the 2015 and 2030 simulations than in the 2030 – scaled simulation. Figure 2-17 gives the change in production per time step. In the 2030 – scaled simulations the production changes more often that in the other simulations.

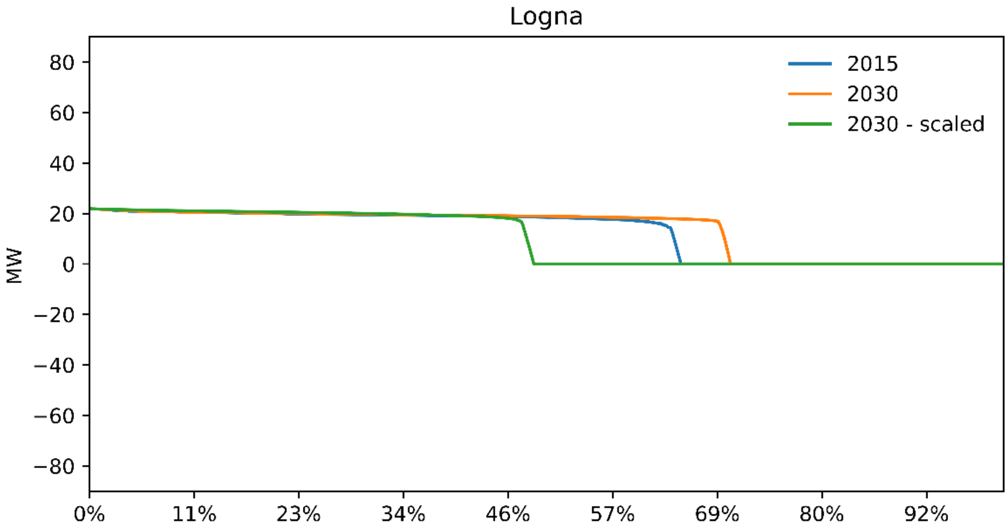

Figure 2-16*. Duration curve of the power production per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios (2015, 2030 and 2030 - scaled).*

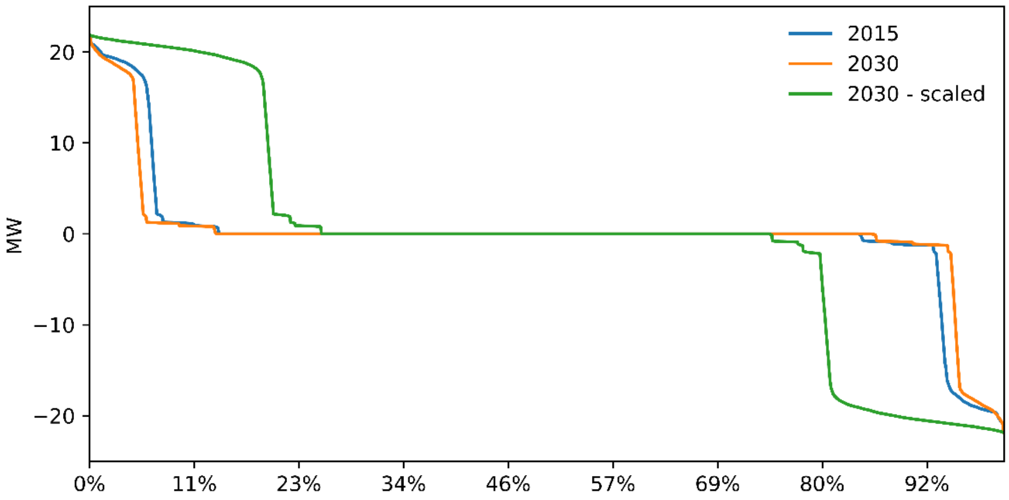

Figure 2-17. *Duration curve of the change in power production (ramping) per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios (2015, 2030 and 2030 - scaled).*

2.2.8 Production Ørevatn PSP

The duration curve for the power production and pumping from the old Haaverstad and Bjelland power stations and the new Ørevatn PSP are given in figure 2-18. Figure 2-19 shows the duration curve of the change in production/pumping from time step to time step. Ørevatn PSP produce 40-50% of the hours and pump up to 20% of the hours. The old power stations are constantly producing, but at a low level most of the year. Some of this production is because of environmental constraints.

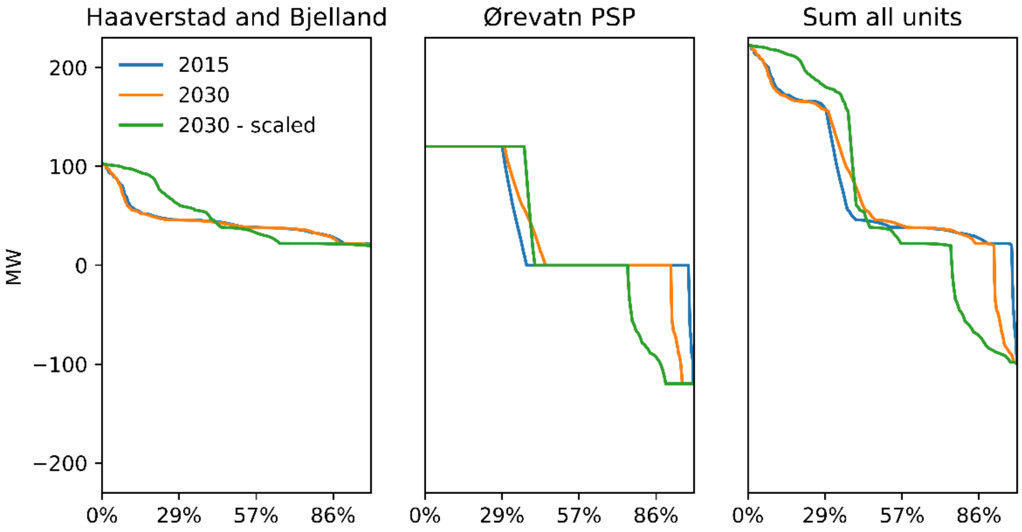

Figure 2-18. *Duration curve of the power production per time step for the Haaverstad + the old Bjelland power stations (left), the Ørevatn PSP (middle) and the duration curve for the total production from all the units (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.*

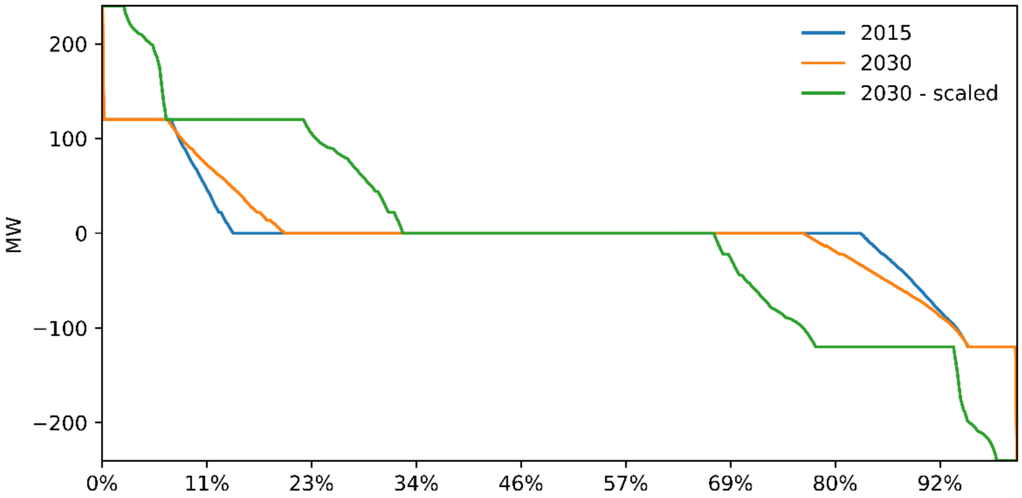

Figure 2-19. *Duration curve of the change in power production (ramping) per time step from Ørevatn PSP power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios (2015, 2030 and 2030 - scaled).*

2.2.9 Overall system

Total production, income and achieved power price are given in table 2-1 for the overall system. Results are provided for scenario 2 (S2) and the current system (today) given all three price scenarios. Comparing the results, we see that both total production and income increase in scenario 2 compared to the current system for the 2015 and 2030 simulations. For the 2030 – scaled simulation however, total production is reduced while the income increase. For all the price scenarios a higher price is realised per unit of energy sold in scenario 2 than in the current system scenario, especially for the 2030 simulations with increased variability (2030 - scaled). In total, yearly income in scenario 2 compared to the current system increase with 10.8 million EUR assuming the 2015 price, 26.1 million EUR assuming the 2030 price and 69.7 million EUR assuming the 2030 price with increased variability (2030 - scaled).

Table 2-1. *Yearly power production and economic results for the overall system for scenario 2 (S2) and today (current system), given all three price scenarios. The results in scenario 2 are compared to the results from the current system.*

		Power production [GWh]	**Net Income [MEUR]**	**Achieved price [EUR/MWh]**
2015	Today	1731.9	51.4	29.7
	S2	1884.9	62.2	33.0
	Increase S2	153	10.8	3.3
		9 %	21 %	11 %
2030	Today	1742.3	72.5	41.6
	S2	1801.3	98.6	54.7
	Increase S2	59	26.1	13.1
		3 %	36 %	32 %
2030 - scaled	Today	1705.8	81.1	47.5
	S2	1441.7	150.8	104.6
	Increase S2	-264.1	69.7	57.1
		-15 %	86 %	120 %

3 Scenario 3: Flood Protection

3.1 Implementation

In scenario 3, the flexibility of the system is increased by installing several new hydropower plants and pumped storage plants, and by expanding the storage capacity in the system. To increase the storage capacity:

4) A new reservoir is created, impounding the natural lake Storavatn. The new reservoir is connected to the Skjerkevann reservoir.

Furthermore, two new pumped storage plants (PSP) are built and two new hydropower stations are added to the system:

5) Storavatn PSP is built in parallel to the Skjerka power station. The plant pumps from Ørevatn to Storavatn (connected to Skjerkevann).
6) Ørevatn PSP is built in parallel to the Haaverstad and the Bjelland power stations. The plant pumps from downstream Bjelland (river intake) to Ørevatn.
7) A new power station is built in parallel to the existing Laudal station.
8) A flood power plant is built downstream of Laudal.

In addition, there are included some new environmental constraints on the operation. Note that the overall water balance in the system remains the same, as no new inflow is added by the changes to the system. For further details on the added power stations and constraints see memos describing the development scenarios.

3.1.1 New Storavatn reservoir

The natural lake, Storavatn, is impounded into a reservoir and connected to the Skjerkevann reservoir. Since the two reservoirs are connected, allowing water to flow between, the two reservoirs are in the model described as one larger reservoir. The description of Skjerkevann reservoir has been modified to describe this larger reservoir as illustrated in figure 3-1, i.e. the storage volume, highest regulated water level, lowest regulated water level and reservoir curve have been adjusted. No new inflow is added to the model.

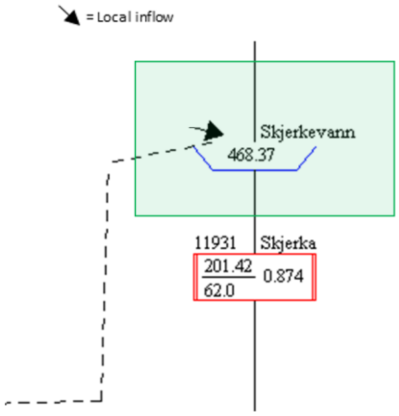

__Figure 3-1__. Illustration of the adjusted Skjerkevann reservoir, in green, describing the characteristics of the "large reservoir" consisting of Skjerkevann and Storavatn reservoirs.

3.1.2 Storavatn PSP

The new Storavatn PSP is constructed in parallel to the old Skjerka power station, as shown in figure 3-2. The PSP can produce in parallel to the old station and can also pump water back up into the Skjerkevann reservoir.

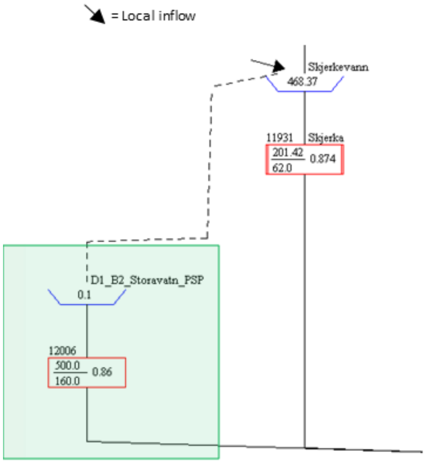

***Figure 3-2**. Illustration of the new Storavatn PSP, marked with green. The PSP is added in parallel to the old Skjerka station. The PSP pump water from Ørevatn to Skjerkevann and get water for production from Skjerkevann. The PSP and the old Skjerka power station can produce at the same time.*

3.1.3 Ørevatn PSP

The new Ørevatn PSP is added in parallel to the existing Haaverstad and Bjelland power stations as shown in figure 3-3. The PSP pumps from a river intake downstream of Bjelland and up to Ørevatn reservoir. The river intake has been modelled by including a dummy module with a very small reservoir downstream of the Bjelland power station.

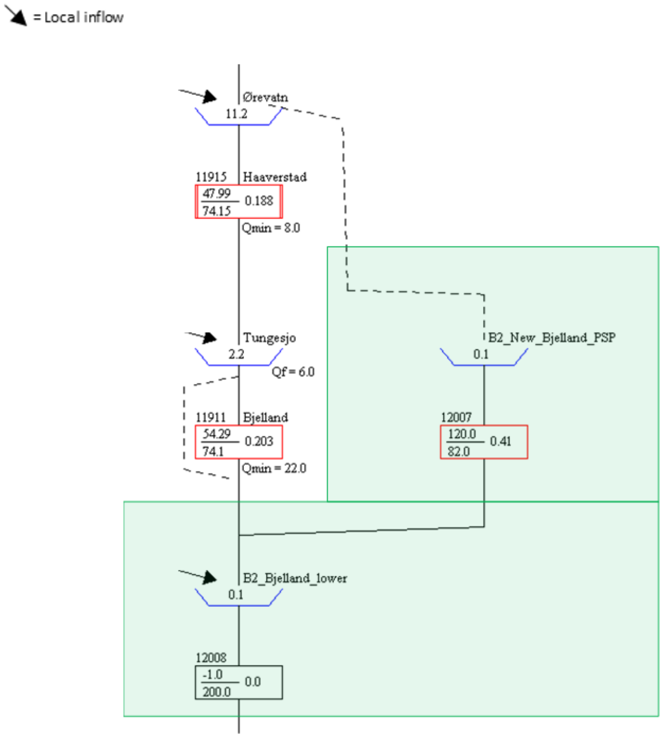

Figure 3-3. *Illustration of the new Ørevatn PSP (in the figure named New Bjelland PSP), marked with green. The PSP is added in parallel to the old Haaverstad and Bjelland power stations. The PSP pump water from a river intake modelled using a dummy module with a small reservoir up to Ørevatn reservoir. The PSP gets water for production from Ørevatn.*

3.1.4 New Laudal power station

New Bjelland and new Laudal power stations are added in parallel to the existing stations, as illustrated in Figure 3-4. The parallel stations have the same head as the original ones, but different flow and turbine capacities. Bypass is used to direct water to the new stations instead of to the old stations (the model chooses optimal use of water).

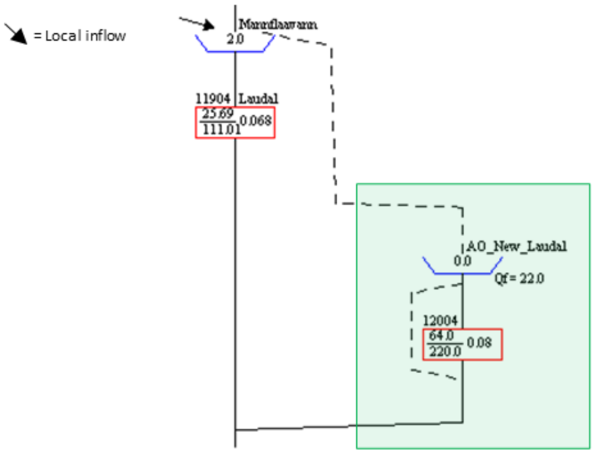

Figure 3-4. *Illustration of the new Laudal power station, marked with green. The new Laudal power station is added in parallel to the old Laudal power station.*

3.1.5 New flood power plant

A new flood power plant has been added downstream of the Laudal power station, as illustrated in Figure 3-5.

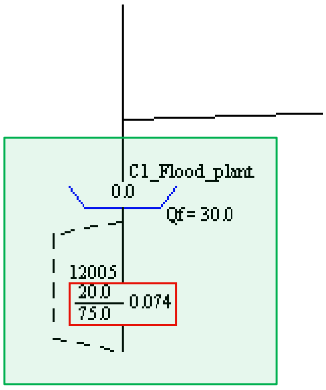

Figure 3-5. *Illustration of the new flood power plant, marked with green, added in parallel downstream of new and old Laudal power station.*

3.2 Results

This chapter present some results from the simulated operation of development scenario 3.

3.2.1 Skjerkevann

Figure 3-6 shows simulated reservoir operation for Skjerkevann simulated for 60 different inflow years, given the different assumptions on power price. We see a difference in the seasonal profile between the different simulations. In the 2015 simulations the reservoir level is drawn down during winter and then increase during spring, summer and fall. In the 2030 simulation the curve is similar, but the filling seems slightly slower and the reservoir is kept at a lower level (the curve is a bit flatter). This tendency is even more distinct in the 2030 – scaled simulation, where the seasonal curve is much flatter and the reservoir level in general is kept lower throughout the year. This is related to the pumping from Skjerkevann to the new Langevann reservoir.

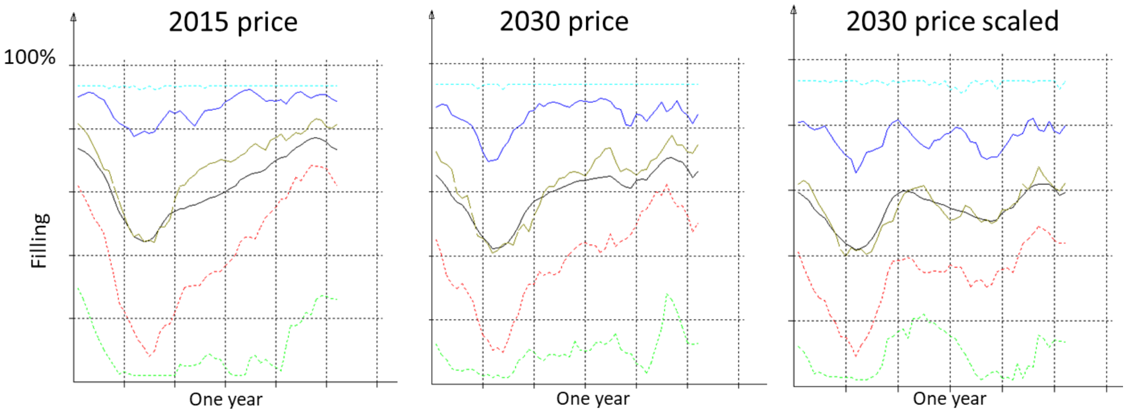

Figure 3-6. *Percentile plots of the reservoir development in Skjerkevann over one year (simulation results over 60 years), given the different input prices. The plots show the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.*

3.2.2 Production Skjerka and Storavatn PSP

The Skjerka power plant and the Storavatn pumped storage plant are located in parallel. Figure 3-7 show the duration curve of the production and pumping in the two stations and the sum production. The Storavatn PSP is operated both in production and pumping mode. In the 2030 – scaled simulation the plant is used considerably more than in the two other simulations, and it seems that the plant is producing and pumping approximately the same number of hours. Notice that the two plants not always produce at the same time (seen by the sum curve). In some hours only the old Skjerka station produce and not the PSP. Figure 3-8 show the change in production from time step to time step. In the 2015 and 2030 simulation the plant is mostly operated at constant level, while the operation mode is changed much more often in the 2030 - scaled simulation. Most of the times when the production is changed it seems to either go from maximum production to zero production or to maximum pumping, or from maximum pumping to zero pumping or maximum production.

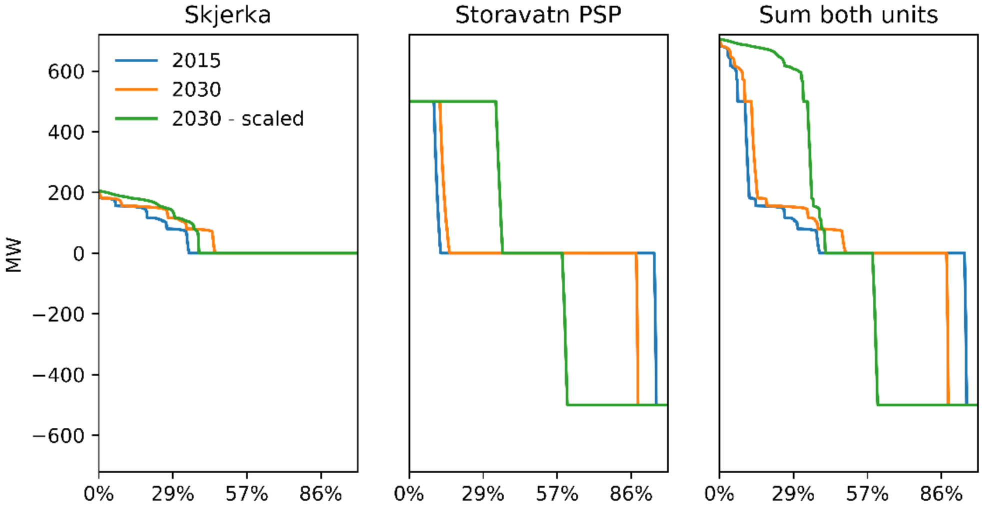

Figure 3-7. *Duration curve of the power production per time step for the Skjerka power station (left), the new Skjerka PSP (middle) and the duration curve for the total production from the two plants (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.*

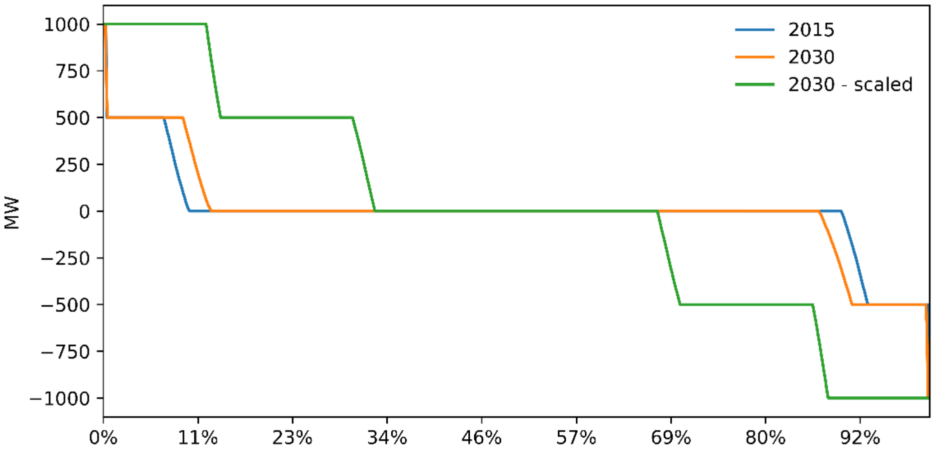

Figure 3-8. *Duration curve of the change in power production and pumping (ramping) per time step from Storavatn PSP. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

3.2.3 Juvann

Figure 3-9 shows simulated reservoir operation for Juvann based on simulations for 60 years of weather data. Comparing the results from the simulations based on different price assumptions, there are some smaller differences in the reservoir curves, but overall the reservoir is operated similarly in the three simulations.

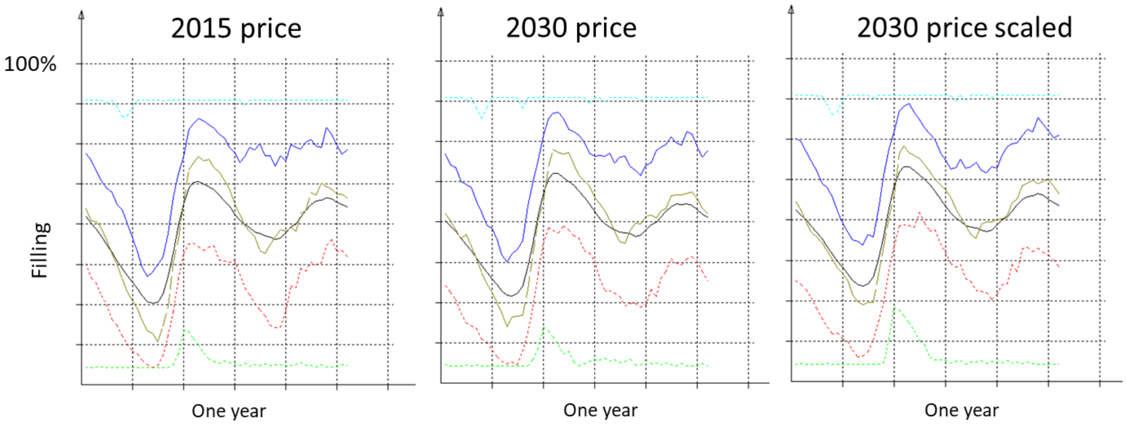

***Figure 3-9**. Percentile plot of the reservoir development in Juvann over one year (simulation results over 60 years), given the different input prices. The plot shows the 0-, 25-, 50-, 75- and 100% percentiles as well as the average.*

3.2.4 Production Logna power station

Figure 3-10 shows the duration curve of the power production in the Logna power station. The plant is producing more than 70-75% of the hours. The production is quite similar between the three simulations. Figure 3-11 gives the change in production per time step. In the 2030 – scaled simulations the production changes more often that in the other simulations, but most of the time the production is constant.

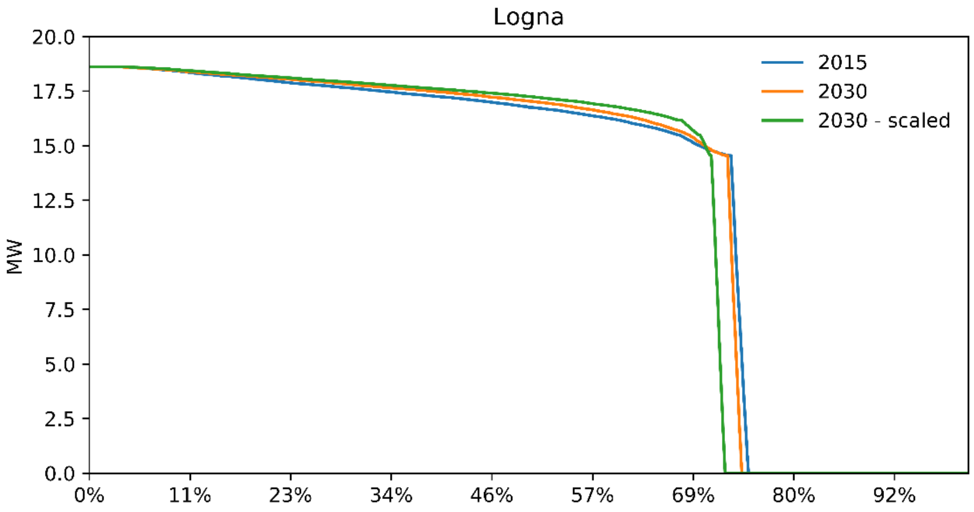

***Figure 3-10**. Duration curve of the power production per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.*

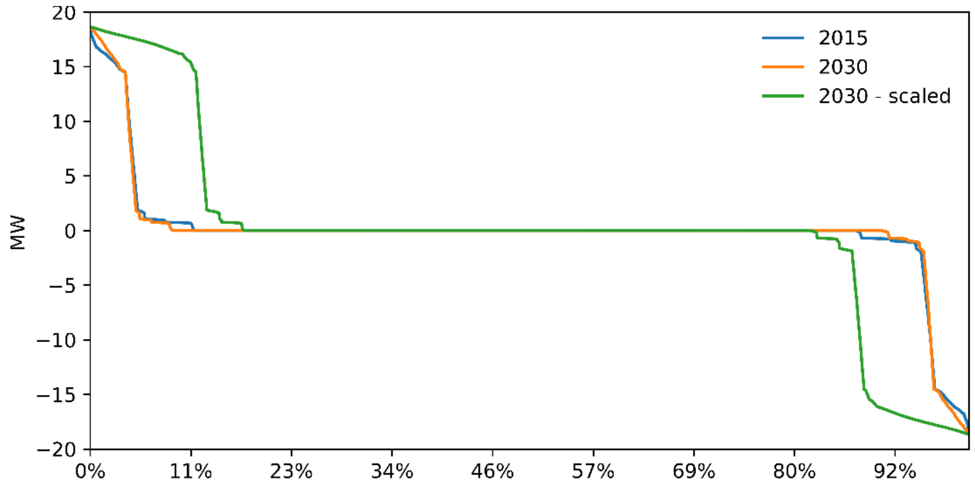

Figure 3-11. *Duration curve of the change in power production (ramping) per time step from Logna power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios.*

3.2.5 Production Ørevatn PSP

Figure 3-12 shows the duration curve for the power production and pumping from the old Haaverstad and Bjelland power stations and the new Ørevatn PSP. Figure 3-13 shows the duration curve of the change in production/pumping from time step to time step. Ørevatn PSP produce 30-40% of the hours and pump up to about 30% of the hours in the 2030 -scaled simulation. The old power stations are constantly producing, but at a low level most of the year. Some of this production is a result of environmental constraints.

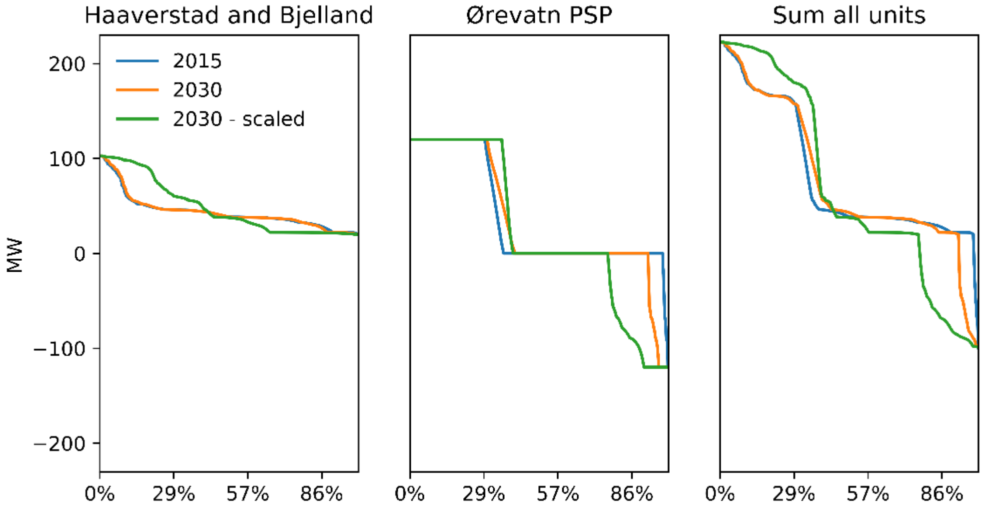

Figure 3-12. *Duration curve of the power production per time step for the Haaverstad + the old Bjelland power stations (left), the Ørevatn PSP (middle) and the duration curve for the total production from all the units (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled). Negative values are pumping.*

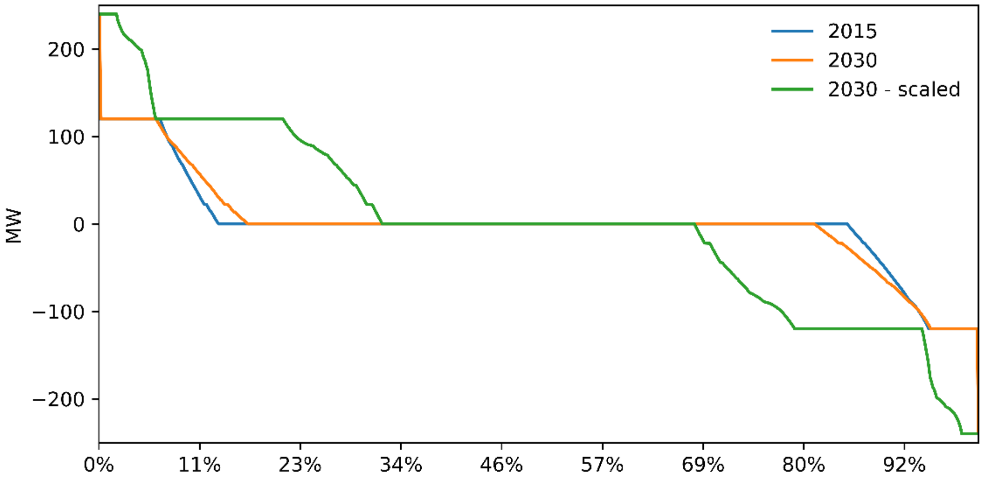

Figure 3-13. *Duration curve of the change in power production (ramping) per time step from Ørevatn PSP power station. The plot shows the results from simulations over all 60 weather years given the three different price scenarios (2015, 2030 and 2030 - scaled).*

3.2.6 Production new and old Laudal

The duration curves for the production from the old and new Laudal power plants are plotted in figure 3-14. The change in production per time step for the new plant is plotted in figure 3-15. The new Laudal power station is operated around 40-50% of the hours, while the old station is operated 80-90% of the hours.

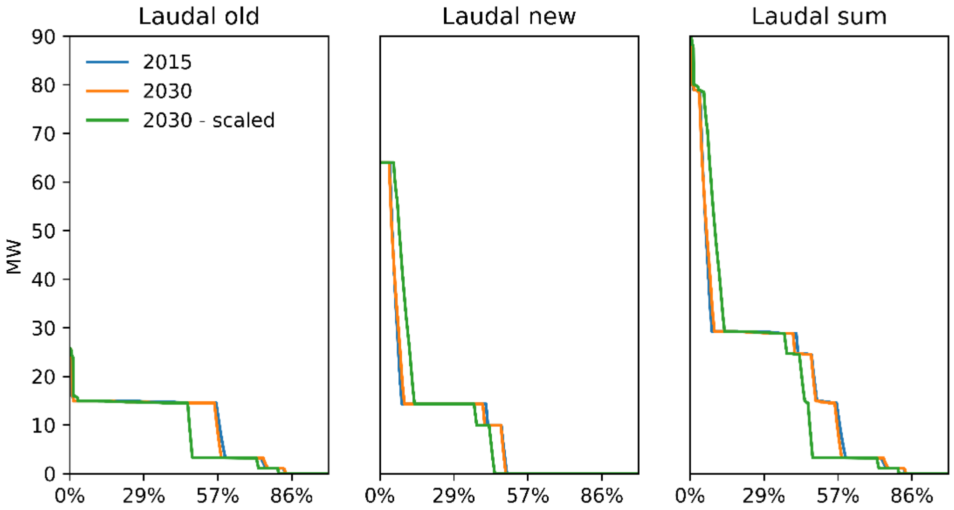

Figure 3-14. *Duration curve of the power production per time step for the old Laudal power station (left), the new Laudal power station (middle) and the duration curve for the total production from the power stations (right). The plots show the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

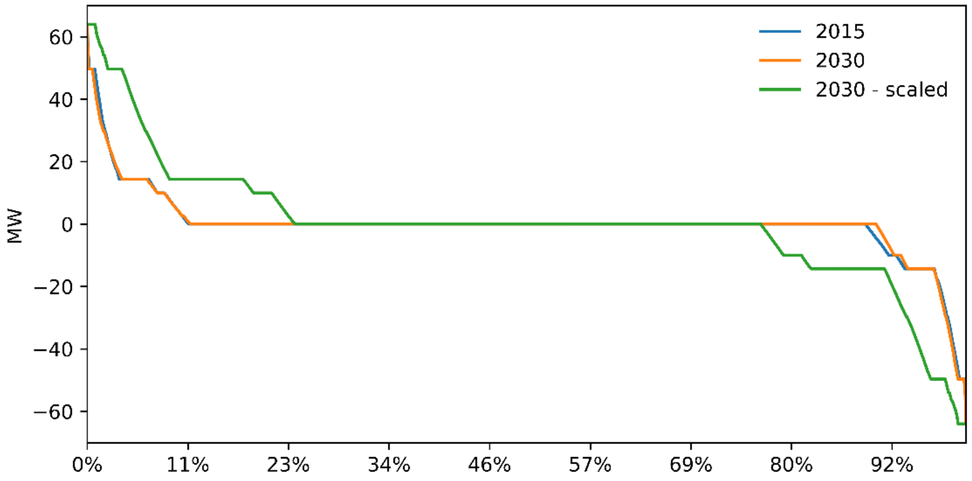

__Figure 3-15.__ The duration curve of the change in power production (ramping) per time step from the new Laudal power station. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).

3.2.7 Production new flood power plant

The duration curve of the power production and change in production per time step for the new flood power plant are shown in figure 3-16 and 3-17 respectively. The power plant is operated 40-60% of the time and is mostly operated at maximum.

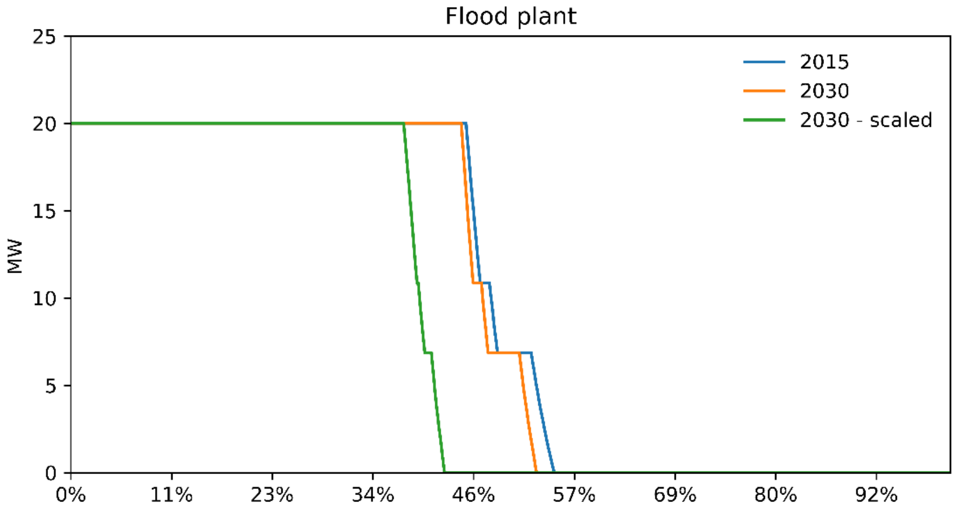

__Figure 3-16.__ Duration curve of the power production per time step from the new flood power plant. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).

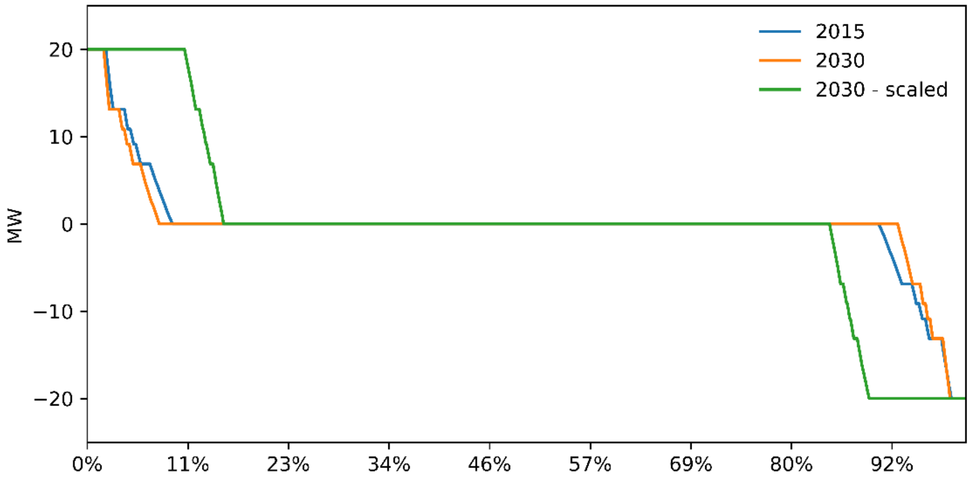

Figure 3-17. *The duration curve of the change in power production (ramping) per time step from the new flood power plant. The plot shows the results from simulations over all 60 weather years (x-axis) given the three different price scenarios (2015, 2030 and 2030 - scaled).*

3.2.8 Overall system

Total production, income and achieved power price are given in table 3-1 for the overall system. Results are provided for scenario 3 (S3) and the current system (today) given all three price scenarios. Comparing the results, we see that both total production and income increase in scenario 3 compared to the current system for the 2015 and 2030 price scenarios. In the 2030 – scaled price scenario total power production is reduced, but the income is still increased. The achieved power price is higher in scenario 3 for all the price scenarios, and especially in the 2030 – scaled scenario, which extra high price variability. In total, yearly income in scenario 3 compared to the current system increase with 7.9 million EUR assuming the 2015 price, 20.3 million EUR assuming the 2030 price and 56.7 million EUR assuming the 2030 price with increased variability (2030 - scaled).

Table 3-2*. Yearly power production and economic results for the overall system for scenario 3 (S3) and today (current system), given all three price scenarios. The results in scenario 3 are compared to the results from the current system.*

		Power production [GWh]	Net Income [MEUR]	Achieved price [EUR/MWh]
2015	Today	1731.9	51.4	29.7
	S3	1852.9	59.3	32.0
	Increase S3	121	7.9	2.3
		7 %	15 %	8 %
2030	Today	1742.3	72.5	41.6
	S3	1758.8	92.8	52.8
	Increase S3	16.5	20.3	11.2
		1 %	28 %	27 %
2030 - scaled	Today	1705.8	81.1	47.5
	S3	1410.1	137.8	97.7
	Increase S3	-295.7	56.7	50.2
		-17 %	70 %	106 %

4 Comparing the scenarios

Comparing the results above we see some trends. For all the development scenarios, the hydropower plants without pumping capability are operating in fewer hours with increasing price variability. They are also start/stopping and changing production more often with increasing variability. The pumped storage plants are also changing operation mode and production/pumping level more often in the price scenarios with higher variability, but these plants are also found to operate in more hours with increasing price variability. Table 4-1 gives some overall results for the different combinations of scenarios. Economically, scenario 2 is the scenario with the highest potential compared to the other scenarios. We also see that the income from this scenario increase the most with increasing variability. In the scenario with highest price variability, the two scenarios with pumping capacity (scenario 2 and 3) have a much larger increase in income than scenario 1. The increase in income between price scenario 2030 and 2030 scaled is quite modest for scenario 1 compared to the increase in income for scenario 2 and 3. Table 4-2 shows economic results per hydropower plant for the different scenarios and price series. We see that there is a big difference in the income of the new power plants. Especially, new Skjerka/Storavatn PSP and New Bjelland/Ørevatn PSP have high incomes. However, it is also necessary to see the change together with change for corresponding parallel power station, as well as the changed operation for the rest of the system. For example, we find that New Juvann PSP in scenario 2 for price series 2015 has a net negative income. Still, the plant is used for pumping, as the water pumped by the plant can be used for power production in other power plants. The economic results in this study only include sale of energy in the day-ahead market. In the future power system, flexible power plants are also expected to have an increasing income from supplying ancillary services, such as providing reserves, and potentially also from delivering services that are not compensated today, such as inertia. It is uncertain how much income these types of services will contribute with. Today, income from these types of markets only constitute a small part of the total income of a hydropower plant.

Table 4-1. *Overall results for all the development scenarios and price scenarios.*

		2015				2030				2030 - scaled			
		Today	S1	S2	S3	Today	S1	S2	S3	Today	S1	S2	S3
Spillage	GWh	223	197	103	262	211	198	102	264	229	202	119	296
Consumption pumping	GWh	-	-	424	221	-	-	764	581	-	-	2 276	1 930
Gain from pumping	GWh	-	-	361	181	-	-	617	449	-	-	1 833	1 506
Net pump energy	GWh	-	-	- 63	- 40	-	-	- 147	- 132	-	-	- 444	- 424
Start reservoir	GWh	349	391	943	684	316	405	918	623	325	325	859	577
End reservoir	GWh	352	394	952	690	320	408	924	628	328	327	865	582
End - start reservoir	GWh	3	3	9	6	3	3	6	5	3	2	7	5
Total production	GWh	1 732	1 960	1 885	1 853	1 742	1 957	1 801	1 759	1 706	1 931	1 442	1 410
Net income	MEUR	51	60	62	59	73	87	99	93	81	110	151	138
Gain compard to today			9	11	8		15	26	20		29	70	57
Achieved price	EUR/MWh	29.7	30.7	33.0	32.0	41.6	44.6	54.7	52.8	47.5	56.9	104.6	97.7

Table 4-2. *The yearly average net income per hydropower plant for the different scenarios and price series.*

Hydropower plant	Unit	Today			S1			S2			S3		
		2015	2030	2030 - scaled	2015	2030	2030 - scaled	2015	2030	2030 - scaled	2015	2030	2030 - scaled
Logna	MEUR	3	5	5	0	0	1	3	5	4	3	5	5
Skjerka	MEUR	21	30	36	8	12	13	9	18	28	12	22	30
Smeland	MEUR	4	6	6	2	3	3	4	5	5	4	5	6
Haaverstad	MEUR	9	13	13	4	6	8	5	8	10	5	8	10
Bjelland	MEUR	10	14	15	5	6	8	6	8	10	6	8	10
Laudal	MEUR	4	5	6	2	3	3	4	6	6	2	3	3
New Skjerka/Storavatn PSP	MEUR				14	22	33	18	28	58	12	19	47
New Logna	MEUR				6	9	10						
New Bjelland/Ørevatn PSP	MEUR				14	20	23	11	16	19	10	15	18
New Laudal	MEUR				3	4	5				3	4	5
New Flood plant	MEUR				2	3	3				3	4	4
New Langevann PSP	MEUR							3	4	7			
New Juvann PSP	MEUR							-1	1	3			

Table 4-3. *Characteristics of the different simulated power prices. The average and standard deviation of the simulated power prices are given, as well as the average and standard deviation of the time series of the change in power price from time step to time step. The last column gives the standard deviation of the change in power price excluding the most extreme values.*

	Price series		**Time step to time step difference**		
	Average	Standard Deviation	Average	Standard Deviation	Standard Deviation[1]
2015	28.84	8.58	0.00	2.26	2.26
2030	38.95	29.40	0.00	39.51	6.98
2030 scaled	38.95	32.64	0.00	44.48	21.66

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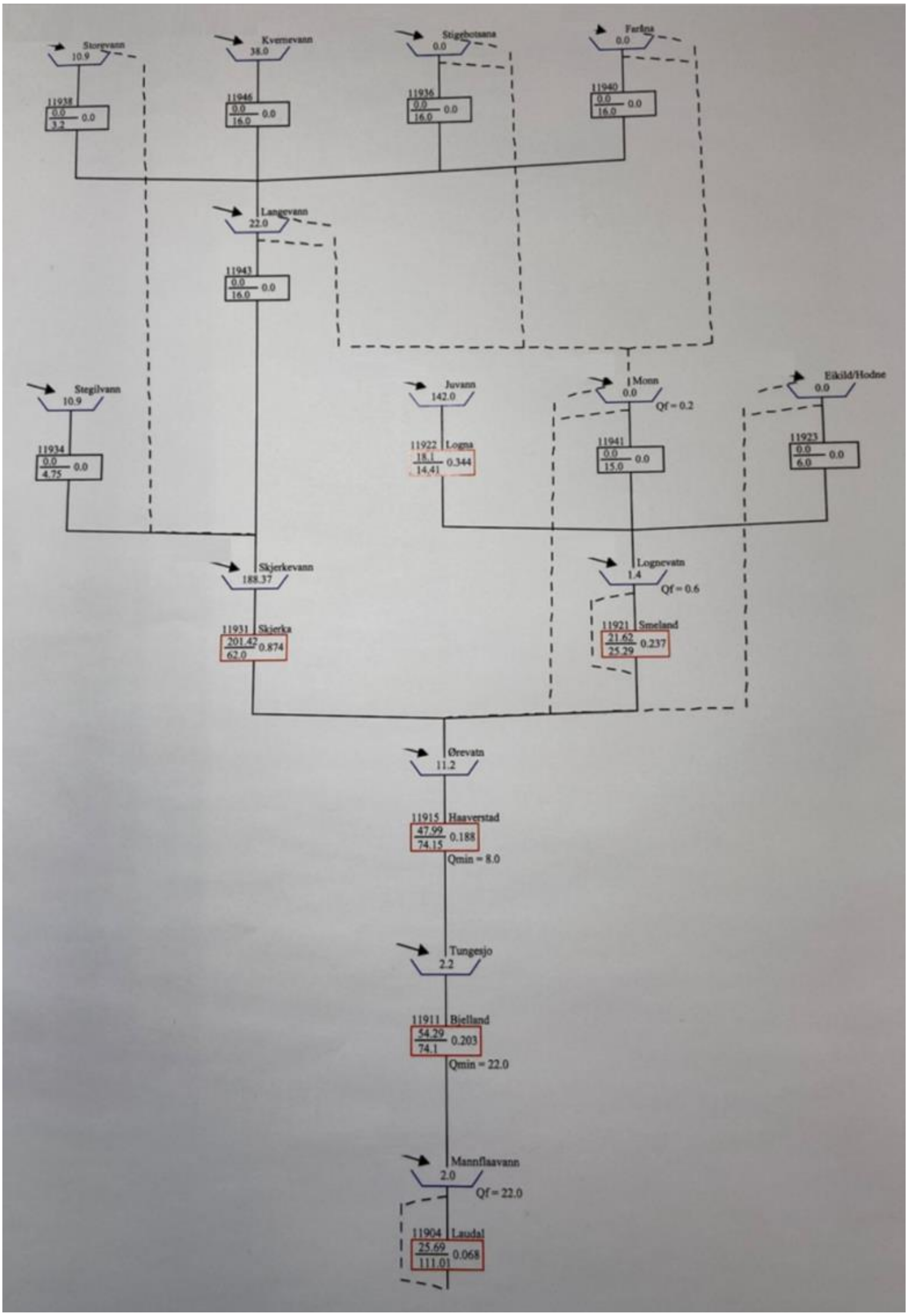
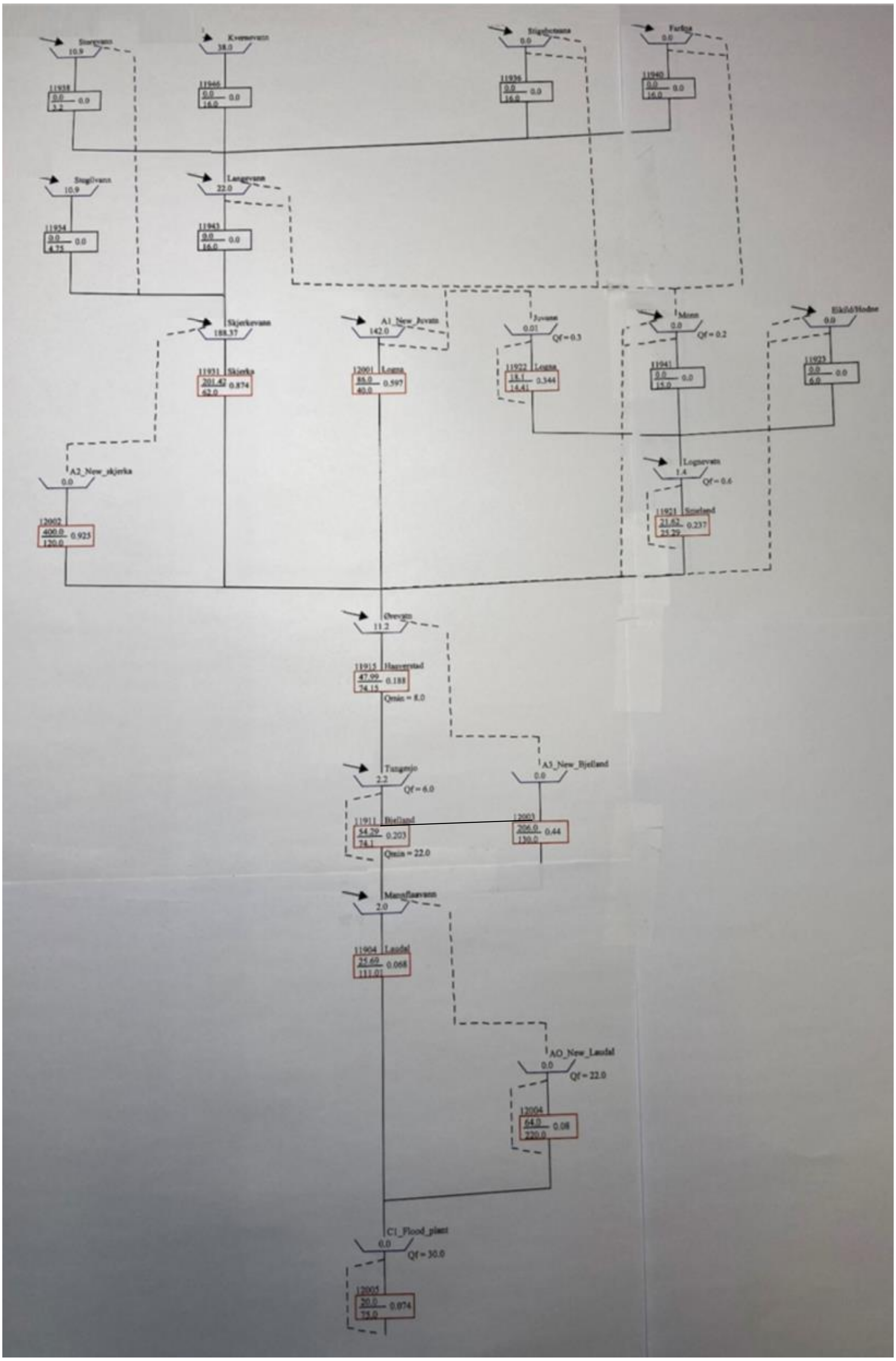
[1] Standard deviation of change in power price from time step to time step, excluding absolute changes larger than 150 EUR/MWh to reduce the impact of the most extreme power prices

5 Appendix: Overview of the systems

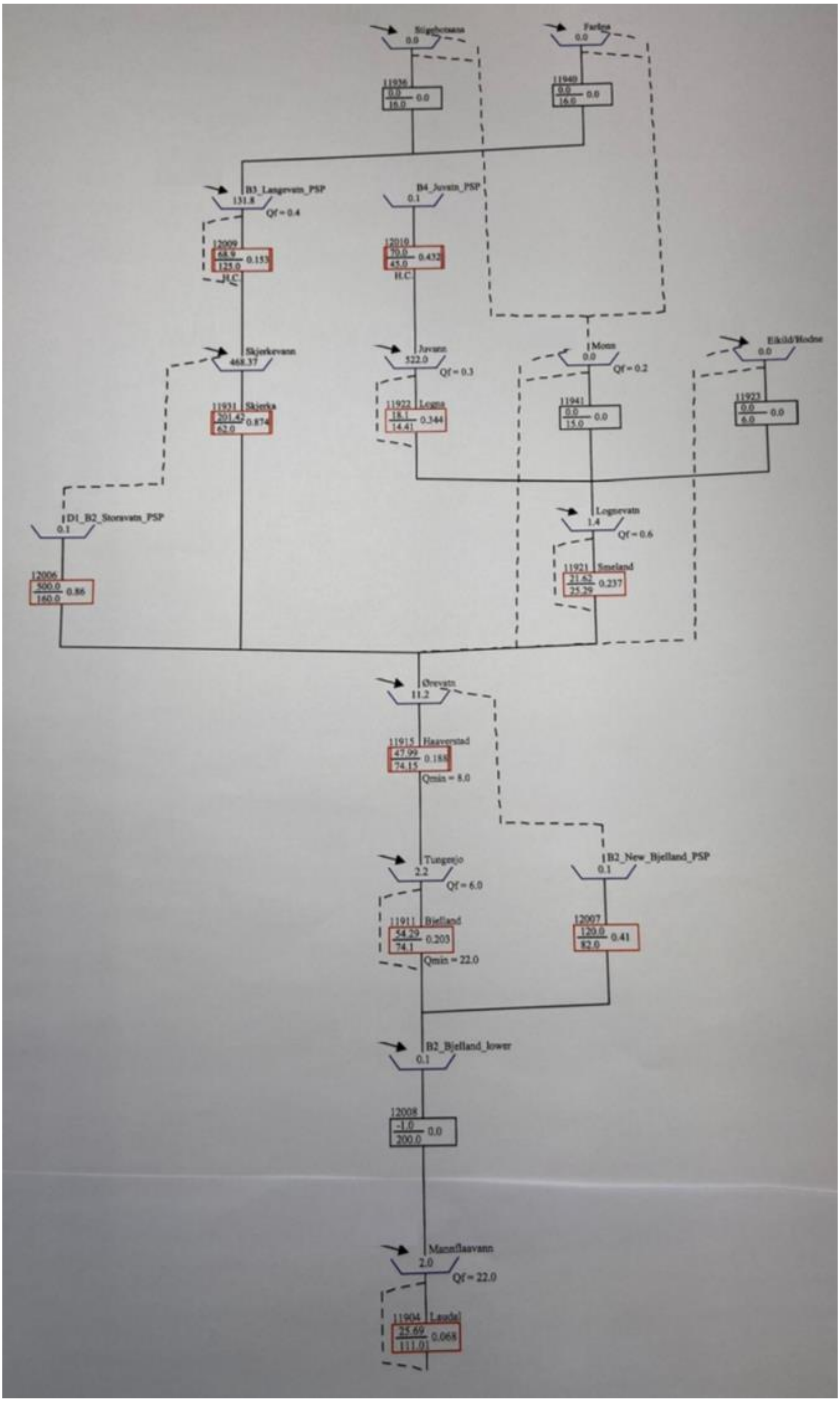
5.1 Overview of the current system



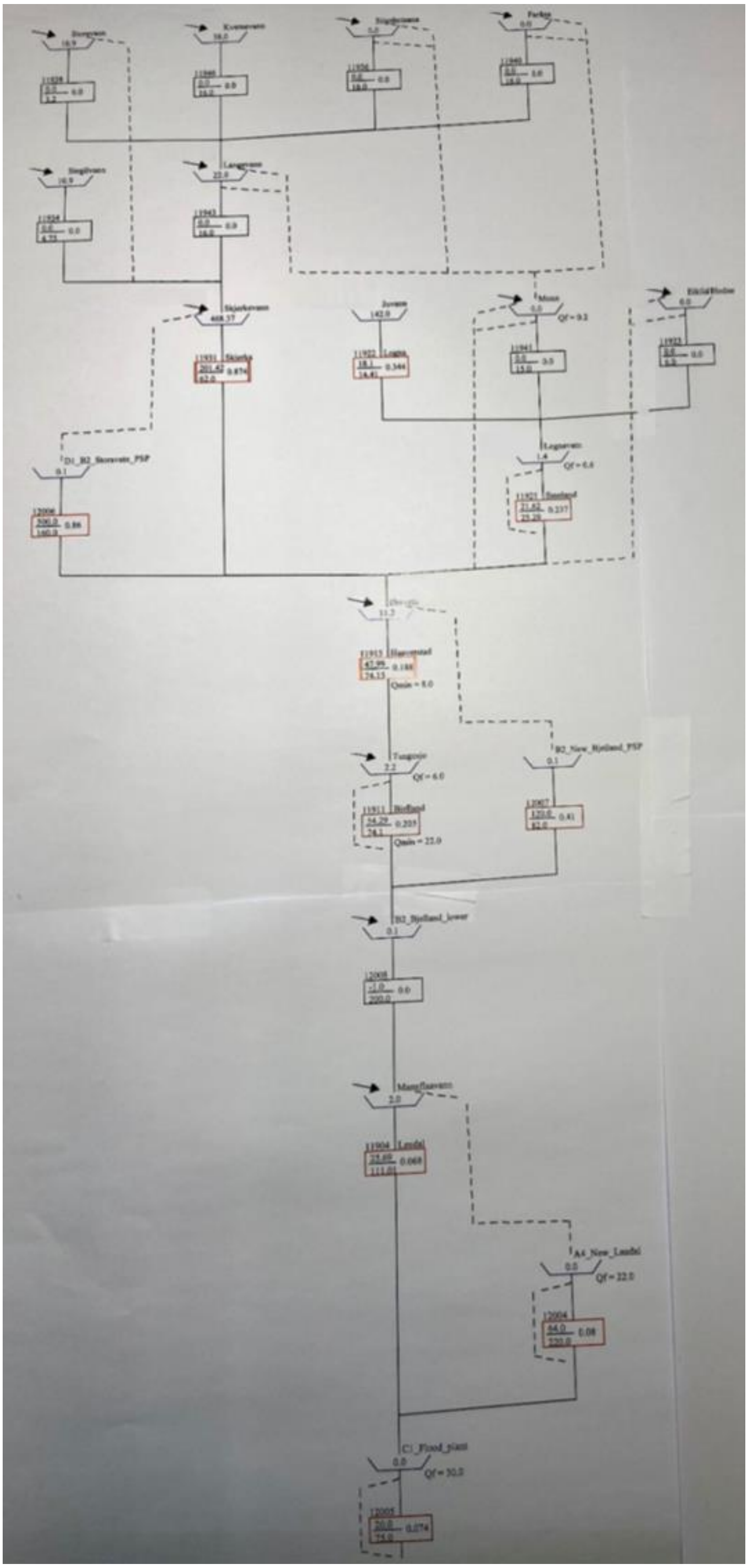
5.2 Overview of scenario 1



5.3 Overview of scenario 2



5.4 Overview of scenario 3



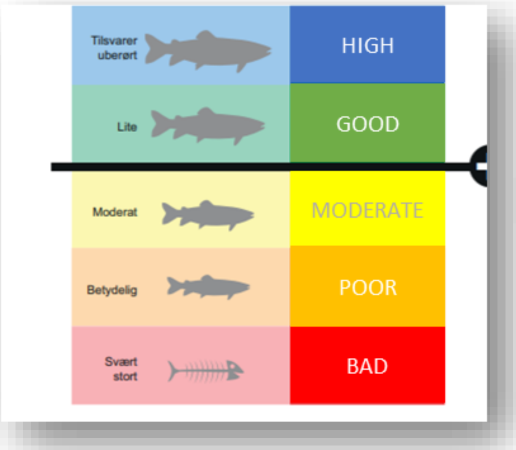
AlternaFuture MEMO nr. 7

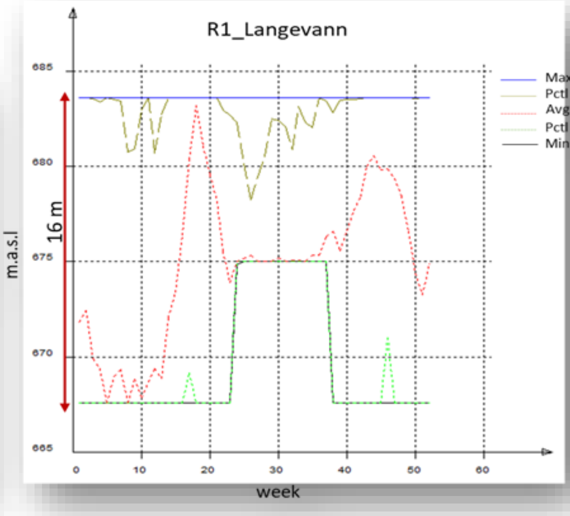
AlternaFuture

A3: Environmental evaluation of three hydropower scenarios

Ana Adeva Bustos, Line Elisabeth Sundt-Hansen, Trygve Hesthagen & Torbjørn Forseth

2020-09-22





Abstract

AlternaFuture is a multidisciplinary project in Hydrocen that aims to develop alternative future redesign solutions, focusing on both flexible hydropower operation and environmental conditions. The project is a desk study and is carried out through developing future Scenarios of an extreme upgrading of an existing hydropower system to create potential for new innovations from the multidisciplinary scientists within the project. The AlternaFuture project explores future hydropower systems that operates with extreme flexibility and explores the potential added value from combinations of the various innovations within the whole system, from dams, to machines, to environmental design solutions. The existing hydropower system in Mandalsvassdraget has been case for this study, where the current situation has been the baseline for developing alterative future scenarios for upgrading of the entire system. The project is divided in three main activities; (A1) mapping the current situation and providing restrictions and targets for reconstruction, (A2) physical scenarios, and (A3) economic and environmental evaluation of the scenarios. In this memo we report results from activity A3, evaluating the environmental effects, both in terms of hydrology and ecology, for the different scenarios based on the reference indicators defined in A1. The main basis for the evaluation is hydrological data based on simulated hydropower operation and water balance provided in the AlternaFuture memo 6.

Three main scenarios were developed for Mandalsvassdraget; triple installed capacity, maximum flexibility and flood protection. Results from the ProdRisk model (AlternaFuture Memo 1, 2, 6) were used to compare present situation with three different hypothetical scenarios and their impacts on environmental status in different parts of the watercourse, including reservoirs, lakes and river reaches impacted by both in, and compare it with three hydropower scenarios. Evaluation of environmental impact was made based on hydrological and ecological reference indicators. Recreation value was based on indices such as accessibility, availability of existing infrastructure, fishing possibilities and degree of pristine areas. A more detailed description of theses indices is reported in AlternaFuture memo 3: Environmental restrictions for reconstruction scenarios and targets for improving the current ecological status.

In scenario 1 the installed capacity in MW was tripled, including a flood power plant. The effect on the ecological and recreational values varied among the assessed water bodies. However, with the implemented mitigation or compensation measures the total effect was classified as weak positive, but if additional measures were implemented, the total effects are classified as positive.

In scenario 2, full flexibility, the current installed capacity was tripled and pumping capacity of 750 MW was included. Strong negative environmental and recreational effects were found for the new Nåvann-Skjerka-Storavatn reservoirs, whereas the Tungefoss-Kavfossen river stretch was the only strong positive effect (present in all the scenarios). However, if additional measures were implemented the total effect are classified as slightly positive for the environment and neutral for recreation (the positive effects are counteracted by the new Storavatn dam representing a major intervention in an attractive area).

In scenario 3, flood dampening, one flood power plant and pumping capacity of at least 620 MW was included. The effects on the ecological and recreational values were strongly negative for the Nåvann-Skjerka-Storevann reservoir, whereas the compensatory measures in the Tungesjø-Kavfossen was regarded as strongly positive. Because of the large interest associated with salmonid fishes the total effects are classified as small positive. The positive societal effects of flood protection are considerable, but not considered in this assessment.

In conclusion, it is found potentially possible to realize extreme upgrading of existing hydropower system, and at the same time have a potential positive effect on the environmental conditions. It is noted that the positive effects require a significant effort in mapping and planning the environmental measures. For such overall upgrading consisting of multiple projects, single projects that have severe negative ecological impacts must be cancelled and not included in the final scheme. Planning of such upgrading projects therefore have to include environmental experts from the very beginning.

Contents

1 Introduction

The AlternaFuture project is a multidisciplinary project in Hydrocen utilizing the whole range of expertise present in Hydrocen, including hydropower engineers, hydraulic engineers, hydropower planning engineers, biologist and social scientists. AlternaFuture aims to develop alternative future redesign solutions, focusing on both flexible operation and environmental conditions. AlternaFuture further aims to reconsider what is possible. It is a desk study and the design scenarios are developed to create potential for new innovations from the multidisciplinary scientists within the project.

The case study of AlternaFuture is the Mandal river hydropower system, currently containing six major hydropower plants in the watercourse, which extends more than 100 km from north to south through Agder county. All the largest lakes in the upper parts are regulated for hydropower, including Juvatn, Langevatn, Nåvatn and Ørevatn, Store Kvernevatn, Storevatn and Stekil. The hydropower regulation involving reservoirs took place between 1932 and 1981. The two lowermost Hydropower (HP) stations, Bjelland and Laudal, were built in 1975 and 1981, respectively.

This memo reports from activity A3 of the project which aims at mapping the differences between the present environmental status in different parts of the watercourse, both in terms of hydrology and ecology, and compare it with three hydropower scenarios (triple installed capacity, maximum flexibility and flood protection). In this memo a total of eight reservoirs and lakes and four river stretches in the Mandal basin has been evaluated based on the change on hydrological and ecological reference indicators. The reservoirs and river stretches has been selected because of their relevance and potential to improve their conditions through environmental restrictions.

2 Methods

2.1 Hydrological classification

2.1.1 Hydrological analyses

Outputs from the ProdRisk model (AlternaFuture memo 1 & 2) for present situation were compared with three different hypothetical scenarios:

Scenario 1: Triple installed capacity

Scenario 2: Maximum Flexibility

Scenario 3: Flood protection

The following indices were used to analyse the hydrological changes in the reservoirs and river stretches and their potential environmental changes under the different scenarios. For reservoirs the following indices were calculated:

- Lowest regulated volume (LRV)
- Highest regulated volume (HRV)
- Minimum water surface elevation (Min)
- Percentile 10 water surface elevation (Pctl 10th)
- Average water surface elevation (Avg)
- Percentile 90 water surface elevation (Pctl 90th)
- Maximum water surface elevation (Max)

For the river stretches, the following six hydrological indices that are ecologically relevant for fish populations and for hydro-morphological changes (Richter et al., 1996, Poff and Zimmerman, 2010) were calculated for the unregulated and regulated period and compared the percentage of change before and after regulation for the present situation and for the different scenarios. The unregulated period data was obtained from NEVINA (http://nevina.nve.no/) and for the regulated period from the ProdRisk model.

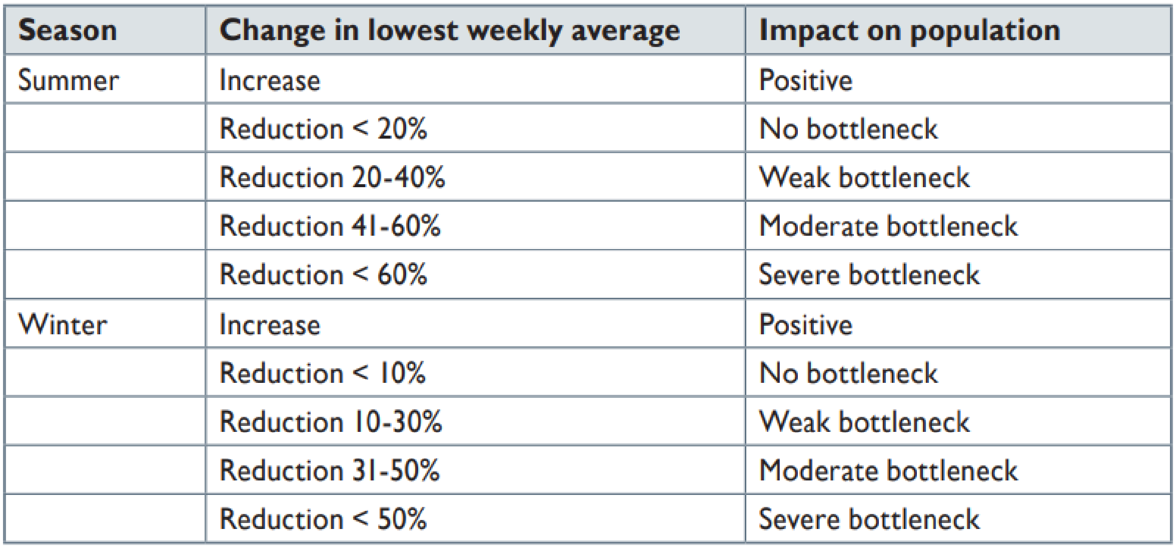
- Annual mean flow (AMF)
- Q95 (the 5-percentile flow)
- Annual mean flood (AMFlood)
- Ten-year flood (10YFlood)
- Summer low flow (7-days minimum summer low flow)
- Winter low flow (7-days minimum winter low flow)

It should be noted that there are uncertainties in the modelling output and their classification. The main uncertainties can be linked to the daily resolution of the data used as input in the hydropower model (ProdRisk) which might result in an underestimation for floods.

2.1. Hydrological classification

The hydrological classification of the reservoirs was based on the Norwegian implementation system for the Water Framework Directive (WFD) concerning classification of heavily modified water bodies, published at Vann-nett (https://www.vann-nett.no/portal/). Here, the impact from hydropower is classified as small, moderate, large or unknown, based on the level of regulation of the reservoir (Direktoratsguppen, 2018). The hydrological indices calculated from each of the reservoir provide detailed overviews of the regulation levels in the reservoir including environmental restrictions in their operational rules. For the river stretches, the classification was done according to the environmental design handbook (Forseth and Harby, 2014). It is based on comparisons of the indices for summer low flow and winter low flow before and after regulation was an indication of likely hydrological bottlenecks (Table 1).

Table 1. A classification system of, and to what extent changes in the lowest weekly average flow from unregulated to regulated state in summer and winter represent a salmon population bottleneck



Season	Change in lowest weekly average	Impact on population
Summer	Increase	Positive
	Reduction < 20%	No bottleneck
	Reduction 20-40%	Weak bottleneck
	Reduction 41-60%	Moderate bottleneck
	Reduction < 60%	Severe bottleneck
Winter	Increase	Positive
	Reduction < 10%	No bottleneck
	Reduction 10-30%	Weak bottleneck
	Reduction 31-50%	Moderate bottleneck
	Reduction < 50%	Severe bottleneck

2.2 Environmental effects

In AlternaFuture Memo 3 we identified reference indicators for ecological status in reservoirs and river stretches with the aim to rank these locations with regards to the potential for improved ecological status. In this report, potential negatives or positive impacts under the different scenarios are assessed based on the changes in the same hydrological indices. Moreover, we also consider mitigation or compensation measures that could be implemented as part of the different hydropower scenarios This also includes measures for recreational use. The total effect is finally assessed based on expert judgements.

It should be noted that we only consider the installed hydropower facilities under the different scenarios, and not potential environmental effects related to the construction of hydropower facilities.

3 Results

Results from all the reservoirs are presented (Figure 1 and Figure 2), as well as for the river stretches which have been selected due to their potential for environmental improvement under the different scenarios.

3.1 Scenario 1: Triple installed capacity

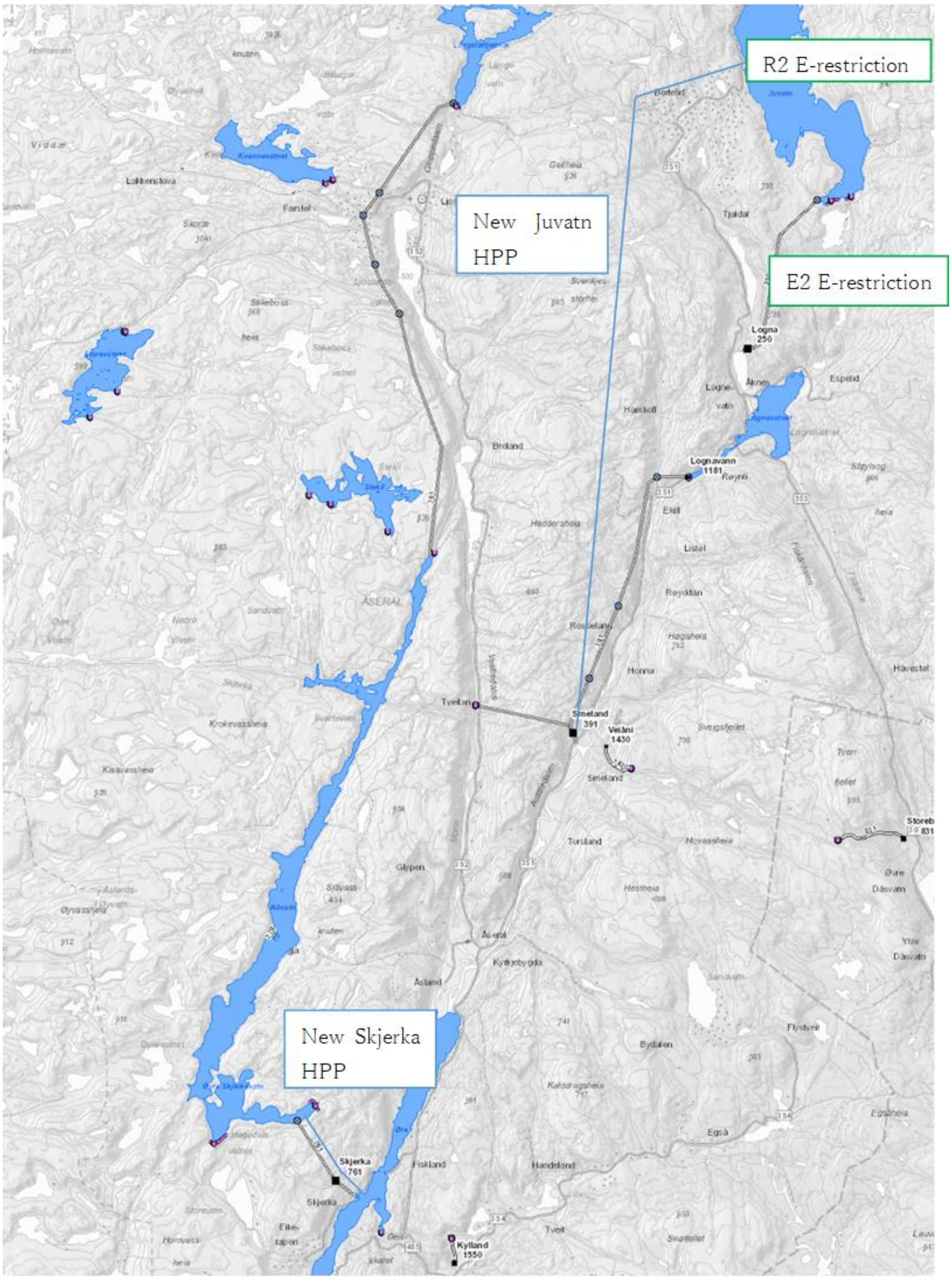


Figure 1. Map illustrating Scenario 1 in Mandalselva (tripled installed capacity), the river stretches affected (E1, E2) and reservoirs (R2: Juvatn, R7_8: Skjerka, R9 Ørevatn).

Figure 2. Map illustrating scenario 1 (tripled installed capacity) in river stretches in Mandalsvassdraget.

3.1.1 R2 The Juvatn reservoir

A new hydropower plant was simulated under scenario 1, to be implemented in parallel with the existing Logna and Smeland hydropower plants. Scenario 1 includes the same volume environmental restriction at 6% during all year as in the present situation, but introduces a new environmental restriction to maintain a minimum water level at 510 m.a.s.l during October (Figure 3).

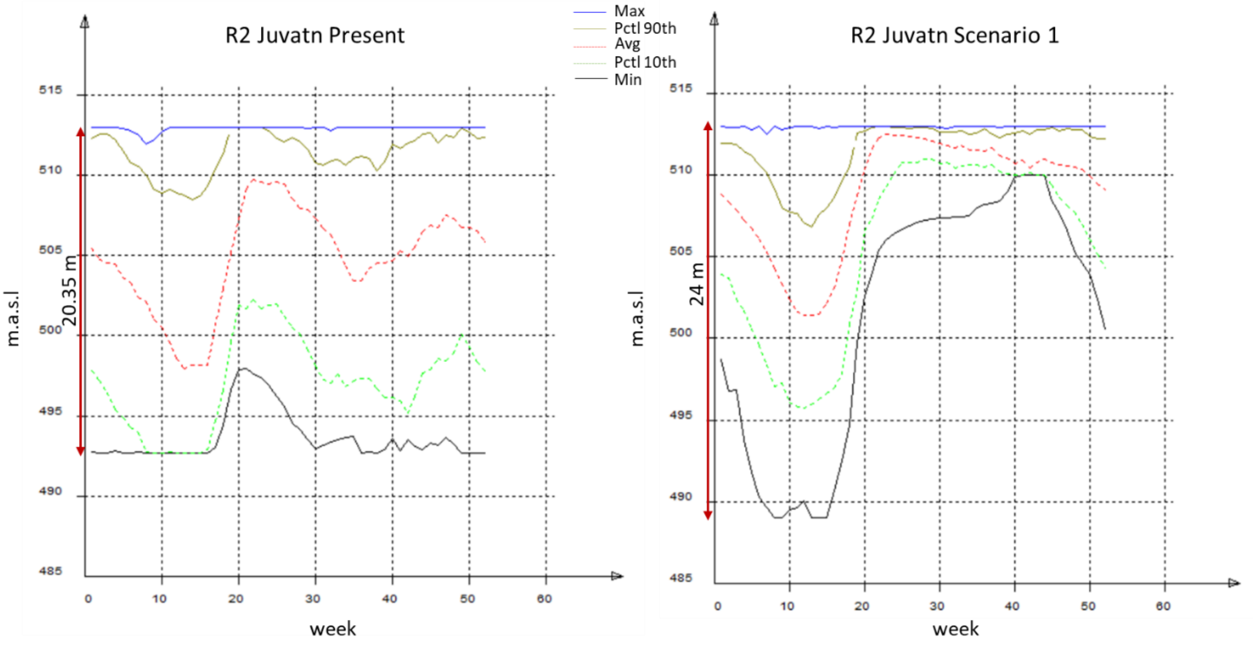


Figure 3. R2, Juvatn reservoir curve under Present situation (left) and under Scenario 1 (right).

Lake Juvatn is presently classified as hydrologically strongly impacted by the HP regulation. Under scenario 1 water levels will be higher during summer and fall than in the present situation. During winter, minimum water levels in the reservoir are somewhat lower than in the present situation, but this is a rare and short-lasting condition since it is the 10 percentile and indeed it is higher under scenario 1 for the rest of the year. The present situation has higher annual variability than scenario 1, with an average of 10 m variability in summer and fall, and 5 m in October.

Under scenario 1 the higher water level in October (the spawning period for trout) from the environmental restriction can likely facilitate upstream spawning migration of trout, a challenge in the present situation. In addition, construction of ramping cell-weir structure with a migration corridor will further improve upstream migration and shoreline shelter for juveniles. It is thus very likely that the combination of the environmental restriction in reservoir operation and the habitat measures (cell-weirs) will improve the recruitment of trout to the reservoir. It is also likely that the generally higher water level during summer, and indeed during the majority of the winters, will elevate pelagic productivity. Adding a second reservoir environmental restriction to avoid the rare cases of very low winter water levels would further improve reservoir biological productivity.

The Lake Juvatn is an important recreational area (high density of cabins, several hiking- and ski tracks in the area), but use of the lake for e.g. boating and fishing is limited by the access for boats (low summer water level). We suggest building a floating pier to improve access. The higher summer water level will also improve conditions, whereas the lowest winter level may impair landscape aesthetics in dry or high HP production years.

In conclusion, scenario 1 with the implemented mitigation and compensation measures will improve the environmental and recreational status for the Lake Juvatn significantly from the present status.

3.1.2 R5 the Logna reservoir

The Logna reservoir is presently regulated 0.7 m, with no environmental restrictions and it does not change in any of three scenarios. The LRV is 357 and HRV is 357.7, and the total volume is 1.4 4 Mm^3. It is presently classified as having a small impact from hydropower regulation. An environmental restriction is applied for the river stretch downstream Lake Logna (see section 3.10.). In the ProdRisk model the Logna reservoir is modelled using a guidance curve instead of an optimization strategy applied for the larger reservoirs. This is because it is a small reservoir and therefore if there are restrictions defined it is better to define them with a guidance curve rather than leaving the reservoir to be operated by the optimization curve. Therefore, it is not possible to estimate the hydrological changes for Logna from the model. While some changes are expected due to the new parallel hydropower plant to the existing Logna and Smeland hydropower plant under scenario 1, and due to the pumping operations under scenario 2, the changes are small because the low regulation height (0.7 m). No changes are expected under scenario 3.

In conclusion, no significant changes in environmental or recreational status is expected for this reservoir under any of the scenarios.

3.1.3 R7-8 The Nåvann-Skjerka reservoir

The Nåvann and Skjerka reservoirs have a total 37 m of regulation. There is an annual environmental restriction of minimum volume at 5.2%. Under scenario 1 a new hydropower plant is constructed, parallel to the existing Skjerka hydropower plant. No environmental restriction was implemented. The HP stations have the same head, but different flow capacities and turbine characteristics. In general, the simulation shows lower water level throughout winter and fall, and higher variations in maximum water level most of the year under scenario 1 than the present, but the differences are rather small. (Figure 4).

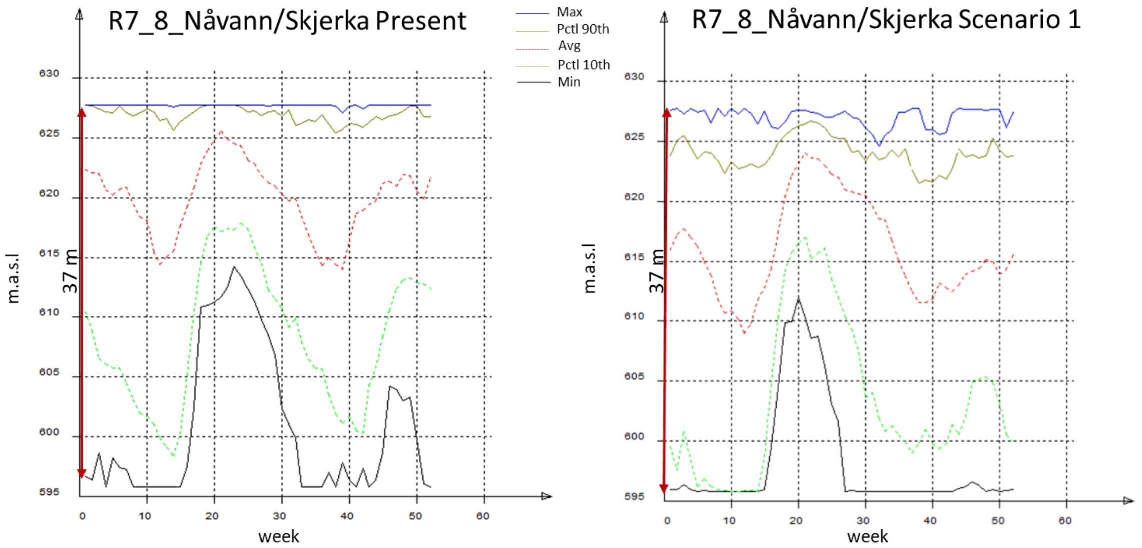


Figure 4. R7 & 8, Nåvann and Skjerka reservoir curves and meters of regulation.

The present ecological status of these reservoirs is classified as poor and under scenario 1 no improvements are expected based on hydrological changes. Indeed, the generally lower water level is likely negative for the ecosystem. Implementing mitigation through improvement of spawning conditions in the major inlet stream (Uvdalsåni) by adding spawning gravel and shell sand (to improve water chemistry) may significantly improve natural recruitment to the trout population.

The reservoir area is moderately important as a recreational area (some cabins and hiking tracks in the area) and use of the lake for e.g. boating and fishing is limited by the access for boats (low summer water level). We suggest building a floating pier to improve access. However, the lower summer water level will challenge such a solution. The lowest winter level may further reduce the landscape aesthetical value in dry or high HP production years.

In conclusion, scenario 1 with the implemented mitigation and compensation measures will at best maintain the present environmental conditions for the Nåvann-Skjerka reservoirs.

3.1.4 R9 The Ørevann reservoir

At present, the reservoir has 3.12 m of regulation, the LRV is 256.08 m.a.s.l and HRV is 259.20 m.a.s.l, and the volume is 11.2 Mill m3. There is an annual environmental restriction of 52.50% for minimum volume. Under scenario 1 a new hydropower plant is installed in parallel with the existing Haverstad and Bjelland Hydropower plants. The new hydropower plant installed in parallel to the upstream Skjerka hydropower plant will influence the inflow. There are no changes in the reservoir or environmental restrictions, under scenario 1.The simulations show that the major changes are much more variable water levels, both in terms of the 10 and 50 percentiles (Figure 5). At the same time, the mean is generally higher during summer and the 90 percentiles display reduced variability.

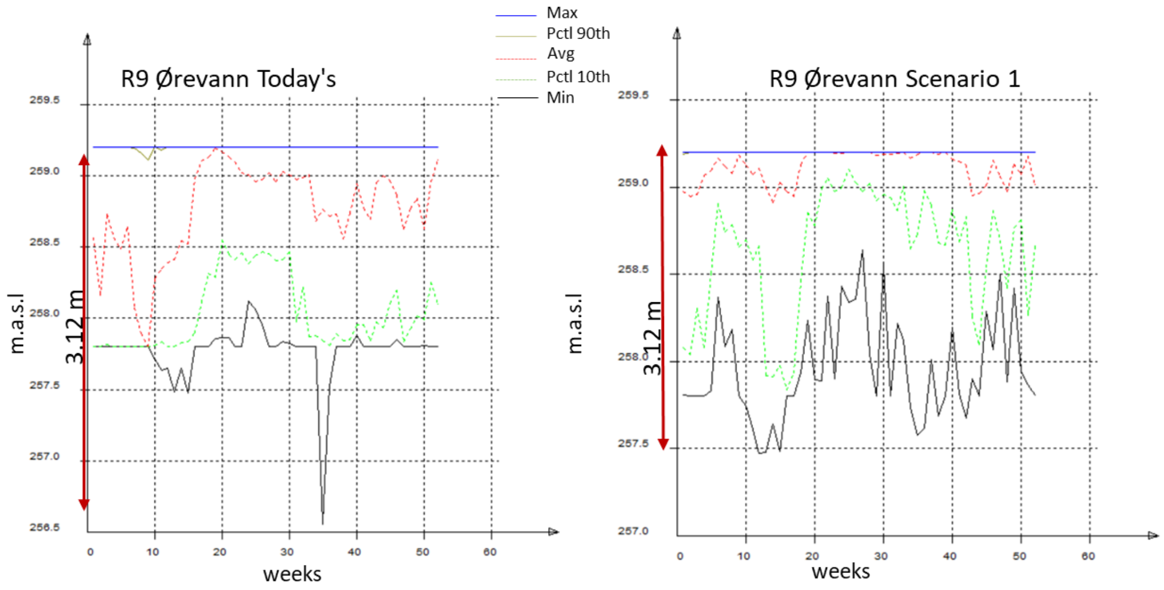


Figure 5. R9, Øravatn reservoir curve and meters of regulation for Present Situation and scenario 1.

At present the effects of HP regulation is classified as moderate and the ecological status as good. Indeed, the recruitment of trout is regarded too high for lake productivity, causing a high density of small bodied fish, generally regarded as unattractive for recreational fishing. Despite the elevated variability in water levels, the generally higher reservoir filling during most of the year indicates no or small changes in lake productivity. To improve average fish size, blocking admission to some of the spawning areas is suggested as a measure. Increased gillnetting or bag-netting may also help.

The recreational value has been classified as high, with a high density of cabins and hiking in nearby areas. If implemented the measures to reduce trout recruitment might increase the attractiveness of the recreational fishery.

In conclusion, if the mitigation measure to reduce trout recruitment is successful the ecological status will maintain at its present level and the recreational value will increase.

3.1.5 E1 The Langevann to Monn river stretch

The river stretch E1 between the Langevann reservoir and Monn intake (which is part of Smeland power plant system) is considered as a residual flow or bypass stretch. It is affected by several HP intakes, starting from Langevann reservoir and continuing with intakes along the tributaries. There are no minimum flow requirements. Under scenario 1, there are generally small changes in the hydrological indices in comparison with the present situation, except for a 10% reduction in annual mean flow, due to higher HP capacity and the changes in prices in future markets.

At present the river stretch is strongly impacted by severe low water bottlenecks with close to zero flows (Table 2). Without mitigation measures the low water bottlenecks will remain and the mean flow will be reduced causing even poorer ecological status than currently assumed. Suggested mitigation minimum flow stipulations at 0.4 m^3/s during summer and 0.2 m^3/s during winter will strongly improve ecological conditions.

The recreational status of this river stretch is unknown.

In conclusion, under scenario 1 improved ecological status can only be obtained by implementing a minimum flow stipulation. As modelled (without minimum flow), strong negative environmental effects of HP will remain and be somewhat strengthened.

Table 2. Hydrological indices for E1 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 1 (right). Note that flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	2.25	-87.66
Q95	1.02	0.00	-100.00
Summer low flow	1.91	0.00	-100.00
Winter low flow	0.89	0.00	-100.00
Annual mean flood	171.84	57.88	-66.31
Ten-year flood	244.1	97.87	-59.90

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	0.38	-97.93
Q95	1.02	0.00	-100.00
Summer low flow	1.91	0.00	-100.00
Winter low flow	0.89	0.00	-100.00
Annual mean flood	171.84	54.91	-68.04
Ten-year flood	244.1	90.65	-62.86

3.1.6 E2 The River Logna (Juvatnet-Lognevatnet stretch)

The river stretch between the Juvatn reservoir and Logna (E2) is characterized as a residual flow stretch or bypass section where water from Lake Juvatn goes through the intake to the turbines and is released downstream. Presently, there is no minimum flow required in this stretch, but the HP company voluntarily release a residual flow in this stretch that varies from 0.009 m^3/s to 0.013 m^3/s, depending on the reservoir volume. This is not included in the model for present situation. Under scenario 1, an environmental flow was implemented, with 0.3 m^3/s discharge during winter and 0.6 m^3/s during summer.

Under the present situation, the river stretch is considered to have severe hydrological bottleneck because of the very low winter and summer 7-day minimum flow after regulation. Under scenario 1, there is a decrease in the annual mean and flood values, but a significant increase in the minimum summer and wither flow (Table 3). The latter reduces the strength of the bottlenecks from severe to nearly moderate. This change will probably improve ecological conditions significantly. Results under scenario 1 shown a summer minimum flow 0.3 m^3/s instead of 0.6 m^3/s. This is because in some circumstances it might be not possible to release 0.6 m^3/s during summer and the model choose to release 0.3 m^3/s instead.

The recreational status is unknown, but the landscape appeared as attractive during a field visit.

In conclusion, the ecological and recreational status is expected to improve significantly under scenario 1, given the implemented environmental flow discharges.

Table 3. Hydrological indices for E2 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 1 (right). Note that flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.33	-96.61
Q95	0.92	0.29	-68.00
Summer low flow	0.89	0.29	-67.42
Winter low flow	0.82	0.30	-63.41
Annual mean flood	102.4	5.01	-95.11
Ten-year flood	148.1	15.46	-89.56

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.73	-92.58
Q95	0.92	0.00	-100.00
Summer low flow	0.89	0.00	-100.00
Winter low flow	0.82	0.00	-100.00
Annual mean flood	102.4	21.50	-79.00
Ten-year flood	148.1	51.96	-64.91

3.1.7 E10 The Tungesjø-Kavfossen river stretch

The E10 river stretch is regulated by the Bjelland HP plant, and is affected by water going into the intake from the Tungesjø reservoir. This river stretch is characterized as a bypass section. The lowermost part of the stretch is the Kavfossen waterfall, representing the natural migratory upper barrier for anadromous salmonids in the River Mandalselva. Here, the unregulated tributary Kosåna flows into Mandalselva. Under scenario 1, there is an implemented minimum flow stipulation at 1.3 m3/s during October-April and 6 m3/s during May-September. Moreover, a fishway is implemented, increasing the anadromous stretch of the River Mandalselva with 2.9 km.

At present this river stretch is completely dry for long periods both during winter and summer, because water is spilled only during floods and during very low flow conditions in the downstream anadromous river stretch. While the simulations under scenario 1 (Table 4) shows reduced mean flows, this is indeed an effect of reduced flood flows and the major effect is that this stretch will now have water flow throughout the year and a functioning aquatic ecosystem can be re-established. Moreover, the implemented flow releases will positively affect the upper part of the current anadromous stretch, from Kavfossen to the outlet of the Bjelland HP station at Monan. The improvement in ecological status is thus regarded as substantial.

The recreational potential was classified as high under current conditions, both for local inhabitants and tourist passing on the road alongside the river. The minimum flow stipulation and establishment of a migration pathway for anadromous fish will likely improve the recreational value, particularly because both the current stretch and the downstream river stretch will become attractive for salmon sport fishery.

In conclusion, under scenario 1 and the implemented compensation measure, both the environmental and recreational status will improve substantially.

Table 4. Hydrological indices for E10 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 1 (right). Note that flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	7.20	-89.76
Q95	8.76	0.00	-100.00
Summer low flow	8.9	0.00	-100.00
Winter low flow	7.66	0.00	-100.00
Annual mean flood	619.4	166.90	-73.05
Ten-year flood	888	305.57	-65.59

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	3.77	-94.64
Q95	8.76	1.19	-86.42
Summer low flow	8.9	1.47	-83.48
Winter low flow	7.66	1.20	-84.31
Annual mean flood	619.4	39.96	-93.55
Ten-year flood	888	100.72	-88.66

3.1.8 E14 Downstream the Laudal Power plant (representing the anadromous stretch below Bjelland outlet)

The hydrological changes in this river section is presented as a representation of the average changes in the whole of the anadromous stretch of the River Mandalselva below the outlet of the Bjelland HP station. Under scenario 1 the simulations show relatively small changes (Table 5) and no new hydrological bottlenecks because the minimum flow in summer and winter are higher than before regulation. However, it is also important to consider the possible effects from hydropeaking. Environmental restrictions should include ramping rates at the Bjelland and Laudal HP stations at maximum 10 cm/h at total flows lower that 30 m^3/s (when stranding mortality is expected for fish), minor early summer environmental restrictions at flows between 30 and 60 $m^{3/}s$, whereas no environmental restrictions is needed at flows higher than 60 m^3/s.

Given that the environmental restrictions on hydropeaking are implemented, no negative environmental effects are expected in the anadromous stretch below the outlet of the Bjelland HP. The expected increased salmonid production in the upper parts (see E10) is expected to improve the salmonid fishing and thus the recreational value.

Table 5. Hydrological indices for E14 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 1 (right).

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	76.29	80.29	5.24
Q95	9.35	27.49	194.16
Summer low flow	9.65	33.10	242.95
Winter low flow	8.73	34.72	297.56
Annual mean flood	660.50	364.00	-44.89
Ten-year flood	948.20	549.13	-42.09

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	76.29	52.37	-31.36
Q95	9.35	26.16	179.90
Summer low flow	9.65	28.43	194.52
Winter low flow	8.73	28.36	224.79
Annual mean flood	660.50	274.83	-58.39
Ten-year flood	948.20	393.29	-58.52

3.1.9 The total environmental and recreational effects under scenario 1.

The effects on the ecological and recreational values varies among the assessed water bodies (Table 6). With the implemented mitigation or compensation measures the total effect is classifies as weak positive, but if additional measures are implemented the total effects is classified as positive.

Table 6. The expected environmental and recreational effects under scenario 1 scored from very negative (---), via no effects (0) to very positive (+++) for each of the assessed water bodies and the total effects. The first two column is based on the simulated mitigation measures, whereas the latter two tabulates the effects after other suggested mitigation or compensation measures are implemented. Signs in brackets indicate particularly uncertain effects. UE indicate unknown effects.

Waterbody	**Environmental effects**	**Recreational effects**	**Environmental effects including environmental projects**	**Recreational effects including environmental projects**
R2 Juvatn	++	+	++	+
R5 Logna	0	0	0	0
R7-8 Nåvann/Skjerka	-	-	0	0
R9 Ørevann	0	0	+	+
EI Langvann-Monn	-	UE	+	UE
E2 Logna	++	+	++	+
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0(+)	+	0(+)	+
TOTAL EFFECT	**+**	**+**	**++**	**++**

3.2 Scenario 2: Maximum Flexibility

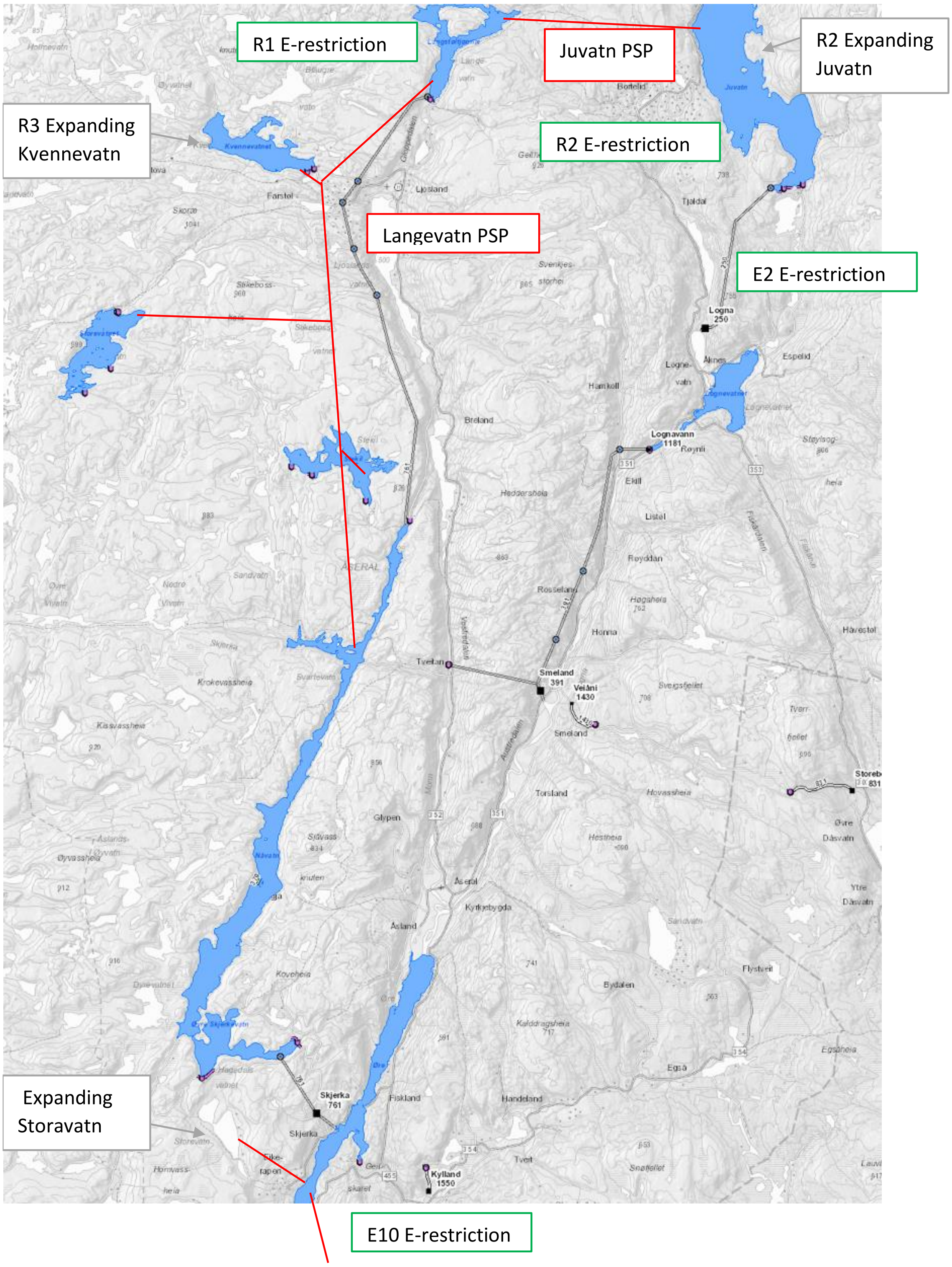


Figure 6. Map illustrating Scenario 2 in Mandalselva (maximum flexibility), the river stretches affected (E1, E2, T4, E10) and reservoirs (R1: Langevann, R2: Juvatn, , R3 Kvannevann, R4 Storevann, R6 Stekil, R7_8: Skjerka, and R9 Ørevatn).

The maximum flexibility scenario involves extensive pump storage systems. The knowledge on the environmental effects of pumping is very limited (Harby et al. 2013, Hirsch et al. 2017, Charmasson et al. 2018), making it difficult to predict environmental effects under this scenario. Pumping may involve changes in temperature, lake circulation patterns, ice-cover, water chemistry, erosion and turbidity which in turn will change the living conditions for aquatic organisms (e.g. Charmasson et al. 2018). Moreover, several organisms are likely to be moved between reservoirs with the pumped water. For fish, we assume that protection systems are installed and that only the smallest fish enters the turbines.

3.2.1 The R1 Langevann, R3 Kvannevann, R4 Storevann & R6 Stekil reservoirs

Under scenario 2 a new pumped storage plant is planned pumping from R7 Nåvatn reservoir to four upper reservoirs: R1 Langevann, R3 Kvennevatn, R4 Storevan and R6 Stekil (Figure 7). In order to model the production under this scenario, the four reservoirs were merged into one single reservoir in the ProdRisk model. However, the four reservoirs will operate individually, with the R4 Storevann reservoir as the first to be pumped due to its highest elevation. In addition to the new pumped storage plant, the Kvannevann (R3) reservoir is expanded by construction of a new dam increasing the HRV by 9 m. The regulation height of the other three reservoirs remain the same as under the present situation.

The technical merging of the four reservoirs in the ProdRisk model limits our ability to describe the hydrological changes and infer on environmental effects. This adds to the generally poor knowledge on the effects of pumping *per se* (Charmasson et al. 2018). In figure 11 we compare the present reservoir curve for R1 Langevann with the merged R1, 3, 4 & 6 reservoirs. The major changes are generally higher water level but increased variation, both in the short term and among years. A similar pattern can be seen for the Juvatn reservoir, individually modelled in ProdRisk (se 3.2.2). We assume that that higher water level and increased frequency but reduced amplitudes for variation in level are a general pattern for the four reservoirs.

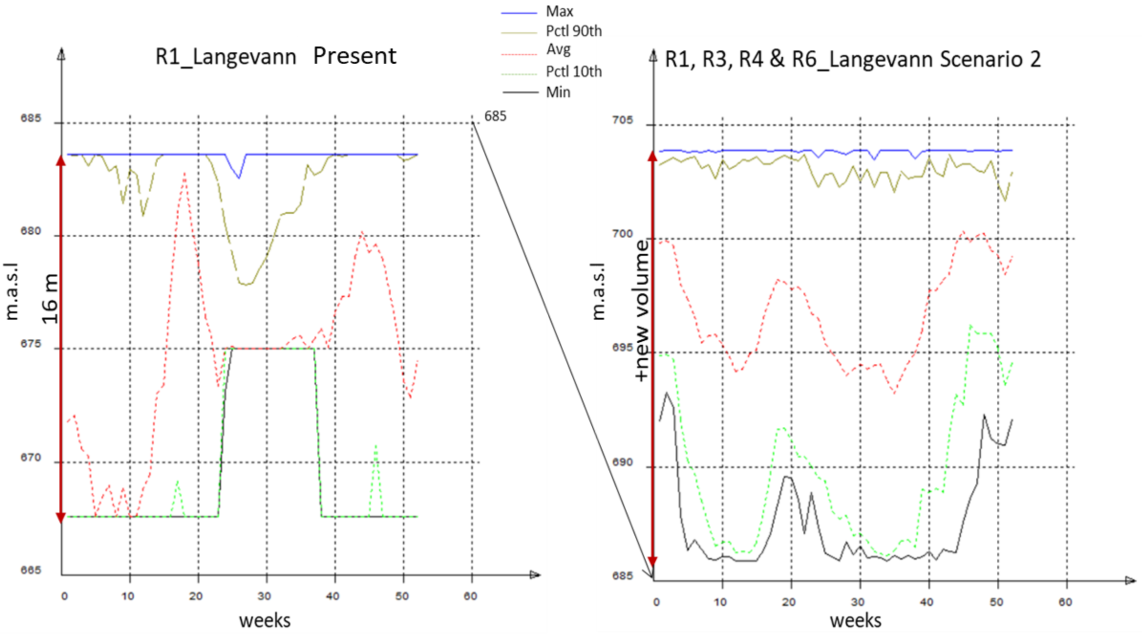


Figure 7. R1 Langevann reservoir curve under Present situation (left) and under scenario 2 (right).

For the Langevann reservoir (R1) in the scenario 2 the environmental restriction during summer of maintaining a minimum volume of 29% and an environmental flow release of 0.4 m^3/s during summer and 0.2 m^3/s during winter were implemented. The reservoir is classified as large impacted by hydropower regulation under present situation. The generally higher water level is regarded as positive both for the environment and for recreational use, but this is challenged by higher variability and other effects of pumping, particularly in terms of ecosystem effects. It is more likely that the environmental effects are negative than positive. Implementing an additional mitigation measure by construction of cell-weir structures with a migration corridor in the inlet rivers will improve natural recruitment of brown trout. However, as natural recruitment is likely no major present bottleneck today, the effects are likely small. The Langevann reservoir has a high recreational value (with cabins and important hiking tracks) and during summer a generally higher water level may be positive in terms of landscape aesthetics and variability may not be regarded as very negative. The most likely effect on recreation is thus neutral.

The Kvennevann reservoir (R3) had 25.8 m of regulation under present situation. Under scenario 2, the reservoir is expanded adding a new volume of 50 Mm^3, and a construction of a new higher dam, increasing the HRV from 771 m.a.s.l. to 780 m.a.s.l. For this expanded reservoir, effects have to be evaluated in terms of a larger regulation zone and more frequent variation in water level, but also likely a generally higher water level and reduced amplitude of variation. A recent analyses of brown trout productivity in Norwegian reservoirs did not, in contrast to previous assumptions, find any relationship between trout abundance and regulation height (Eloranta et al. 2018). At present, the reservoir is classified as strongly impacted. It is this more likely that the environmental effects under scenario 2 are negative than positive, particularly due to potential negative effects of pumping. Rather, productivity depended on other local conditions. Thus, increased regulation height may not override positive effects of generally higher water levels. Moreover, this reservoir presently has no or very low natural recruitment of brown trout and depend on hatchery fish releases. If the suggested measures of securing access to the two potential spawning streams are implemented construction of cell-weir structures with migration corridors, natural recruitment can be re-established and fish releases terminated. The Langevann reservoir has a high recreational value (with large cabin areas nearby and several hiking tracks) and during summer a generally higher water level may be positive in terms of landscape aesthetics and variability may not be regarded as very negative. Naturally recruited trout may be more attractive for recreational fisheries. However, the higher dam will become a more dominant part of the landscape, and the 9 m higher maximum water level may influence recreational activities. The most likely effect on recreation is thus negative.

Presently, the Storevann reservoir (R4) is regulated 6 m and has no environmental restriction. Under scenario 2, the reservoir will not be modified and there are no environmental restrictions implemented. Under scenario 2 the reservoir is operated both in production and pumping mode. Since it is the highest reservoir in the pumping regime, it is expected to experience high variability of water levels in the reservoir. From memo 6 results show that the plant will be producing and pumping approximately the same number of hours during a year. At present, the reservoir is moderately impacted by HP. The extensive shifts in pumping and production in a reservoir with only 6 m of regulation height would likely cause very frequent changes in water level between the minimum and maximum. The potential negative effects of the pump storage plants will likely be strong, with potentially particular strong effects on erosion and turbidity, causing reduced productivity. The current environmental status is poor, and the environmental effects under scenario 2 is likely to be strongly negative. However, this reservoir presently has no or very low natural recruitment of brown trout and depend on hatchery fish releases (but the quality of the fish caught is regarded as high). If the suggested measure of securing access to one of the potential spawning streams is implemented by construction of cell-weir structures with migration corridors, natural recruitment can be re-established, and fish releases terminated. Fish growth may however be challenges by low and reduced productivity. Even after mitigation the effect is thus likely negative. The recreational value of the Storevann reservoir is moderate, with rather low activity. On the other hand, the lake is rather remote and pristine-like. The strong variation is likely to challenge the recreational value of the reservoir and its immediate surroundings and the effects are classified as negative. Reestablishment of natural recruited brown trout may increase recreational fisheries.

In Stekil (R6), the moderate elevation and small volume likely imply that this reservoir will be the least used in the pumping-production regime. However, Stekil is the reservoir that is closest to Nåvatn, and pumping to this reservoir will thus have the lowest friction losses. Under the present situation it is classified as having large impact from HP. A generally higher water level (the lowest can be actively avoided by pumping) may improve conditions somewhat, but without additional measures the likely effect under scenario 2 is neutral. However, this reservoir presently has very low natural recruitment of brown trout and depend on hatchery fish releases If the suggested measures of securing access to two potential spawning streams are implemented by construction of cell-weir structures with migration corridors, natural recruitment can be re-established and fish releases terminated. If so, positive effects under the scenario is expected. The recreation value is moderate, due to limited access and low activity. However, it is a rather pristine area. No changes is expected under scenario 2, and naturally recruited brown trout may increase the value recreational fisheries.

In conclusion, for Langevann (R1) , Kvennevann (R3) and Storevann (R4) it is likely that the environmental impacts of scenario 2 are negative. For Stekil (R6), the environmental impact of scenario 2 may be neutral to positive, depending on success of mitigation measures. Recreation is expected to be neutrally impacted in R1 and R6, however for R3 and R4 the effect on recreation is likely negative.

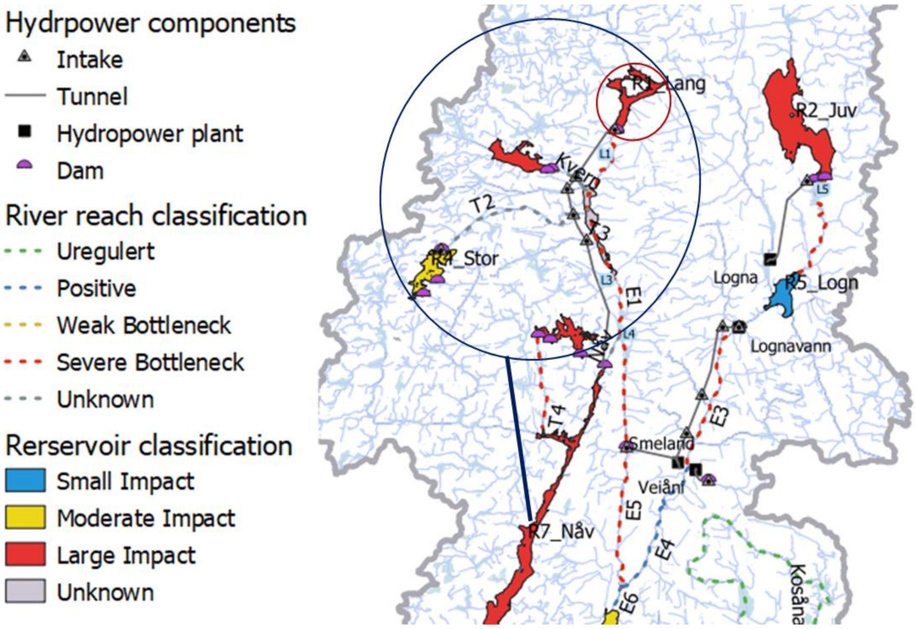


Figure 8. Hydrological classification for R1 in Present situation, Langevann (red circle), merged reservoirs included (blue circle) pumped connected with R7-8 Nåvann-Skjerka (blue line).

3.2.2 R2 The Juvatn reservoir

The Juvatn reservoir it is also expected to be impacted under scenario 2 (Maximum Flexibility) by a new pumped plant pumping from Juvann reservoir to the Langevann reservoir. Since the ProdRisk model Langevann reservoir also include the other three reservoirs, the model is set to pump from Juvatn to the merged Langevann. Scenario 2 also includes an expansion of the reservoir by including a new and higher dam, adding a new volume of 380 Mm^3 and more than doubling of the regulation height. Environmental restriction for the 6% volume during the year and the new environmental restriction for October with a minimum of 510 m.a.s.l. are implemented (Figure 9).

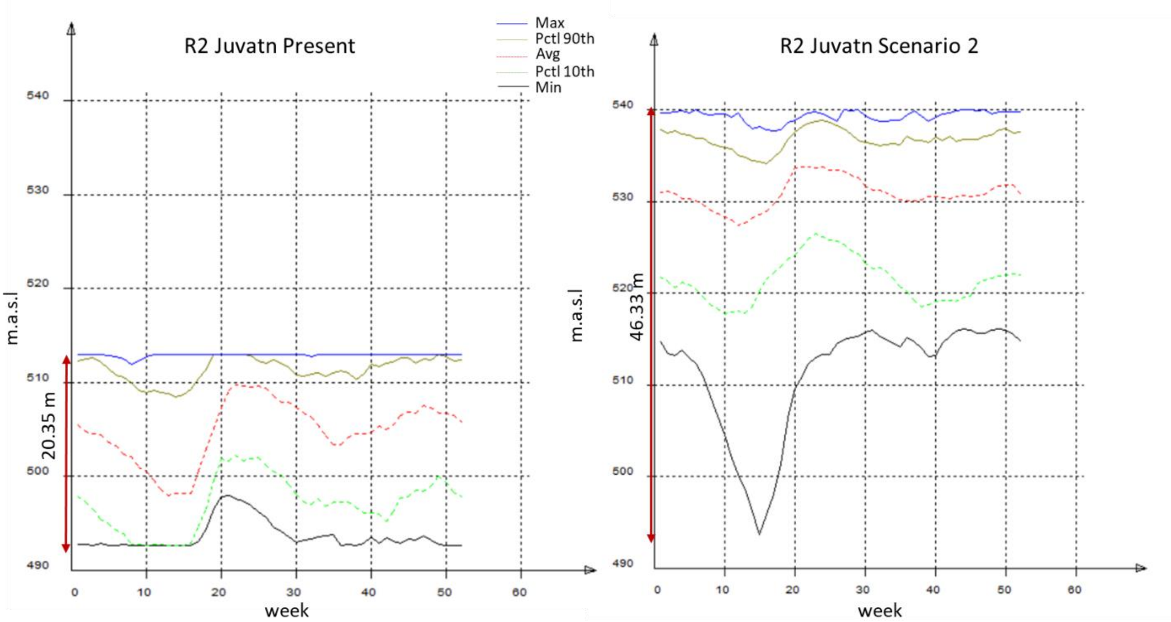


Figure 9. R2, Juvatn reservoir curve under Present situation (left) and under scenario 2 (right).

The results show that minimum water level under scenario 2 are higher than in the present situation, and that the increased regulation height is very rarely exploited. Moreover, the 10 % percentile varies around 20 m below the maximum (60% filling). Indeed, the reservoir is typically more than half full during most of the year in most years, and on average the water level is within 10 m of the maximum (90% filling) throughout most of a year. During large parts of the year the average relative filling was lower than that in the present scenario. Annual variability is higher under scenario 2 based on the spread between the percentiles, and the variability among years is particularly high early in the year. The maximum water level also shows higher interannual variability compared with the present condition.

In the present situation the Juvatn reservoir is hydrologically classified as strongly impacted by HP. While the regulation height is more than doubled (from 20.35 to 50 m) under scenario 2, the typical regulation amplitude is smaller than the present, relative to total regulation height and indeed relatively similar also in absolute numbers. Given that regulation height is not a good predictor for ecological status (as indicated for brown trout abundance by Eloranta et al. 2018), we believe the generally higher water level during most year will be environmentally favourable. At present the natural recruitment of brown trout is low and the filling restriction implemented during October in scenario 2 is likely to improve access to inlet spawning streams and thus increase natural recruitment. The total environmental effects are thus predicted to be weak positive. Given that additional physical measures are implemented, by construction of cell weir structures with a migration corridor in the inlet stream, the positive effect will increase. We furthermore suggest that an additional reservoir restriction on minimum filling during winter (not implemented in the modelling) that prevent the rare occurrence of very low water level in April, would improve the general ecological status in the reservoir.

The Lake Juvatn is an important recreational area (high density of cabins, several hiking- and ski tracks in the area) but use of the lake for e.g. boating and fishing is limited by the access for boats (low summer water level). It is very difficult to predict how the new higher dam and higher regulation will affect recreational use. The present dam is actually regarded as a tourist attraction (due to the view from the top), but a higher dam will be a more dominant part of the landscape. Whereas the lowest winter level may impair landscape aesthetics in dry or high HP production years, the regulation zone during summer (ca. 10 m) will be approximately the same as in the present situation, and boat access will remain a challenge. We assume that the effects on recreational use will be neutral. Additional measures by bulling a floating pier to improve boat access may significantly improve recreational status.

In conclusion, scenario 2 may have a weak positive impact on environmental conditions for brown trout and the impact on recreation will likely be neutral.

3.2.3 R5 The Logna reservoir

The Logna reservoir is presently regulated 0.70 m (357-357.7 m.a.s.l.), the total volume is 1.4 Mm^3 and there are no environmental restrictions. It is classified as having small impacted from hydropower regulation. Environmental restriction is applied for the river stretch below Logna, see section 3.10. In the model ProdRisk the reservoir is modelled using a guidance curve, instead of an operational strategy curve which larger reservoirs will typically do. In this case, it is not possible to extract the reservoir curve from the model. However, there are expected water level changes since it is affected by a hydropower plant constructed in parallel to the existing Logna and Smeland hydropower plants and in addition, changes are also expected from the pumping operation.

In conclusion, it is not possible to assess environmental and recreational effects for R5 since we lack hydrological scenario data

3.2.4 R7-8 The Nåvann-Skjerka reservoirs

Under scenario 2, new pumped storage plants are constructed both upstream and downstream of the reservoir. Further, the Lake Storavatn is impounded into a reservoir and connected to the Skjerkevann reservoir by building a new large dam. Since the two reservoirs are connected, allowing water to flow between, the two reservoirs are merged into one large reservoir in the model. The storage volume is higher with an additional volume of 280 Mm^3, and the regulation height increased from the present at 37 m to 87 m. The annual environmental restriction of 5.2% is implemented both under present situation and scenario 2. The results show that under scenario 2, the seasonal curve is much flatter, with a higher annual variability based on the different between the lowest and the maximum percentile (Figure 10).

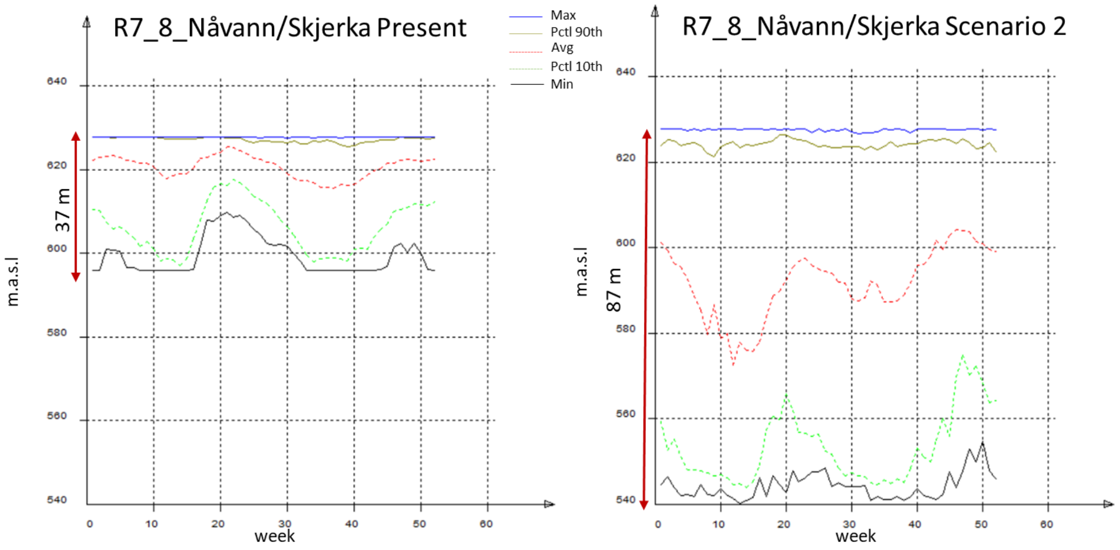


Figure 10. R7&8, Nåvann and Skjerka reservoir curves and meters of regulation

Presently, Nåvann-Skjerka reservoirs are hydrologically classified as highly impacted by HP regulation. Due to the large capacity and high head in the three scenario 2 hydropower stations the large regulation height of the new reservoir is heavily exploited with both the simulated maximum and minimum and 10 and 90 percentiles close to their respective limits. The average water level (to the extent that is relevant) fluctuates around half filling throughout the year, 20-30 m below the maximum. Adding to this among year variability the short-term variation is likely to be large. A very high regulation height, new dammed areas and high exploitation of the regulation volume is likely to be detrimental to the ecosystem and very large negative environmental effects are expected. The natural recruitment of brown trout is presently low, in large part due du acidification of the main spawning tributary. Mitigation by adding shell sand (or other types of liming) in the tributary will improve recruitment, but the trout population may be challenged by the feeding conditions in the strongly fluctuating reservoir.

The present reservoir area is moderately important as a recreational area (some cabins and hiking tracks in the area) and use of the lake for e.g. boating and fishing is limited by the access for boats (low summer water level). It is likely that the present rather large regulation height is negatively affecting the attractiveness of the surroundings and a low density of medium sized brown trout is not very attractive for recreational fishers. The Lake Storavatn, to be included in the new reservoir under scenario 2, is situated close to an important ski resort and a skiing track passes around. The recreational value is high. The almost 100 m high dam will dominate the landscape and significantly reduce the recreational value of the area. In summary, under scenario 2 the recreational effects will be strongly negative. The mitigation measures suggested (improving natural recruitment of brown trout through liming of tributary and improving boat access by building floating piers) are unlikely to reduce negative effects significantly.

In conclusion, scenario 2 will have a strongly negative environmental impact on R7 and R8. The impact on recreation is also regarded to be strongly negative.

3.2.5 R9 The Ørevatn reservoir

The Ørevatn reservoir is impacted under scenario 2 by two new pumped storage plants that are connected to Storavatn. The first pumps water from the downstream River Kosåna (or actually from the River Mandalselva further downstream) to the reservoir, whereas the second pumps from the reservoir to new Storavatn reservoir. The annual environmental restriction is the same as in present situation, with a 52% as minimum reservoir volume. Results show higher variability in water level changes through the year and lowest minimum water level values (Figure 11).

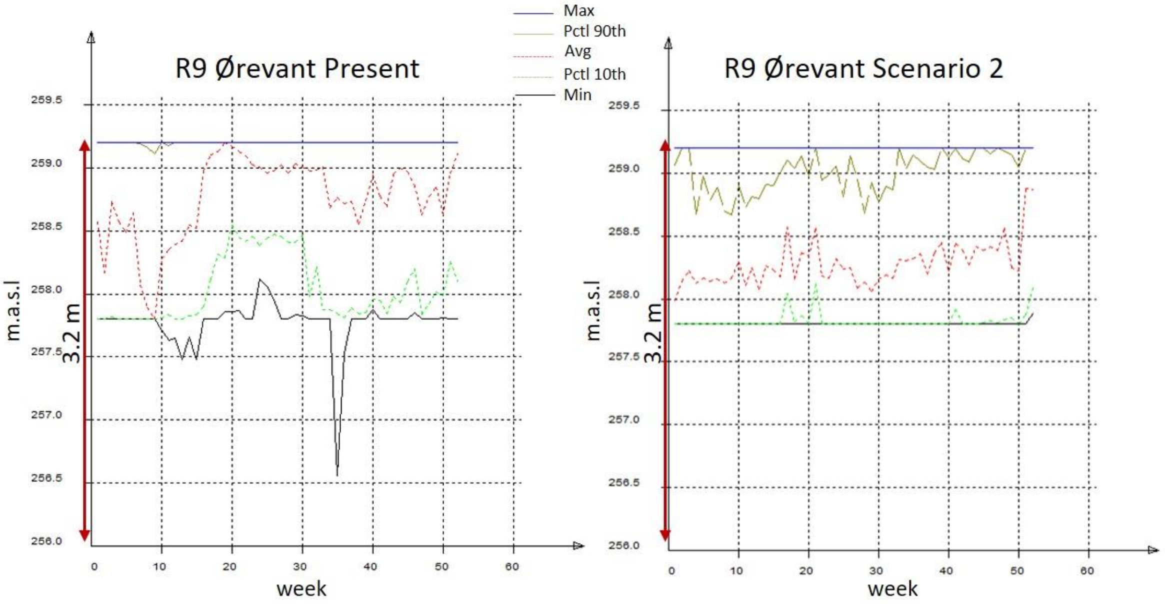


Figure 11. R9, Ørevatn reservoir curve and meters of regulation for Present Situation and scenario 2.

The regulation height of the Ørevatn reservoir is small (3.2 m) and the restriction limits water level variation even more. The ecological status is classified as good, with little impact from HP. However, the average water level is lower in the scenario 2.

3.2.6 E1 Langevann-Monn river stretch

Under scenario 2, the river stretch E1 remain a bypass section with a residual flow and it is affected by the pumping system. Presently, this river stretch is classified as having severe bottlenecks (

left). Under scenario 2, environmental restrictions are implemented, 0.4 m^3/s from May to September and 0.2 m^3/s from October to April, as can be seen in the summer and winter low flow indices (

right). The annual mean flow is reduced under scenario 2, this could be result of the higher capacity in the system, the 2030 scale price and the environmental restrictions applied in the system.

Under present situation, the river stretch is classified as having severe bottleneck. Despite the environmental restrictions implemented under scenario 2, the river stretch remains classified as having severe bottleneck due to the initial high reduction in summer and winter low flows after regulation. However, improved hydrological conditions are expected after the release of the minimum flow.

The recreational status of this river stretch is unknown, thus the impact of scenario 2 is therefore not accessed.

Table 7. Hydrological indices for E1 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 2 (right). Note that flow might be slightly higher than 0 but still con-sider extremely low. Output from the model is 0

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	2.25	-87.66
Q95	1.02	0.00	-100.00
Summer low flow	1.91	0.00	-100.00
Winter low flow	0.89	0.00	-100.00
Annual mean flood	171.84	57.88	-66.31
Ten-year flood	244.1	97.87	-59.90

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	0.28	-98.46
Q95	1.02	0.2	-80.39
Summer low flow	1.91	0.4	-79.06
Winter low flow	0.89	0.2	-77.53
Annual mean flood	171.84	NA	NA
Ten-year flood	244.1	NA	NA

3.2.7 E2 Logna (Juvatnet-Lognevatnet) river stretch

The river stretch E2 remains a bypass or residual flow river stretch, and the same environmental restrictions as in scenario 1 are implemented with a minimum flow of 0.3 m^3/s released during winter and 0.6 m3/s during summer. Results show an increase in the minimum flow values under scenario 2, (Table 8). Under the present scenario, it is classified as having severe hydrological bottleneck and under scenario 2, the hydrological bottleneck is closer to moderate, thanks to the minimum flow released.

The recreational status is unknown, but the landscape appeared as attractive during a field visit.

In conclusion, the ecological and recreational status is expected to improve significantly under scenario 2, given the implemented environmental flow discharges.

Table 8. Hydrological indices for E2 stretch for unregulated and regulated period and the percentage of change in % under Present situation (left) and Scenario 2 (right). Note that flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.73	-92.58
Q95	0.92	0.00	-100.00
Summer low flow	0.89	0.00	-100.00
Winter low flow	0.82	0.00	-100.00
Annual mean flood	102.4	21.50	-79.00
Ten-year flood	148.1	51.96	-64.91

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.39	-96.05
Q95	0.92	0.30	-67.39
Summer low flow	0.89	0.60	-32.58
Winter low flow	0.82	0.30	-63.41
Annual mean flood	102.4	17.61	-82.80
Ten-year flood	148.1	44.65	-69.85

3.2.8 T4 Uvdalsåni (Stekil-Nåvatn) river stretch

Results under scenario 2 cannot be obtained because Stekil reservoir was merged with three other reservoirs in the pumping operation model. Since there are no regulations applied, the classification under scenario 2 is expected to be the same as under the present situation, which is classified as having severe bottleneck (Table 9).

Table 9. Hydrological indices for T4 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 2 (not available because it is merged in the system). Note that flow might be slightly higher than 0 but still consider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	1.67	0.39	-76.65
Q95	0.24	0	-100.00
Summer low flow	0.13	0	-100.00
Winter low flow	0.18	0	-100.00
Annual mean flood	16.5	69.30449	320.03
Ten-year flood	23.6	117.4297	397.58

3.2.9 E10 Tungesjo-Kavfossen river stretch

The E10 river stretch is regulated by the Bjelland HP plant, and is affected by water going into the intake from the Tungesjø reservoir. This river stretch is characterized as a bypass section. The lowermost part of the stretch is the Kavfossen waterfall, representing the natural migratory upper barrier for anadromous salmonids in the River Mandalselva. Here, the unregulated tributary Kosåna flows into Mandalselva. Under scenario 2, there is an implemented minimum flow stipulation at 1.3 m^3/s during October-April and 6 m^3/s during May-September. Moreover, a fishway is implemented, increasing the anadromous stretch of the River Mandalselva with 2.9 km.

At present this river stretch is completely dry for long periods both during winter and summer, because water is spilled only during floods and during very low flow conditions in the downstream anadromous river stretch. While the simulations under scenario 1 (Table 10) shows reduced mean flows, this is indeed an effect of reduced flood flows and the major effect is that this stretch will now have water flow throughout the year and a functioning aquatic ecosystem can be re-established. Moreover, the implemented flow releases will positively affect the upper part of the current anadromous stretch, from Kavfossen to the outlet of the Bjelland HP station at Monan. The improvement in ecological status is thus regarded as substantial.

The recreational potential was classified as high under current conditions, both for local inhabitants and tourist passing on the road alongside the river. The minimum flow stipulation and establishment of a migration pathway for anadromous fish will likely improve the recreational value, particularly because both the current stretch and the downstream river stretch will become attractive for salmon sport fishery.

In conclusion, under scenario 2 and the implemented compensation measure, both the environmental and recreational status will improve substantially.

Table 10. Hydrological indices for E10 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 2 (right). Note that flow might be slightly higher than 0 but still con-sider extremely low. Output from the model is 0

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	7.20	-89.76
Q95	8.76	0.00	-100.00
Summer low flow	8.9	0.00	-100.00
Winter low flow	7.66	0.00	-100.00
Annual mean flood	619.4	166.90	-73.05
Ten-year flood	888	305.57	-65.59

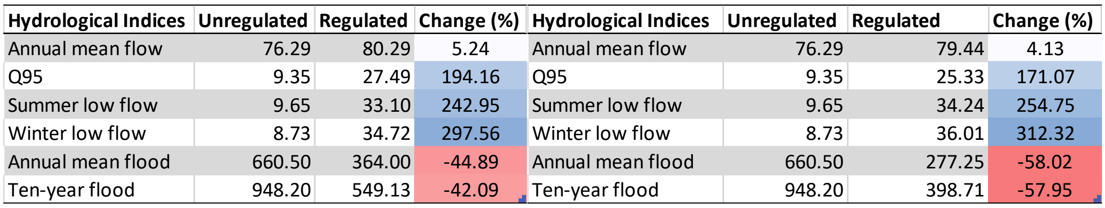
Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	3.97	-94.36
Q95	8.76	1.30	-85.16
Summer low flow	8.9	1.61	-81.91
Winter low flow	7.66	1.30	-83.03
Annual mean flood	619.4	35.81	-94.22
Ten-year flood	888	97.48	-89.02

3.2.10 E14 Downstream Laudal Power plant

The hydrological changes in this river section is presented as a representation of the average changes in the whole of the anadromous stretch of the River Mandalselva below the outlet of the Bjelland HP station. Under scenario 2 the simulations show relatively small changes (Table 11) and no new hydrological bottlenecks because the minimum flow in summer and winter are higher than before regulation. However, it is also important to consider the possible effects from hydropeaking. Environmental restrictions should include ramping rates at the Bjelland and Laudal HP stations at maximum 10 cm/h at total flows lower that 30 m^3/s (when stranding mortality is expected for fish), minor early summer environmental restrictions at flows between 30 and 60 m^3/s, whereas no environmental restrictions is needed at flows higher than 60 m^3/s.

Given that the environmental restrictions on hydropeaking are implemented, no negative environmental effects are expected in the anadromous stretch below the outlet of the Bjelland HP. The expected increased salmonid production in the upper parts (see E10) is expected to improve the salmonid fishing and thus the recreational value.

Table 11 Hydrological indices for E14 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 2 (right).



Hydrological Indices	Unregulated	Regulated	Change (%)	Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	76.29	80.29	5.24	Annual mean flow	76.29	79.44	4.13
Q95	9.35	27.49	194.16	Q95	9.35	25.33	171.07
Summer low flow	9.65	33.10	242.95	Summer low flow	9.65	34.24	254.75
Winter low flow	8.73	34.72	297.56	Winter low flow	8.73	36.01	312.32
Annual mean flood	660.50	364.00	-44.89	Annual mean flood	660.50	277.25	-58.02
Ten-year flood	948.20	549.13	-42.09	Ten-year flood	948.20	398.71	-57.95

3.2.11 The total environmental and recreational effects under scenario 2

The effects on the ecological and recreational values varies among the assessed water bodies (Table 12), from strong negative to strong positive effects. Strong negative environmental and recreational effects are found for the new Nåvann-Skjerka-Storavatn reservoirs, whereas the Tungefoss-Kavfossen river stretch has the only strong positive effects (present in all the scenarios). With the implemented mitigation or compensation measures the total effect is classifies as weak negative both for the environment and recreation, but if additional measures are implemented the total effects is classified as slightly positive for the environment and neutral for recreation (the new dam represents a major intervention in an attractive area).

Table 12. The expected environmental and recreational effects under scenario 2 scored from very negative (---), via no effects (0) to very positive (+++) for each of the assessed water bodies and the total effects. The first two column is based only on the simulated mitigation measures, whereas the latter two tabulates the total effects after other all the suggested mitigation or compensation measures are implemented. Signs in brackets indicate particularly uncertain effects. UE indicate unknown effects.

Waterbody	**Environmental effects**	**Recreational effects**	**Environmental effects including environmental projects**	**Recreational effects including environmental projects**
R1 Langevann	(-)	0	0	0
R2 Juvatn	+	0	++	(+)
R3 Kvennevann	(-)	-	+	-
R4 Storevann	---	--	-	-
R5 Logna	UE	UE	UE	UE
R6 Stekil	0	0	+	(+)
R7-8 Nåvann/Skjerka	---	---	---	---
R9 Ørevann	0	0	0	+
EI Langvann-Monn	-	UE	+	UE
E2 Logna	++	+	++	+
T4 Uvdalsåni (river stretch	0	0	0	0
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0(+)	+	0(+)	+
TOTAL EFFECT	**-**	**-**	**++**	**++**

3.3 Scenario 3: Flood protection

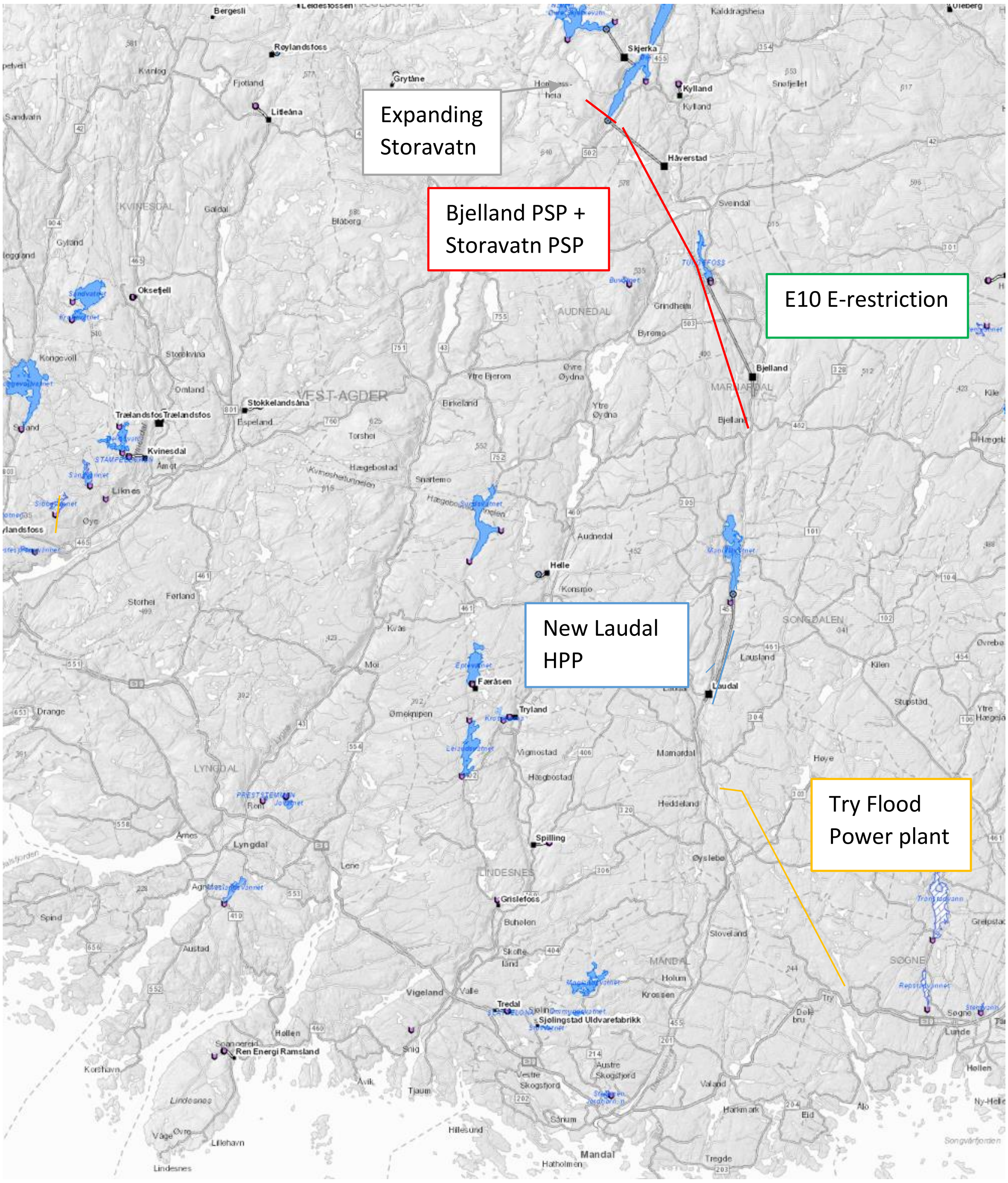


Figure 12. Map illustrating Scenario 3 in Mandalselva (flood protection) and the affected river stretches (E10, E14) and reservoirs (R7_8: Skjerka, R9 Ørevatn).

3.3.1 The R7-8 Nåvann-Skjerka reservoir

Under scenario 3, a new pumped storage plant in constructed downstream the reservoir, pumping from the Ørevatn reservoir. Further, the Lake Storavatn is impounded into a reservoir and connected to the Skjerkevann reservoir by building a new large dam. Since the two reservoirs are connected, allowing water to flow between, the two reservoirs are merged into one large reservoir in the model. The storage volume is higher with an additional volume of 280 Mm^3, and the regulation height increased from the present at 37 m to 87 m. The annual environmental restriction of 5.2% is implemented both under present situation and scenario 3. The results show that during scenario 3, there is higher variability in the annual regulation and higher fluctuation in the minimum water level values (Figure 13).

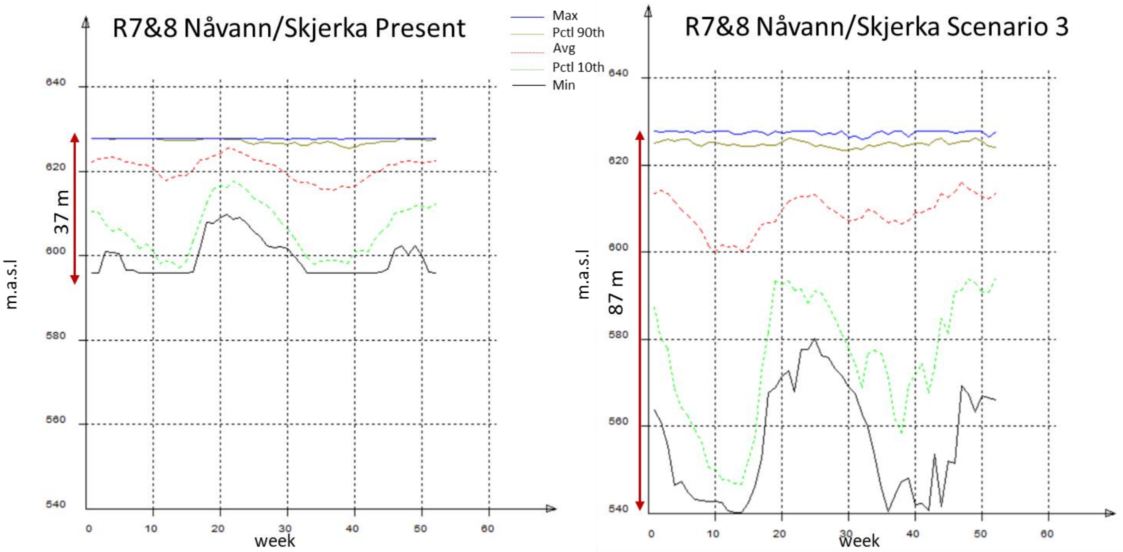


Figure 13. R7&8, Nåvann and Skjerka reservoir curves and meters of regulation under scenario 3.

Presently, Nåvann-Skjerka reservoirs are hydrologically classified as highly impacted by HP regulation. Due to the large capacity and high head in the existing and new hydropower stations the large regulation height of the new reservoir is heavily exploited during parts of the year (spring and autumn) with both the simulated maximum and minimum and 10 and 90 percentiles close to the their respective limits. The average water level (to the extent that is relevant) fluctuates around ¾ th filling throughout the year, 15-25 m below the maximum. Adding to this among year variability, the short-term variation is likely to be large. A very high regulation height, new dammed areas and high exploitation of the regulation volume during both spring an autumn are likely to be detrimental to the ecosystem and very large negative environmental effects are expected. The natural recruitment of brown trout is presently low, in large part due du acidification of the main spawning tributary. Mitigation by adding shell sand (or other types of liming) in the tributary will improve recruitment, but the trout population may be challenged by the feeding conditions in the strongly fluctuating reservoir.

The present reservoir area is moderately important as a recreational area (some cabins and hiking tracks in the area) and use of the lake for e.g. boating and fishing is limited by the access for boats (low summer water level). It is likely that the present rather large regulation height is negatively affecting the attractiveness of the surroundings and a low density of medium sized brown trout is not very attractive for recreational fishers. The Lake Storavatn, to be included in the new reservoir under scenario 2, is situated close to an important ski resort and a skiing track passes around. The recreational value is high. The almost 100 m high dam will dominate the landscape and significantly reduce the recreational value of the area. In summary, also under scenario 3 the recreational effects will be strongly negative. The mitigation measures suggested (improving natural recruitment of brown trout through liming of tributary and improving boat access by building floating piers) are unlikely to reduce negative effects significantly.

3.3.2 R9 The Ørevatn reservoir

The Ørevatn reservoir is similarly impacted under scenario 3 as in scenario 2, in terms of the two new pumped storage plants. The first pumps water from the downstream River Kosåna (or actually from the River Mandalselva further downstream) to the reservoir, whereas the second pumps from the reservoir to new Storavatn reservoir. The annual environmental restriction is the same as in present situation, with a 52% as minimum reservoir volume. (Figure 25). As in scenario 2, results show higher variability in water level changes through the year with lowest minimum values during the year.

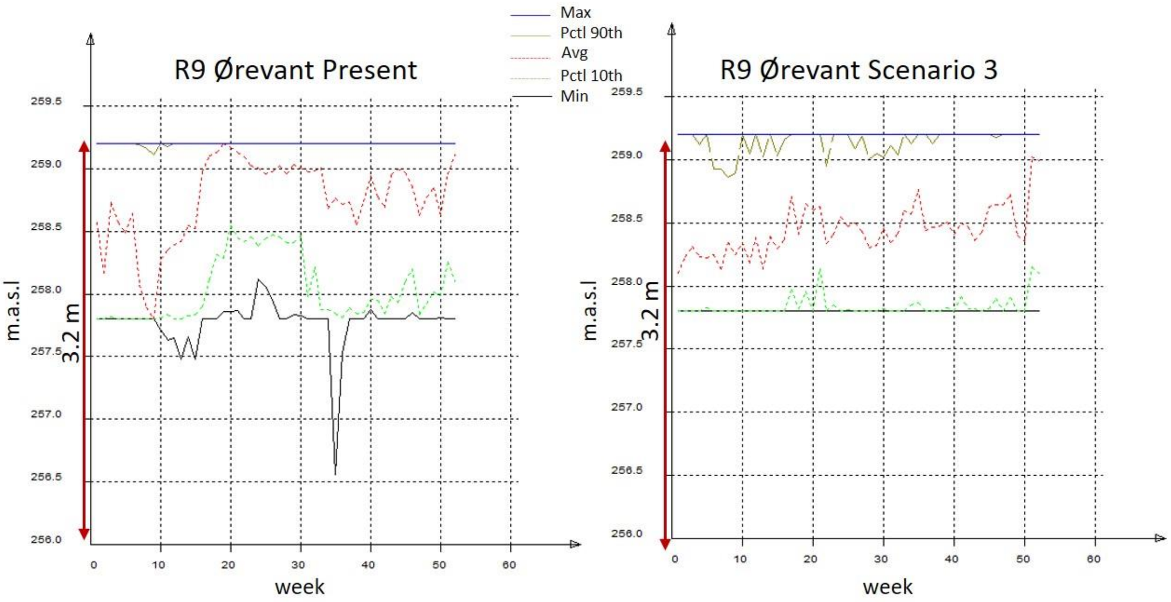


Figure 14. R9, Øravatn reservoir curve and meters of regulation for Present Situation and Scenario 3.

The effects in terms of hydrological changes under scenario 3 is very similar to the changes under scenario 2, and the below assessment of environmental and recreational effects are the same as for scenario 2. The regulation height of the Ørevatn reservoir is small (3,2 m) and the restriction limits water level variation even more. The ecological status is classified as good, with little impact from HP. Natural recruitment of brown trout is regarded too high, casing high densities of small bodied fish, of little interest for recreational fisheries. Under scenario 3 the water level is expected to fluctuate more rapidly, but with generally smaller amplitudes. Some rare occasions of very low water level (see minimum values) evident in the present-day simulations are not present in scenario 3 simulations. Such drops may have negative effects but are rare. While effects of pumping *per se* cannot be ruled out, scenario 3 is likely to have neutral environmental effects. If additional measures are implemented (blocking of access to selected spawning streams and thinning measures) fish densities may be reduced and individual growth improve. However, this will improve recreational status, but not environmental status. The recreational value of this reservoir and its surrounding is regarded as high, with a high density of cabins, hiking tracks and easy access. Under scenario 3 no changes in recreational status is expected, but measures to increase average fish size may improve the attractiveness of the reservoir for recreational fisheries.

3.3.3 E1 Langevann-Monn river stretch

Under scenario 3, there are no changes implemented in the upstream part of the catchment and therefore there are no changes expected in the hydrological indices. There is a difference in the indices for flood, annual mean flood and ten-year flood (left), and this might be because of the higher flexibility in the system to handle floods. There are no environmental restrictions implemented in the system, and the classification of the river stretch is still with severe hydrological bottlenecks as in present situation due to low winter and summer flows.

No effects on the environmental status is expected, and the recreational status of this river stretch is unknown.

Table 13. Hydrological indices for E1 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and Scenario 3 (right). Note that flow might be slightly higher than 0 but still con-sider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	2.25	-87.66
Q95	1.02	0.00	-100.00
Summer low flow	1.91	0.00	-100.00
Winter low flow	0.89	0.00	-100.00
Annual mean flood	171.84	57.88	-66.31
Ten-year flood	244.1	97.87	-59.90

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	18.21	2.32	-87.24
Q95	1.02	0.00	-100.00
Summer low flow	1.91	0.00	-100.00
Winter low flow	0.89	0.00	-100.00
Annual mean flood	171.84	82.41	-52.04
Ten-year flood	244.1	140.01	-42.64

3.3.4 E2 Logna (Juvatnet-Lognevatnet) river stretch

Under the flood protection scenario, there are no modification or environmental restrictions implemented in this river stretch. The results show an increase in the flood indices values, therefore a smaller reduction after regulation (Table 14). As in previous cases this might be due to a more flexible and optimal model to handle floods. The hydrological classification is severe bottleneck in both scenarios (Present and Scenario 3).

Table 14. Hydrological indices for E2 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 3 (right). Note that flow might be slightly higher than 0 but still con-sider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.73	-92.58
Q95	0.92	0.00	-100.00
Summer low flow	0.89	0.00	-100.00
Winter low flow	0.82	0.00	-100.00
Annual mean flood	102.4	21.50	-79.00
Ten-year flood	148.1	51.96	-64.91

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	9.79	0.82	-91.67
Q95	0.92	0.00	-100.00
Summer low flow	0.89	0.00	-100.00
Winter low flow	0.82	0.00	-100.00
Annual mean flood	102.4	43.20	-57.81
Ten-year flood	148.1	90.31	-39.02

No changes in environmental status is expected. The recreational status is unknown, but the landscape appeared as attractive during a field visit.

3.3.5 T4 Uvdalsåni (Stekil-Nåvatn) river stretch

Under the flood protection scenario, there are no modification or environmental restrictions implemented in this river stretch. (Table 15). Therefore, the classification is expected to be also severe hydrological bottleneck as in Present scenario.

Table 15. Hydrological indices for T4 stretch for Unregulated and Regulated period and the percentage of change in % under Present situation (left) and scenario 3 (right). Note that flow might be slightly higher than 0 but still con-sider extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	1.67	0.39	-76.65
Q95	0.24	0	-100.00
Summer low flow	0.13	0	-100.00
Winter low flow	0.18	0	-100.00
Annual mean flood	16.5	69.30449	320.03
Ten-year flood	23.6	117.4297	397.58

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	1.67	0.46367017	-72.24
Q95	0.24	0	-100.00
Summer low flow	0.13	0	-100.00
Winter low flow	0.18	0	-100.00
Annual mean flood	16.5	56.39176035	241.77
Ten-year flood	23.6	84.1985186	256.77

No effects are expected for environmental and recreational status.

3.3.6 E10 Tungesjo-Kavfossen

The E10 river stretch is regulated by the Bjelland HP plant and is affected by water going into the intake from the Tungesjø reservoir. This river stretch is characterized as a bypass section. The lowermost part of the stretch is the Kavfossen waterfall, representing the natural migratory upper barrier for anadromous salmonids in the River Mandalselva. Here, the unregulated tributary Kosåna flows into Mandalselva. Under scenario 2, there is an implemented minimum flow stipulation at 1.3 m^3/s during October-April and 6 m^3/s during May-September. Moreover, a fishway is implemented, increasing the anadromous stretch of the River Mandalselva with 2,9 km.

At present this river stretch is completely dry for long periods both during winter and summer, because water is spilled only during floods and during very low flow conditions in the downstream anadromous river stretch. While the simulations under scenario 1 (Figure 9) shows reduced mean flows, this is indeed an effect of reduced flood flows and the major effect is that this stretch will now have water flow throughout the year and a functioning aquatic ecosystem can be re-established. Moreover, the implemented flow releases will positively affect the upper part of the current anadromous stretch, from Kavfossen to the outlet of the Bjelland HP station at Monan. The improvement in ecological status is thus regarded as substantial.

The recreational potential was classified as high under current conditions, both for local inhabitants and tourist passing on the road alongside the river. The minimum flow stipulation and establishment of a migration pathway for anadromous fish will likely improve the recreational value, particularly because both the current stretch and the downstream river stretch will become attractive for salmon sport fishery.

In conclusion, under scenario 3 and the implemented compensation measure, both the environmental and recreational status will improve substantially.

Table 16. Hydrological indices for E10 stretch for unregulated and regulated period and the percentage of change in % under Present situation (left) and scenario 3 (right). Note that flow might be slightly higher than 0 but still considered extremely low. Output from the model is 0.

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	7.20	-89.76
Q95	8.76	0.00	-100.00
Summer low flow	8.9	0.00	-100.00
Winter low flow	7.66	0.00	-100.00
Annual mean flood	619.4	166.90	-73.05
Ten-year flood	888	305.57	-65.59

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	70.34	4.32	-93.86
Q95	8.76	1.30	-85.16
Summer low flow	8.9	1.56	-82.50
Winter low flow	7.66	1.30	-83.03
Annual mean flood	619.4	52.68	-91.50
Ten-year flood	888	136.80	-84.59

3.3.7 E14 Downstream Laudal Power plant

The hydrological changes in this river section are presented as a representation of the average changes in the whole of the anadromous stretch of the River Mandalselva below the outlet of the Bjelland HP station. The results under scenario 3 show a reduction in annual mean flow because they are impacted by a flood power plant called “Try” (Table 17). This is problematic since the upper part is affected only by pumping of the Kosåna water (intake at Monan) and the parts below Øyslebø also by the Try. It is a new hydropower plant combined with a flood bypass tunnel to protect the city of Mandal and the Øyslebø community. It has an operational environmental restriction during September-May of 30 m^3/s and during the fishing season June-August the power plant cannot run, except for flood bypass. A system to prevent fish from entering the Try HP and flood bypass tunnel has been suggested, and we assume it to be implemented in the scenario.

There is currently no hydrological bottleneck since the minimum flow in both summer and winter are higher than before regulation.

Table 17. Hydrological indices for E14 stretch for unregulated and regulated period and the percentage of change in % under present situation (left) and scenario 3 (right).

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	76.29	80.29	5.24
Q95	9.35	27.49	194.16
Summer low flow	9.65	33.10	242.95
Winter low flow	8.73	34.72	297.56
Annual mean flood	660.50	364.00	-44.89
Ten-year flood	948.20	549.13	-42.09

Hydrological Indices	Unregulated	Regulated	Change (%)
Annual mean flow	76.29	49.52	-35.10
Q95	9.35	24.84	165.76
Summer low flow	9.65	27.54	185.34
Winter low flow	8.73	28.43	225.58
Annual mean flood	660.50	232.08	-64.86
Ten-year flood	948.20	352.04	-62.87

There are only very small reductions in the minimum summer and winter flows, too small to affect the production of salmonids. These 7 days minimum flows are regarded as much more important for the carrying capacity of salmonids (Forseth & Harby 2014) than the annual mean flow, which is reduced by nearly 40%. This reduction is in partly due to the strongly reduced floods, but also due to pumping from the upper parts at the outlet of the present Bjelland HP and production in the Try HP outlet flood events. Reduction in the amplitudes of floods may negatively affect habitat conditions for the fish in the long term, though reduced fine sediment transport and increased riverbed embeddedness, although this is not known as a challenge at present. The expected increased salmonid production in the upper parts (see E10) is expected to significantly increase the salmonid population size and improve the salmonid fishing and thus the recreational value.

In conclusion, in the short term the Try HP/flood tunnel and pumping from the upper part are not expected to have negative environmental effects, but long-term reductions in habitat quality cannot be ruled out. Reduction in moderate sized floods may negatively impact fishing, because such floods are generally regarded as positive for recreational fisheries.

3.3.8 The total environmental and recreational effects under scenario 3.

The effects on the ecological and recreational values are strongly negative for the Nåvann/Skjerka/Storevann reservoir whereas the compensatory measures in the Tungesjø-Kavfossen is strongly postive (Table 18). Because of the large interest associated for salmonid fishes the total effect is classified as small positive. The positive societal effects of flood protection are considerable, but not considered in this assessment. While salmonid fishing is an important recreational activity, the negative effects on recreational interests of construction of a large dam in a recreationally important area, is not compensated by the improved conditions for salmonid fishing. Total effects on recreational values are thus negative.

Table 18. The expected environmental and recreational effects under scenario 3 scored from very negative (---), via no effects (0) to very positive (+++) for each of the assessed water bodies and the total effects. The first two column is based on the simulated mitigation measures, whereas the latter two tabulates the effects after other suggested mitigation or compensation measures are implemented.

Waterbody	**Environmental effects**	**Recreational effects**	**Environmental effects including environmental projects**	**Recreational effects including environmental projects**
R7-8 Nåvann/Skjerka	---	---	---	---
R9 Ørevann	0	0	0	+
EI Langvann-Monn	0	UE	0	UE
E2 Logna	0	UE	0	UE
E10 Tungesjo-Kavfossen	+++	+++	+++	+++
E14 anadromous stretch	0 (-)	0	0	0
TOTAL EFFECT	-	**0**	**0**	**+**

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5 Appendix: Maps of the current situation in Mandal river

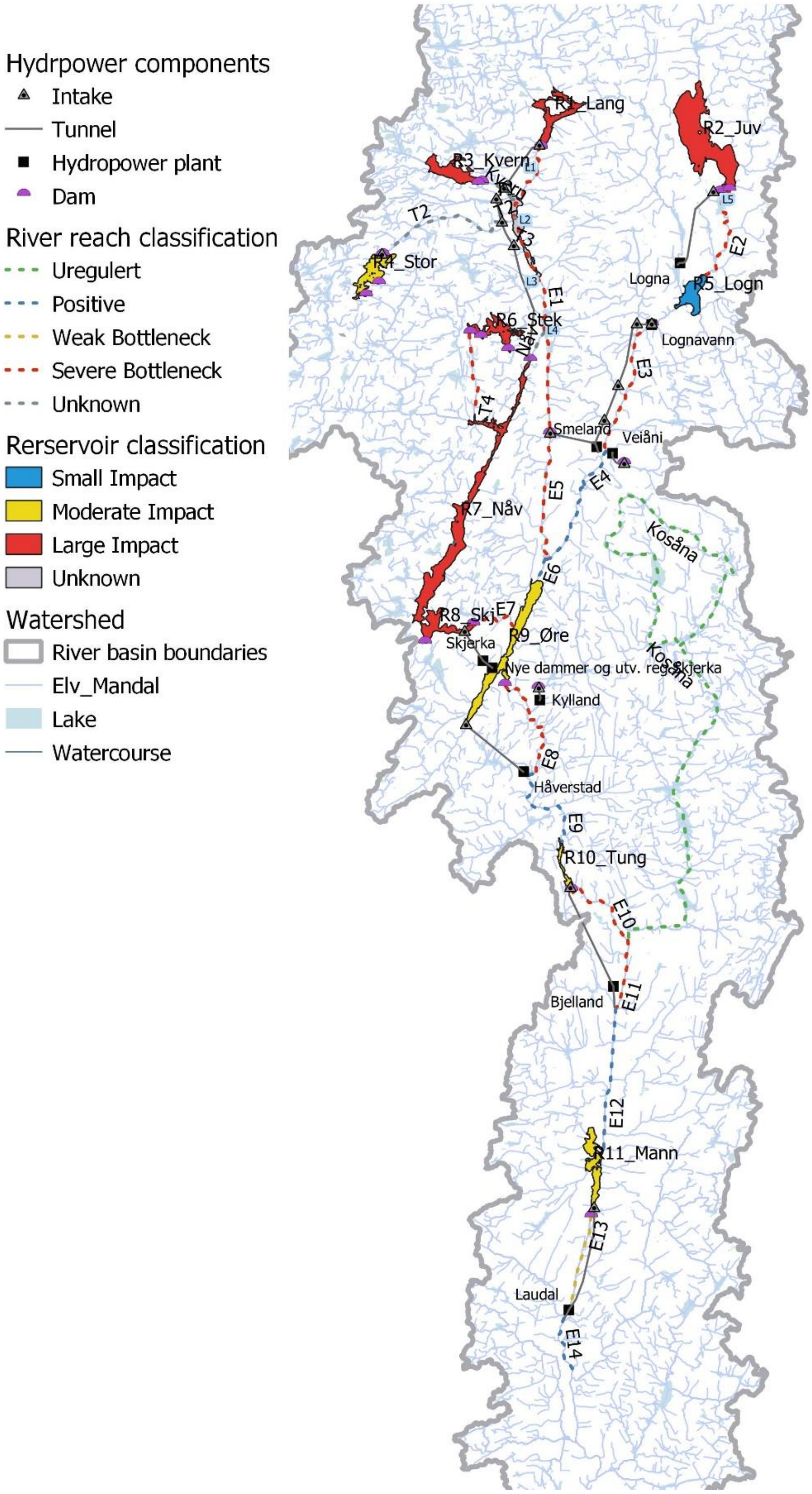


Figure 15. Hydrological classification for reservoirs based on Vann-Net classification and for river stretches based on potential hydrological bottlenecks from the environmental design handbook (Forseth and Harby, 2014).

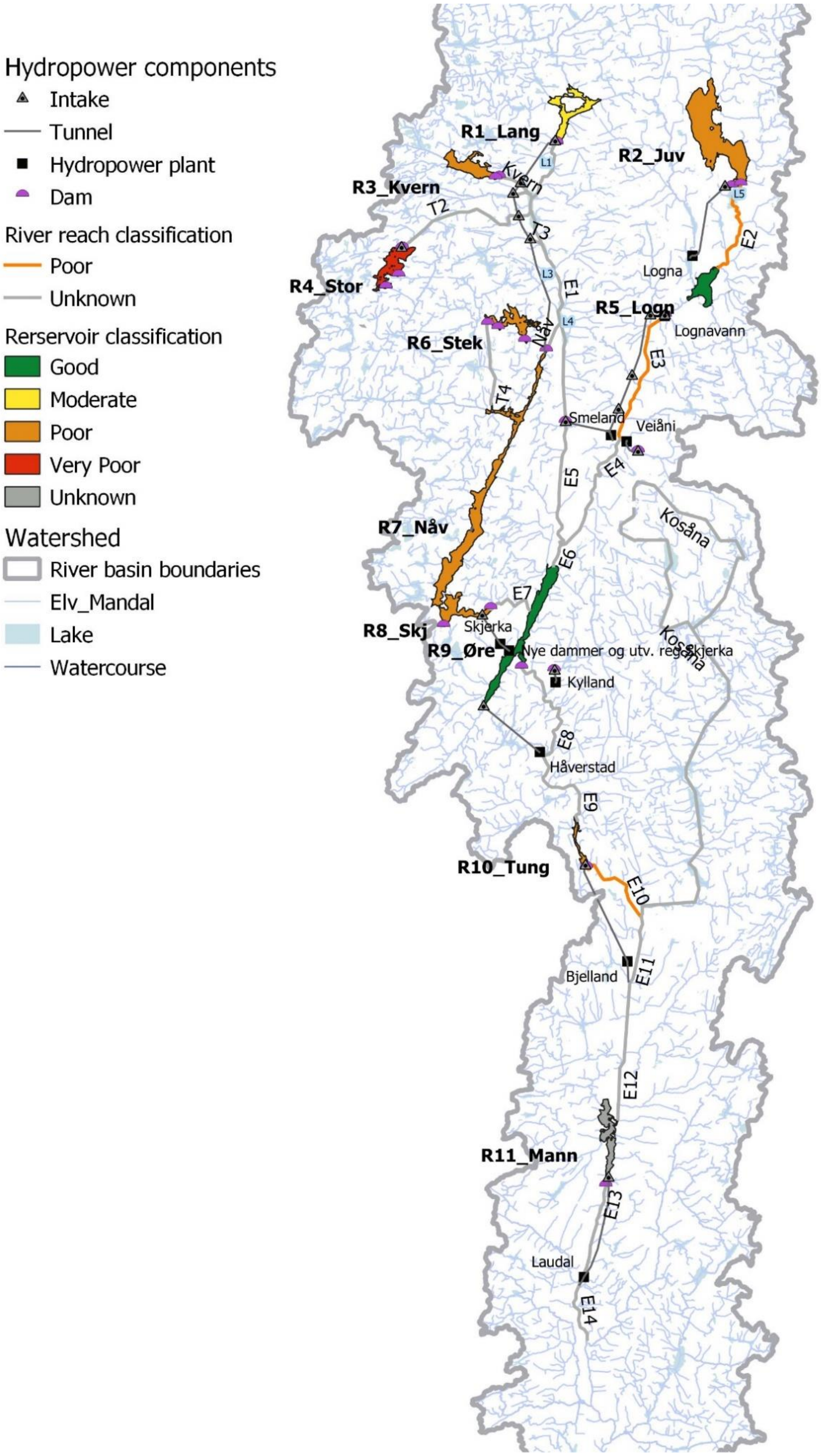


Figure 16. Ecological classification.

AlternaFuture MEMO nr.8

AlternaFuture

A3: Assessing the economic feasibility

Kaspar Vereide and Leif Lia

2020-09-22

SUMMARY

This memo presents an assessment of the economic feasibility of the scenarios. A net present value (NPV) calculation of the different scenarios has been carried out based on the construction costs from Memo 4 and the simulated production and income from Memo 6. It is concluded that the scenarios for extreme upgrading are not economically feasible with current power prices or with the expected 2030 power prices. However, scenario 2&3 with pumped storage are found to be economically feasible in the 2030scaled scenario. The scenarios are not optimized, and the scenarios are only evaluated as a whole and not per power plant. An improved economic feasibility can be expected after an optimization.

Contents

1 Introduction

This memo presents calculations of the economic feasibility of the three scenarios for extreme reconstruction of the Mandal river hydropower system. The costs calculated for each scenario in Memo 4 and the resulting production and achieved power price from Memo 6 are used to perform at net present value (NPV) calculation. The analysis has been simplified by assuming that the achieved power price from the ProdRisk simulations are constant over the economic lifetime. The analysis is conducted for the power system as a whole, not per individual power plant. The NPV calculation is conducted with current tax levels, industry standard discount rate and loan interest rate.

2 Input data

The table below present the common economic assumptions for the NPV calculation. In addition, operation and maintenance costs (O&M) are estimated as 0.2% of civil costs and 0.4% of electromechanical costs per year. This is used for both hydropower projects and environmental projects. As a simplification, it is assumed that the project can be financed without loans. There is also not assumed any additional income from green certificates and system services.

Table 1: Economic assumptions

Parameter	**Value**	**Unit**
Discount rate	3.5	%
Economic lifetime	40	Years
Interest rate, loan	0	%
Loan % of costs	0	%
Grid tariff	0.0018	€/kWh
Tax, nature resources	0.0013	€/kWh
Tax, company	22	%
Tax, hydropower	37	%
Norm free income	2	%
Tax, concession	0.0007	€/kWh
Tax, property	0.0016	€/kWh
Amount of concession power	10	%
Price concession power	0.0113	€/kWh
Green certificates	0	€/kWh
Income from system services	0	€/kWh

The construction costs for the three scenarios are presented in Memo 4. Table 2 below presents a summary including information of the amount of civil and elmech costs. Table 3 presents the results from production simulation in ProdRisk, taken from Memo 6.

Table 2: Construction costs

Scenario	**S1**	**S2**	**S3**
Civil costs (mill. €)	183	324	288
Elmech costs (mill. €)	210	189	172
Total costs (mill. €)	393	514	460

Table 3: ProdRisk results

		2015				**2030**				**2030scaled**			
		CS	**S1**	**S2**	**S3**	**CS**	**S1**	**S2**	**S3**	**CS**	**S1**	**S2**	**S3**
Spillage	GWh	223	197	103	262	211	198	102	264	229	202	119	296
Consumption pumping	GWh	-	-	424	221	-	-	764	581	-	-	2276	1930
Gain from pumping	GWh	-	-	361	181	-	-	617	449	-	-	1833	1506
Net pump energy	GWh	-	-	-63	-40	-	-	-147	-132	-	-	-444	-424
Start reservoir	GWh	349	391	943	684	316	405	918	623	325	325	859	577
End reservoir	GWh	352	394	952	690	320	408	924	628	328	327	865	582
Total production	GWh	1732	1960	1885	1853	1742	1957	1801	1759	1706	1931	1442	1410
Net income	Mill. €	51	60	62	59	73	87	99	93	81	110	151	138
Compared to current system	Mill. €		9	11	8		15	26	20		29	70	57
Achieved price	€/MWh	29.7	30.7	33.0	32.0	41.6	44.6	54.7	52.8	47.5	56.9	104.6	97.7

All the scenarios are seen to generate a higher annual income from power production. However, there is a large difference between the scenarios and for the different price forecasts. The maximum flexibility scenario is seen to generate the highest income for all the price forecasts. And the 2030scaled prices are seen to generate the highest income for all reconstruction scenarios.

3 Results and Discussion

To assess the economic feasibility of the reconstruction scenarios, a net present value (NPV) calculation is conducted. The NPV is calculated based on the marginal power production and marginal power price compared with the 0-alternative without reconstruction. The power price is assumed constant during the economic lifetime of the project. The marginal price is the marginal income/marginal production. The table below summarizes the construction costs, marginal production, marginal power price, marginal income and NPV for each scenario.

Table 4: NPV-calculations

		2015			**2030**			**2030scaled**		
		S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Construction costs	Mill. €	393	514	460	393	514	460	393	514	460
Marginal production	GWh	228	153	121	215	59	17	225	-264	-296
Marginal income	Mill. €	9	11	8	15	26	20	29	70	57
Marginal price	€/MWh	39.5	71.9	66.1	69.8	440.7	1176.5	128.9	-265.2	-192.6
NPV	Mill. €	-300	-387	-363	-252	-265	-262	-142	98	31

The results show that the scenarios for extreme reconstruction are not profitable with the current prices (2015). It is also not profitable for the assumed 2030 prices. However, for the 2030scaled prices scenario 2 (extreme flexibility) and scenario 3 (flood protection) are found profitable. The main contribution to the increased income is the pumped storage plants which are able to exploit the increasing variability in power prices.

An overview of the spreadsheet used for calculation of the NPV is presented in the appendix. As can be seen the scenarios with pumped storage plants yield negative marginal production for the 2030scaled prices. This is because there is no new water in the system, and the pumping of water results in efficiency losses, and a resulting lower energy production than in the scenario without pumped storage plants. However, the pumping allows exploitation of the power price variability, and storing of water to the high-price periods, resulting in a high net economic profit.

Because of the net reduction on energy production, the resulting taxes on the total system is reduced, as many of the taxes are calculated based on produced GWh. This is valid for property tax, nature resource tax and concession tax and concession power.

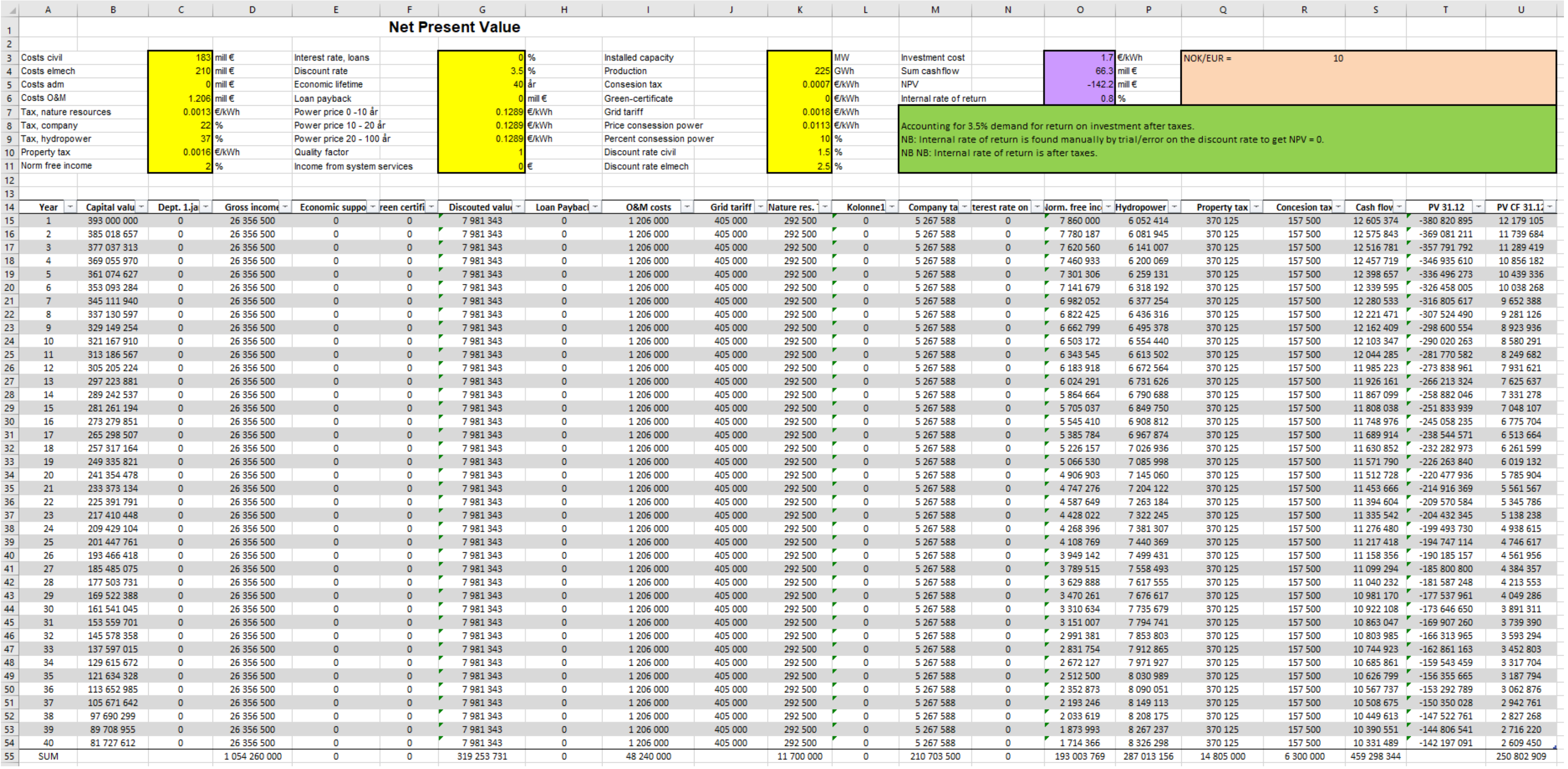
It is pointed out that the scenarios are not optimized. Also, it is likely that only some of the projects within each scenario may be economically feasible, while other are not. If only the most economically feasible projects are constructed, the resulting profit is likely to increase.

4 Conclusion

It is concluded that the scenarios for extreme upgrading are not economically feasible with current power prices or with the expected 2030 power prices. However, scenario 2&3 with pumped storage are found to be economically feasible in the 2030scaled scenario.

The scenarios are not optimized, and the scenarios are only evaluated as a whole and not per power plant. An improved economic feasibility can be expected after an optimization.

5 Appendix



Net Present Value

Costs civil	183	mill €	Interest rate, loans	0	%	Installed capacity		MW	Investment cost	1.7	€/kWh
Costs elmech	210	mill €	Discount rate	3.5	%	Production	225	GWh	Sum cashflow	66.3	mill €
Costs adm	0	mill €	Economic lifetime	40	år	Consesion tax	0.0007	€/kWh	NPV	-142.2	mill €
Costs O&M	1.206	mill €	Loan payback	0	mill €	Green-certificate	0	€/kWh	Internal rate of return	0.8	%
Tax, nature resources	0.0013	€/kWh	Power price 0 -10 år	0.1289	€/kWh	Grid tariff	0.0018	€/kWh			
Tax, company	22	%	Power price 10 - 20 år	0.1289	€/kWh	Price consession power	0.0113	€/kWh			
Tax, hydropower	37	%	Power price 20 - 100 år	0.1289	€/kWh	Percent consession power	10	%			
Property tax	0.0016	€/kWh	Quality factor	1		Discount rate civil	1.5	%			
Norm free income	2	%	Income from system services	0	€	Discount rate elmech	2.5	%			

NOK/EUR = 10

Accounting for 3.5% demand for return on investment after taxes.
NB: Internal rate of return is found manually by trial/error on the discount rate to get NPV = 0.
NB NB: Internal rate of return is after taxes.

Year	Capital valu	Dept. 1.ja	Gross income	Economic suppo	reen certifi	Discouted valu	Loan Paybacl	O&M costs	Grid tariff	Nature res.	Kolonne1	Company ta	terest rate on	orm. free inc	Hydropower	Property tax	Concesion tax	Cash flow	PV 31.12	PV CF 31.1
1	393 000 000	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 860 000	6 052 414	370 125	157 500	12 605 374	-380 820 895	12 179 105
2	385 018 657	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 780 187	6 081 945	370 125	157 500	12 575 843	-369 081 211	11 739 684
3	377 037 313	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 620 560	6 141 007	370 125	157 500	12 516 781	-357 791 792	11 289 419
4	369 055 970	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 460 933	6 200 069	370 125	157 500	12 457 719	-346 935 610	10 856 182
5	361 074 627	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 301 306	6 259 131	370 125	157 500	12 398 657	-336 496 273	10 439 336
6	353 093 284	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	7 141 679	6 318 192	370 125	157 500	12 339 595	-326 458 005	10 038 268
7	345 111 940	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 982 052	6 377 254	370 125	157 500	12 280 533	-316 805 617	9 652 388
8	337 130 597	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 822 425	6 436 316	370 125	157 500	12 221 471	-307 524 490	9 281 126
9	329 149 254	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 662 799	6 495 378	370 125	157 500	12 162 409	-298 600 554	8 923 936
10	321 167 910	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 503 172	6 554 440	370 125	157 500	12 103 347	-290 020 263	8 580 291
11	313 186 567	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 343 545	6 613 502	370 125	157 500	12 044 285	-281 770 582	8 249 682
12	305 205 224	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 183 918	6 672 564	370 125	157 500	11 985 223	-273 838 961	7 931 621
13	297 223 881	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	6 024 291	6 731 626	370 125	157 500	11 926 161	-266 213 324	7 625 637
14	289 242 537	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 864 664	6 790 688	370 125	157 500	11 867 099	-258 882 046	7 331 278
15	281 261 194	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 705 037	6 849 750	370 125	157 500	11 808 038	-251 833 939	7 048 107
16	273 279 851	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 545 410	6 908 812	370 125	157 500	11 748 976	-245 058 235	6 775 704
17	265 298 507	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 385 784	6 967 874	370 125	157 500	11 689 914	-238 544 571	6 513 664
18	257 317 164	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 226 157	7 026 936	370 125	157 500	11 630 852	-232 282 973	6 261 599
19	249 335 821	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	5 066 530	7 085 998	370 125	157 500	11 571 790	-226 263 840	6 019 132
20	241 354 478	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 906 903	7 145 060	370 125	157 500	11 512 728	-220 477 936	5 785 904
21	233 373 134	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 747 276	7 204 122	370 125	157 500	11 453 666	-214 916 369	5 561 567
22	225 391 791	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 587 649	7 263 184	370 125	157 500	11 394 604	-209 570 584	5 345 786
23	217 410 448	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 428 022	7 322 245	370 125	157 500	11 335 542	-204 432 345	5 138 238
24	209 429 104	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 268 396	7 381 307	370 125	157 500	11 276 480	-199 493 730	4 938 615
25	201 447 761	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	4 108 769	7 440 369	370 125	157 500	11 217 418	-194 747 114	4 746 617
26	193 466 418	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 949 142	7 499 431	370 125	157 500	11 158 356	-190 185 157	4 561 956
27	185 485 075	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 789 515	7 558 493	370 125	157 500	11 099 294	-185 800 800	4 384 357
28	177 503 731	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 629 888	7 617 555	370 125	157 500	11 040 232	-181 587 248	4 213 553
29	169 522 388	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 470 261	7 676 617	370 125	157 500	10 981 170	-177 537 961	4 049 286
30	161 541 045	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 310 634	7 735 679	370 125	157 500	10 922 108	-173 646 650	3 891 311
31	153 559 701	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	3 151 007	7 794 741	370 125	157 500	10 863 047	-169 907 260	3 739 390
32	145 578 358	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 991 381	7 853 803	370 125	157 500	10 803 985	-166 313 965	3 593 294
33	137 597 015	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 831 754	7 912 865	370 125	157 500	10 744 923	-162 861 163	3 452 803
34	129 615 672	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 672 127	7 971 927	370 125	157 500	10 685 861	-159 543 459	3 317 704
35	121 634 328	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 512 500	8 030 989	370 125	157 500	10 626 799	-156 355 665	3 187 794
36	113 652 985	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 352 873	8 090 051	370 125	157 500	10 567 737	-153 292 789	3 062 876
37	105 671 642	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 193 246	8 149 113	370 125	157 500	10 508 675	-150 350 028	2 942 761
38	97 690 299	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	2 033 619	8 208 175	370 125	157 500	10 449 613	-147 522 761	2 827 268
39	89 708 955	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	1 873 993	8 267 237	370 125	157 500	10 390 551	-144 806 541	2 716 220
40	81 727 612	0	26 356 500	0	0	7 981 343	0	1 206 000	405 000	292 500	0	5 267 588	0	1 714 366	8 326 298	370 125	157 500	10 331 489	-142 197 091	2 609 450
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Environmental Cards

E.1 Langevann

Category: Environmental mitigation			
Mitigation measure: Access to spawning habitat by construction of cell structure weirs			
Costs:	0.5-1 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.5-1 MNOK
Target species:	Brown trout		
Ecological status:	Moderate		
	Wild brown trout CPUE: 8.7. Hatchery reared brown trout CPUE: 1.8. Good natural recruitment. Medium density, medium fish (female 26 cm, 36 % of catch).		
Ecological potential:	Increased abundance of naturally recruited brown trout of a medium size		
Recreational status:	Good		
	Tourist cabins, hiking tracks.		
Recreational potential:	Avoid high regulation height due to esthetics		

Detailed description

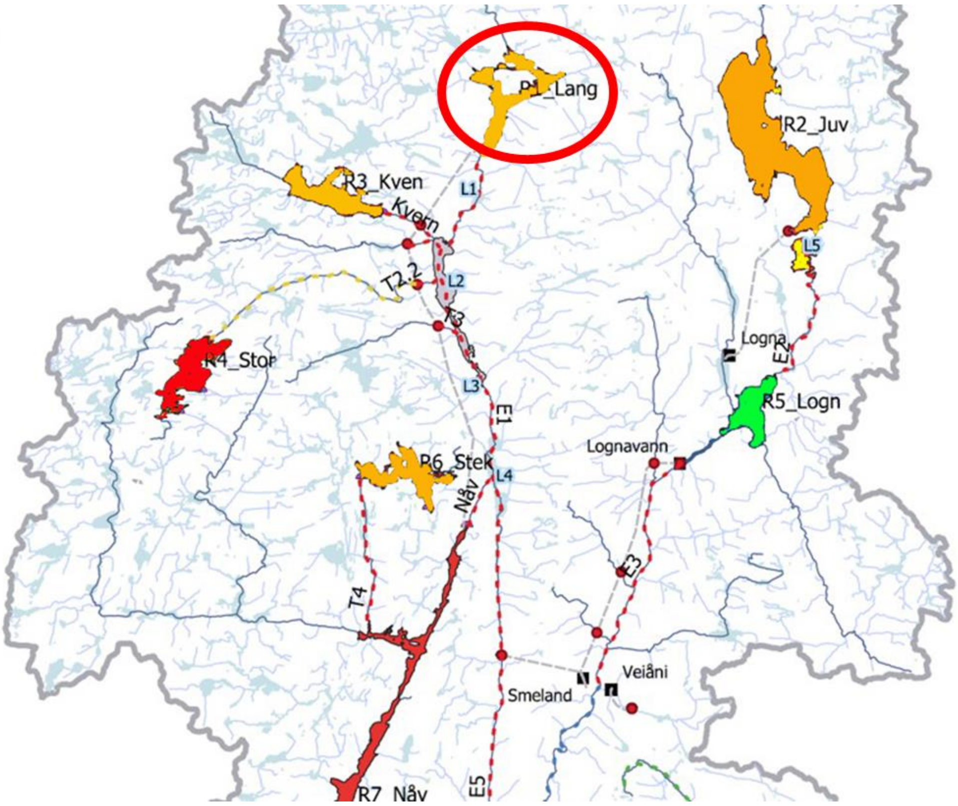
Purpose
Construct cell weirs to secure access to spawning grounds to increase abundance of naturally recruited brown trout.

Construction works
Cell structure weirs to secure access for spawning trout after new regulation height.

Environmental effect
Facilitate natural recruitment and increase abundance.

Social effect
Increased recreational value of fishing.

Costs
0.5-1 Mill NOK



Environmental Cards

E.2 Juvatn

Category:	Environmental mitigation		
Mitigation measure: Establish pools (areas with some depth) and construct cell structure weirs to increase abundance of naturally recruited brown trout. Minimum water level 510 masl during October. Floating dock close to Bortelid cabin area that will function with variable water level.			
Costs:	0.5-1 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.5-1 MNOK
Target species:	Brown trout		
Ecological status:	Poor		
	Currently, the normal water level is 4-5 meter lower than 510 in October. Wild brown trout CPUE: 1,8. Hatchery reared brown trout CPUE: 6.4. Some natural recruitment, difficult for fish to access spawning grounds when water level is below HRV. Medium density, medium fish (female 26 cm, 29 % of catch).		
Ecological potential:	Increase recruitment of brown trout.		
Recreational status:	Good		
	High density of cabins, several hiking and ski tracks in the area.		
Recreational potential:	Establishment of floating pier will increase usability of boats.		

Detailed description

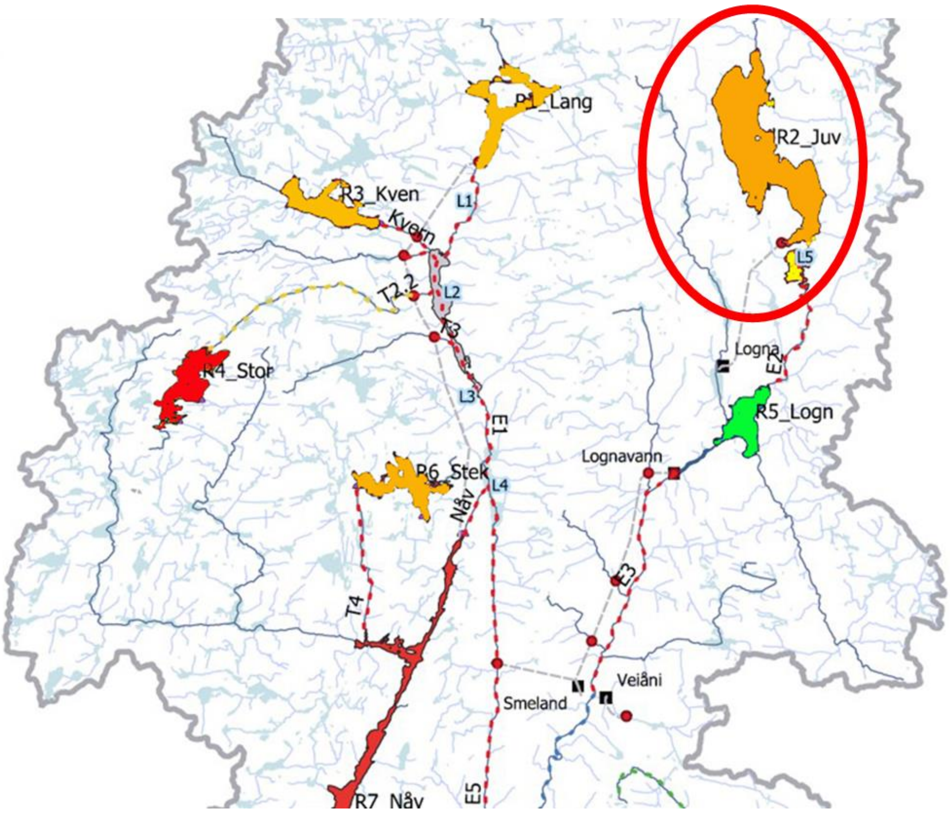
Purpose
Increased abundance of naturally recruited brown trout.

Construction works
Cell structure weirs to secure access for spawning trout after new regulation height.
Establish pools at the downstream part of the inlet stream.

Environmental effect
Facilitate natural recruitment and increase recruitment.

Social effect
Increased recreational value of fishing and use of lake Juvatn.

Costs
0.5-1 MNOK



E.3 Logna (Juvatnet-Lognevatnet)

Category: Environmental mitigation			
Mitigation measure: Minimum discharge (0.3 m^3/s), construction of cell structure weirs			
Costs:	0.4 MNOK	Season:	All year
Production loss:	2-3 GWh/year	NPV:	(-) 8-12 MNOK
Target species:	Brown trout		
Ecological status:	Poor. No minimum discharge.		
Ecological potential:	Currently the minimum flow is 30 l/s. More water will give a higher water table, more spawing and less dry exposing of eggs. Make small ponds at the entrance to Lognevann. Minimum discharge may increase recruitment and prevent stranding of juvenile brown trout. Winter survival may be increased by construction of deeper pools (cell structure weirs) in inlet to Lognevatnet. The minimum flow is also valid for river reach from intak to outlet of Smeland HPP. Environmental flow of 0.3 m3/s during winter. Must also keep the current requirement 0.6 m3/s during summer.		
Recreational status:	Unknown.		
Recreational potential:	Establish hiking track close to river will increase recreation value of area.		

Detailed description

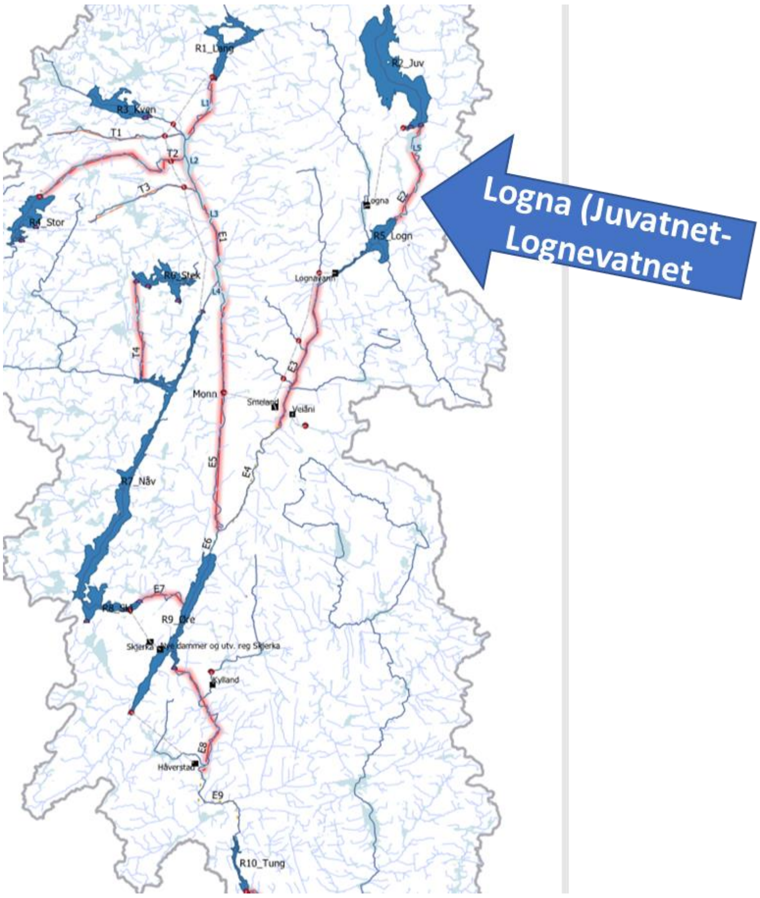
Purpose
Increase available area for brown trout

Construction works
Construct cell structure weirs

Environmental effect
Increase abundance of and size of trout in the area.

Social effect
Increased recreational value of fishing.

Costs
0.4 MNOK construction costs.
2-3 GWh production loss.


Logna (Juvatnet-Lognevatnet

Environmental Cards

E.4 Kvennevann

Category:	Environmental mitigation		
Mitigation measure: Secure access to two spawning streams to facilitate natural spawning (Sandvassåna og Øyvassånæ) by construction of cell weirs. Terminate cultivation.			
Costs:	0.5-1 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.5-1 MNOK
Target species:	Brown trout		
Ecological status:	Poor		
	Wild brown trout CPUE: 1.9. Hatchery reared brown trout CPUE: 6.5. None to little natural recruitment. Medium density, small fish (female 24 cm, 12% of catch)		
Ecological potential:	Mitigation measures aim to increase abundance of naturally recruited brown trout		
Recreational status:	Good		
	Tourist cabins, hiking and ski tracks in the area		
Recreational potential:	Avoid high regulation height due to esthetics		

Detailed description

Purpose

Facilitate natural recruitment of brown trout by securing access to spawning streams. Add spawning gravel to stream Sandvassåna and Øyvassånæ.

Construction works

Cell structure weirs to secure access to two spawning streams.

Environmental effect

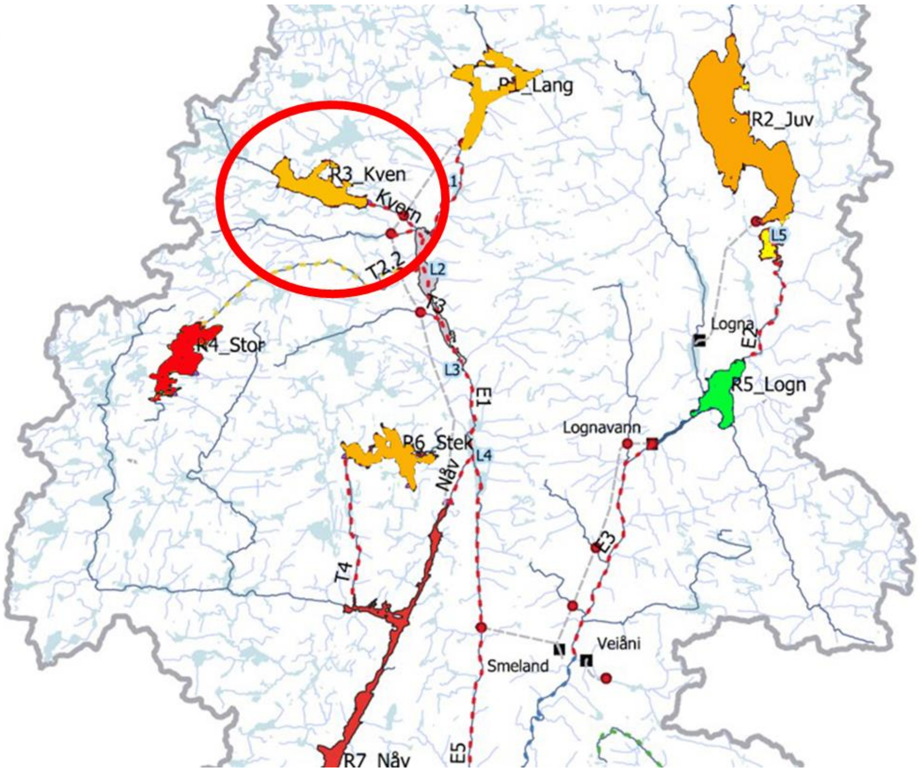
Facilitate natural recruitment.

Social effect

Increased recreational value of fish abundance and fish size increases.

Costs

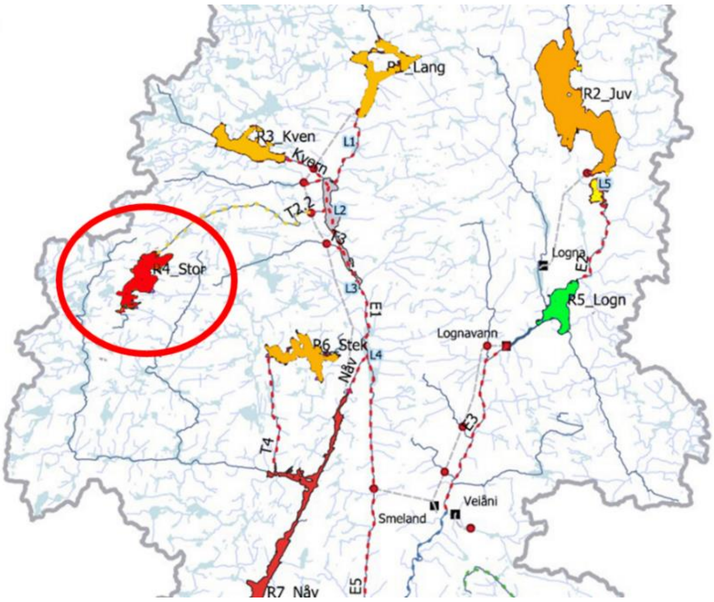
0.5-1 MNOK



Environmental Cards

E.5 Storevatn

Category:	Environmental mitigation		
Mitigation measure: Replace cultivation with natural recruitment in inlet stream (southern end). Cell structure weirs.			
Costs:	0.5-1 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.5-1 MNOK
Target species:	Brown trout		
Ecological status:	Bad		
	Wild brown trout CPUE: 0. Hatchery reared brown trout CPUE: 5.0. No natural recruitment. Medium density, medium fish (female 28 cm, 36% of catch). Lack of streams for recruitment.		
Ecological potential:	Mitigation measures aim establish naturally recruited population of brown trout		
Recreational status:	Good		
	Pristine nature.		
Recreational potential:	Increased recreational value for fishing		



Detailed description

Purpose
Establish naturally recruited brown trout by giving access to a stream with spawning habitat.

Construction works
Cell structure weirs to secure access to spawning streams.

Environmental effect
Facilitate natural recruitment.

Social effect
Increased recreational value of fishing.

Costs
0.5-1 MNOK

Environmental Cards

E.6 Stekil

Category:	Environmental mitigation		
Mitigation measure: Secure natural recruitment by constructing cell structure weir which will give access to two streams where spawning is possible.			
Costs:	0.5-1 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.5-1 MNOK
Target species:	Brown trout		
Ecological status:	Bad		
	Wild brown trout CPUE: 0.2. Hatchery reared brown trout CPUE: 3.1. Little natural recruitment. Low density, medium sized fish (female 28 cm, 39% of catch). Lack of spawning habitat, regulation height of 6 m leads to periodically large areas above water.		
Ecological potential:	Mitigation measures aim establish naturally recruited population of brown trout, however potential is moderate because of nutrient poor water.		
Recreational status:	Good		
	Pristine nature.		
Recreational potential:	Avoid large regulation height due to esthetics		

Detailed description

Purpose

Establish naturally recruited brown trout by giving access to a stream with spawning habitat.

Construction works

Cell structure weirs to secure access to spawning streams.

Environmental effect

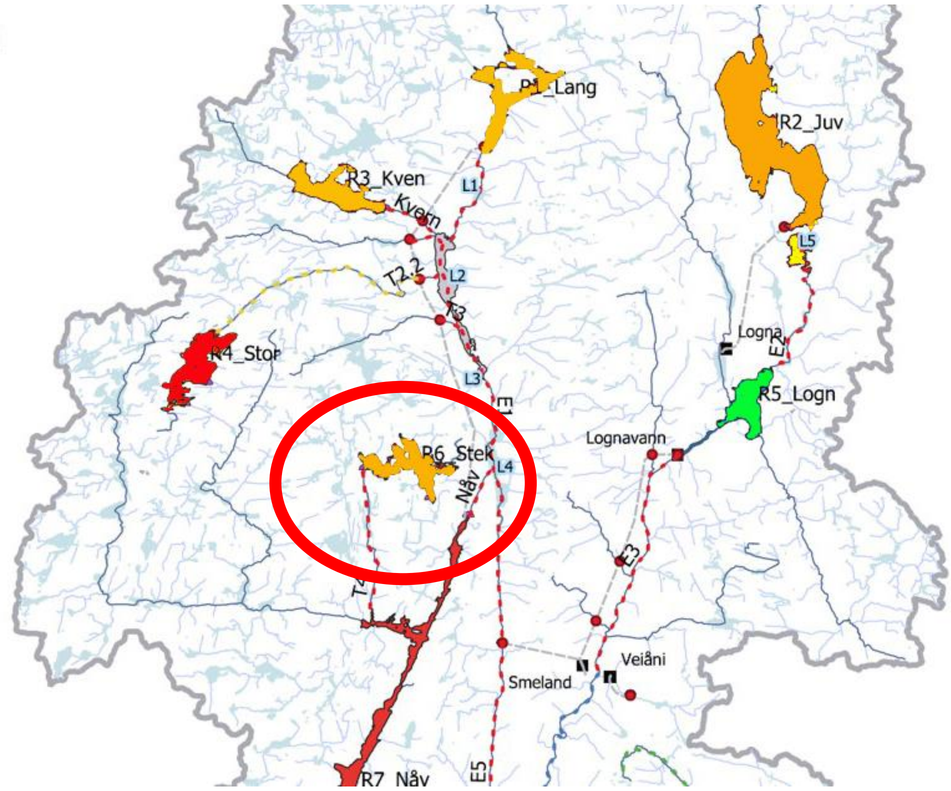
Facilitate natural recruitment. Potential benefits of pumping from Nåvatn; more nutricious water compared to Stekil.

Social effect

Increased recreational value of fish abundance and fish size increases.

Costs

0.5-1 MNOK



E.7 Nåvann/Skjerkevann

Category: Environmental mitigation			
Mitigation measure: Improve spawning habitat and water quality in an inlet stream; Uvdalsåni, by adding shell sand.			
Costs:	0.3 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.3 MNOK
Target species:	Brown trout		
Ecological status:	Poor		
	Wild brown trout CPUE: 0-1.8. Hatchery reared brown trout CPUE: 5,4. Little natural recruitment. Low density, medium sized fish (female 28cm, 33% of catch). Limited recruitment in southern part.		
Ecological potential:	Mitigation measures aims to establish naturally recruited population of brown trout, by improving spawning habitat in an inlet stream.		
Recreational status:	Cabins and hiking tracks in nearby area		
Recreational potential:	Potential for use of boat on the lake if a floating pier is built. Fluctuating water level make it difficult to access boats from land.		

Detailed description

Purpose

Improve recruitment of brown trout by improving spawning habitat and water quality in an inlet stream; Uvdalsåni, by adding shell sand.

Construction works

Add shell sand to Uvdalsåni. Construct floating pier.

Environmental effect

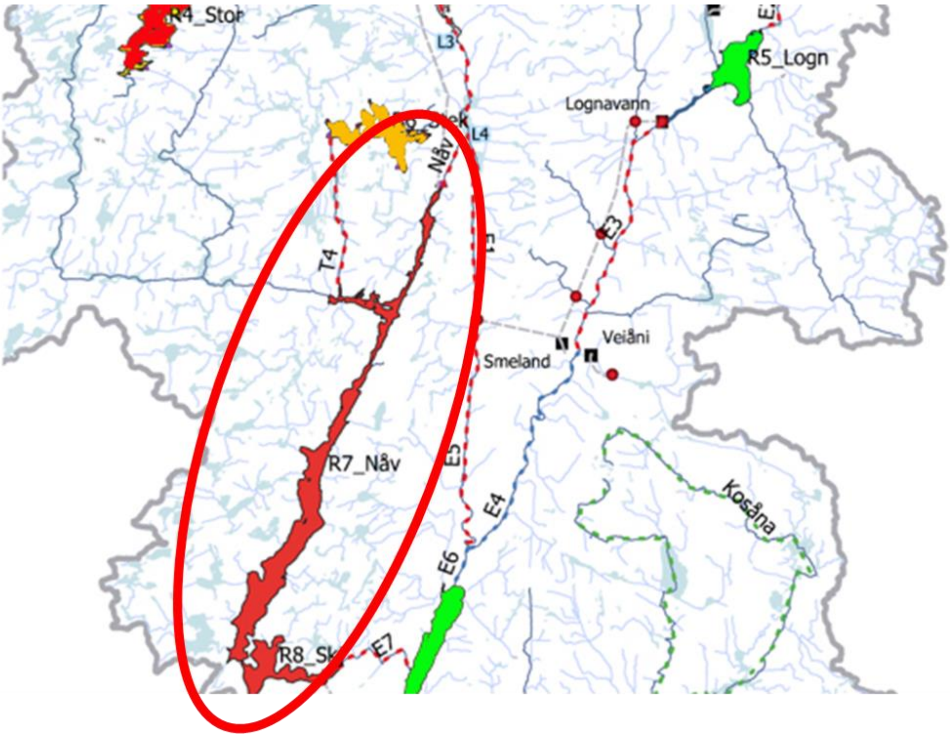
Facilitate natural recruitment.

Social effect

Increased recreational value of lake.

Costs

0.3 MNOK



Environmental Cards

E.8 Ørevann

Category:	Environmental mitigation		
Mitigation measure: Reduce density by reducing recruitment/access to spawning habitat and recruitment areas. Thinning of population through gill net fishing.			
Costs:	0.4 MNOK	Season:	All year
Production loss:	0 GWh/year	NPV:	(-) 0.4 MNOK
Target species:	Brown trout		
Ecological status:	Good		
	Wild brown trout CPUE: 15.8. Hatchery reared brown trout CPUE: 3.7. Natural recruitment good. Medium-high density of small sized fish (female 23 cm, 44% of catch). Recreation al fishing not attractive due to small size of fish.		
Ecological potential:	Reduce recruitment by blocking admission to spawning. Thinning of population through fishing will decrease abundance but increase average size,		
Recreational status:	High density of cabins and hiking in nearby area; high value.		
Recreational potential:	Increased value of recreational fishing if ecological mitigation measure is implemented.		

Detailed description

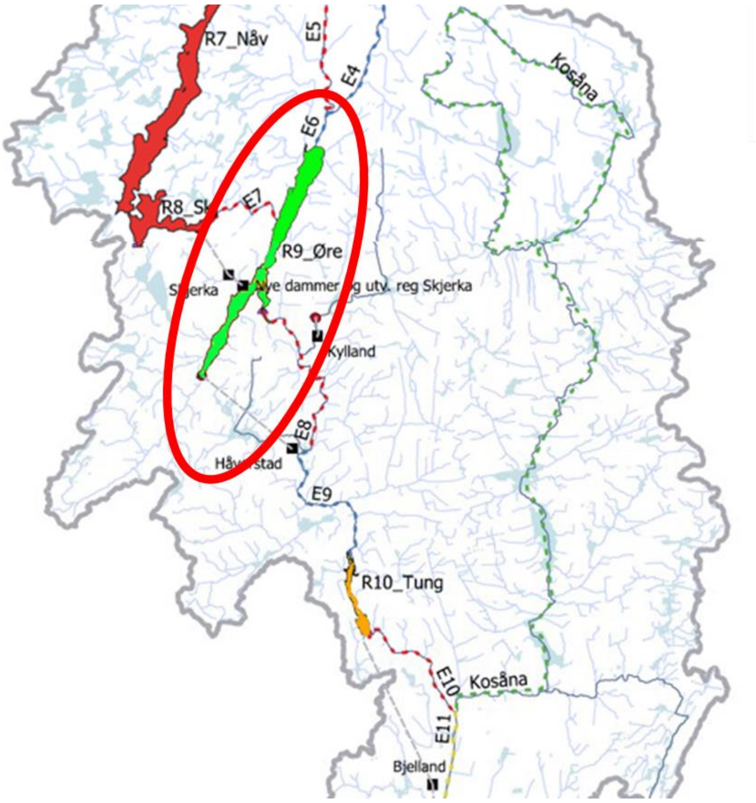
Purpose
Improve quality of fish population by reducing abundance and reducing access to spawning areas to reduce recruitment. In addition, thinning of population by the use of gill nets.

Construction works
Construct barriers to spawning streams.

Environmental effect
Increase of average size of individual trout after thinning of population.

Social effect
Increased recreational value of lake as body size of fish increases.

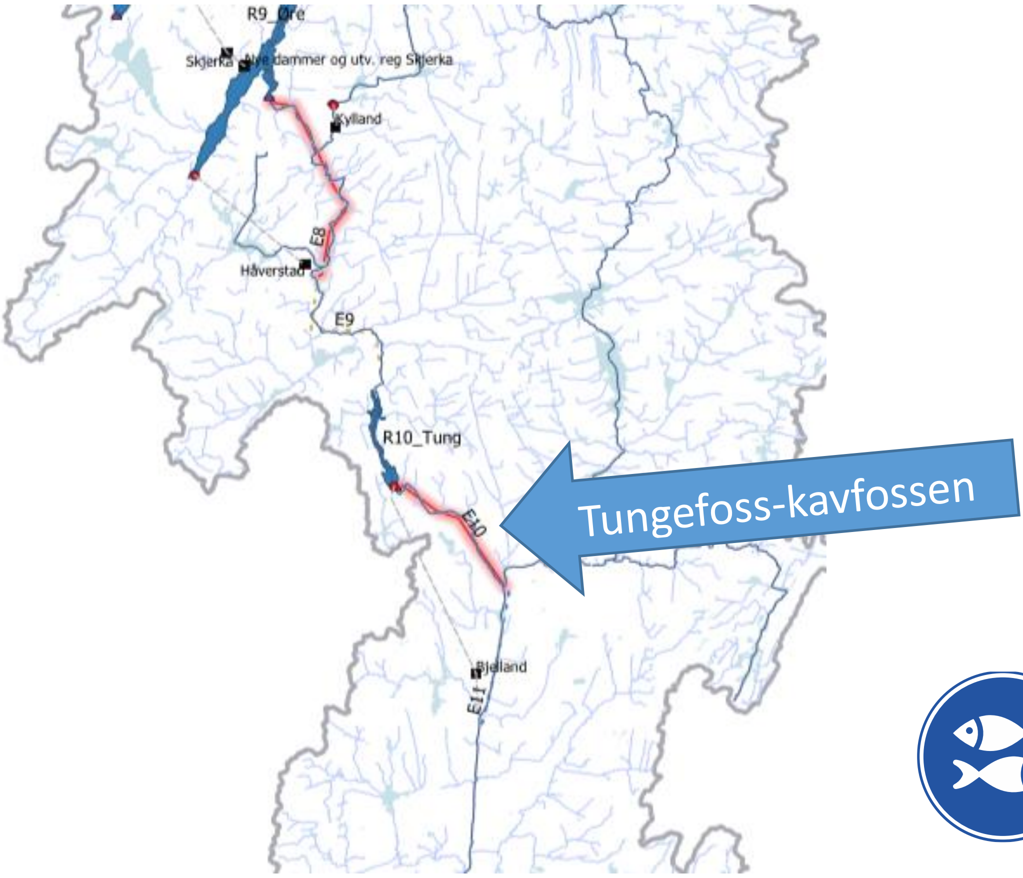
Costs
0.4 Mill NOK



Environmental Cards

E.9 Tungefoss

Category: Environmental mitigation			
Mitigation measure: Salmon ladder and migratory fish way. Increased anadromous stretch with 2.9 km, minimum discharge for winter and summer.			
Costs:	10-15 MNOK	Season:	All year
Production loss:	20-30 GWh/year	NPV:	(-) 90-130 MNOK
Target species:	Atlantic salmon		
Ecological status:	Poor		
Ecological potential:	Increase anadromous stretch with 2.9 km		
Recreational status:	High value for both local inhabitants and tourists. Road alongside river and cabins in the area.		
Recreational potential:	Area will become more attractive for recreational fishing. Minimum discharge is important for salmon production, but also for the esthetical impression of the river.		



Detailed description

Purpose
Install fish ladder and fish way to Increase anadromous stretch for Atlantic salmon with 2.9 km.

Construction works
Construct salmon ladder and fish way.

Environmental effect
Increase salmon abundance as river stretch has all the characteristics of a salmon river, with recruitment and spawning areas.

Social effect
Increased recreational value; both for local inhabitants and tourists.

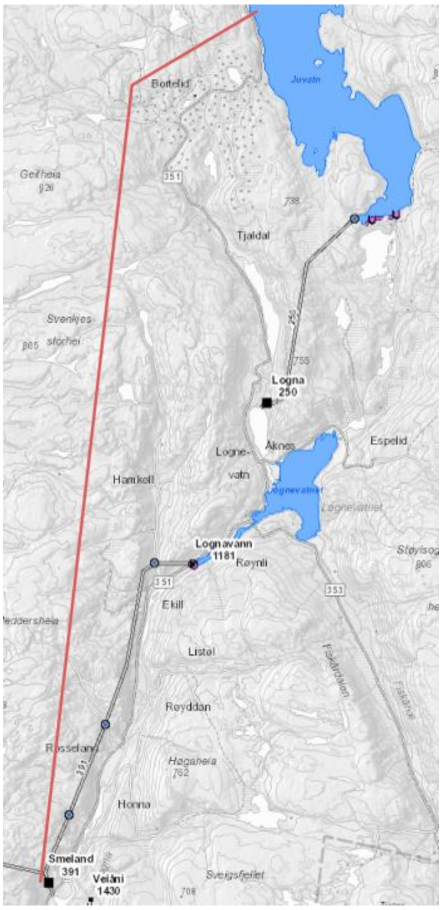
Costs
10-15 Mill NOK

- Alt 1: Minimum discharge winter 3, summer 6
- Alt 2: Minimum discharge winter 5, summer 10

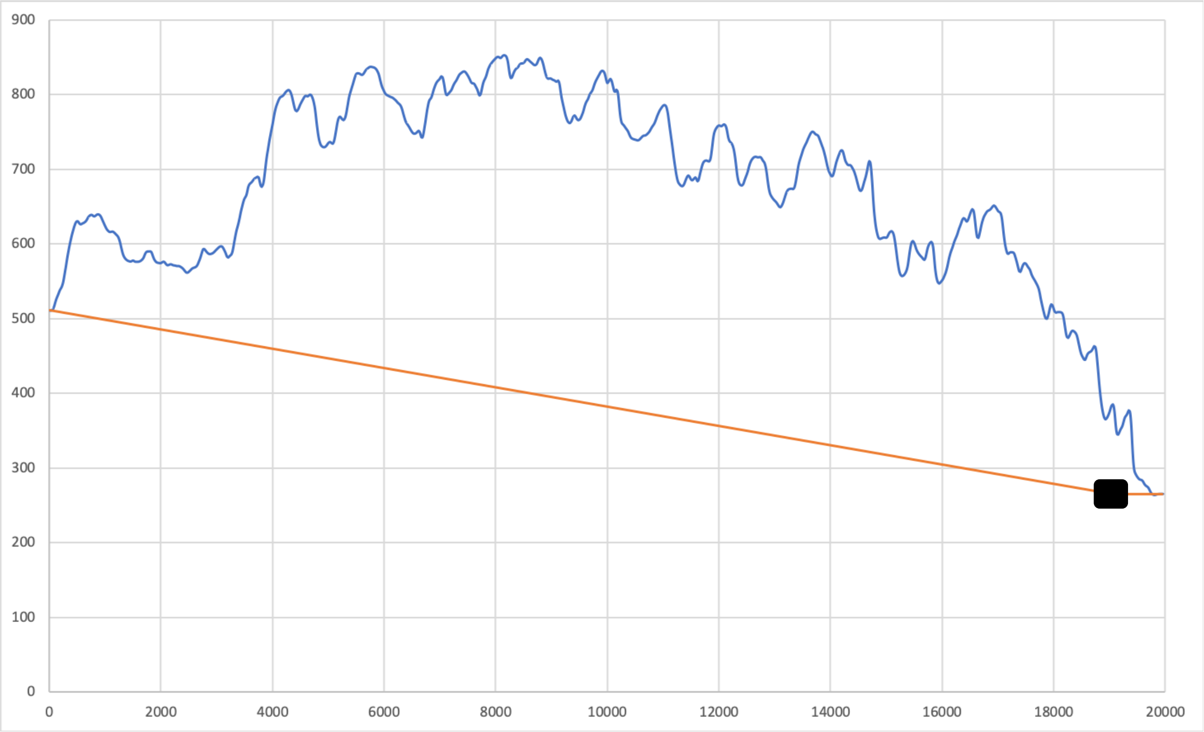
Category A – Conventional Power Plants

A.1
Juvatn – Smeland

Design principle:	Triple installed capacity	
Construction costs:	680 MNOK	
Power:	$P = 86$ MW	Turbine type: Vertical Francis
Gross head:	$H_0 = 245$ m	Units: 1x100 MVA
Discharge:	$Q = 40\ m^3/s$	Frequency converter: 1x30 MVA
Tunnel length:	$L = 20$ km	Rotational speed: 375
Tunnel area:	$A = 20\ m^2$	Speed number: 0.42



Tunnel profile



Variants

<u>Tunnel alignment:</u> Can reduce the tunnel length, but this requires crossing the valley.

Potential research topics

Environmental design for outlet into river.

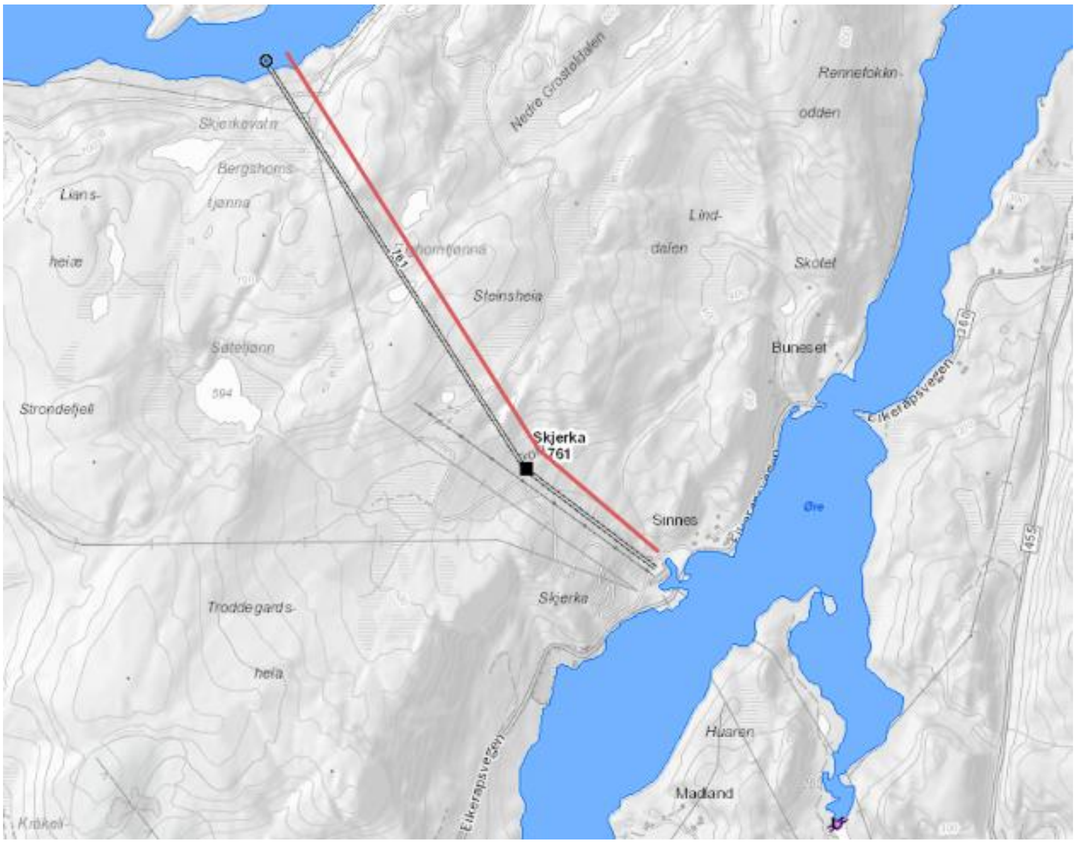
Long tunnels with low overburden.

Category A – Conventional Power Plants

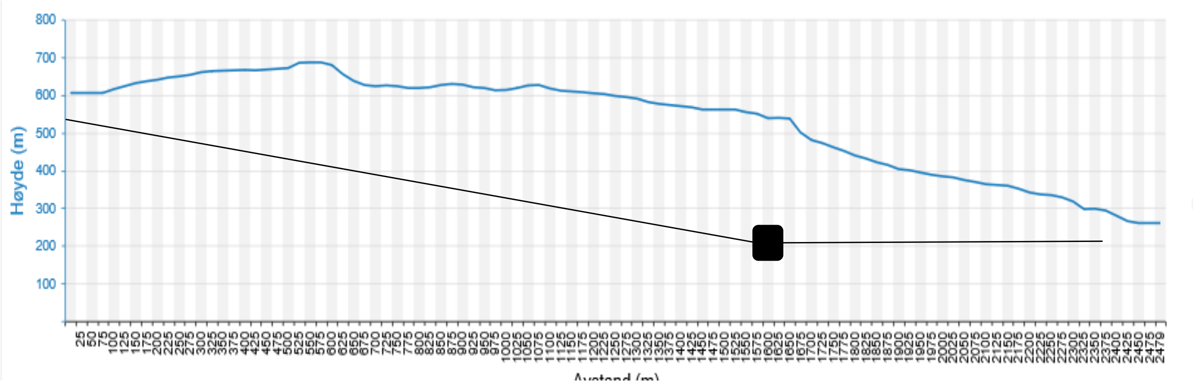
A.2

Nåvatn - Ørevatn

Design principle:	Triple installed capacity	
Construction costs:	790 MNOK	
Power:	$P = 400$ MW	Turbine type: Vertical Francis
Gross head:	$H_0 = 357$ m	Units: 1x465 MVA
Discharge:	$Q_{prod.} = 120\ m^3/s$	Frequency converter: 1x130 MVA
Tunnel length:	$L = 1.8$ km	Rotational speed: 214.3
Tunnel area:	$A = 60\ m^2$	Speed number: 0.32



Tunnel Profile



Variants

<u>Location:</u> Can potentially construct the power plant from the new reservoir Storavatn. This will give a shorter tunnel length and will utilize both reservoirs fully.

Potential Research Topics

HydroPeaking

Optimum use of frequency converters.

Steep tunneling.

Cleaning of unlined rock tunnels before commissioning.

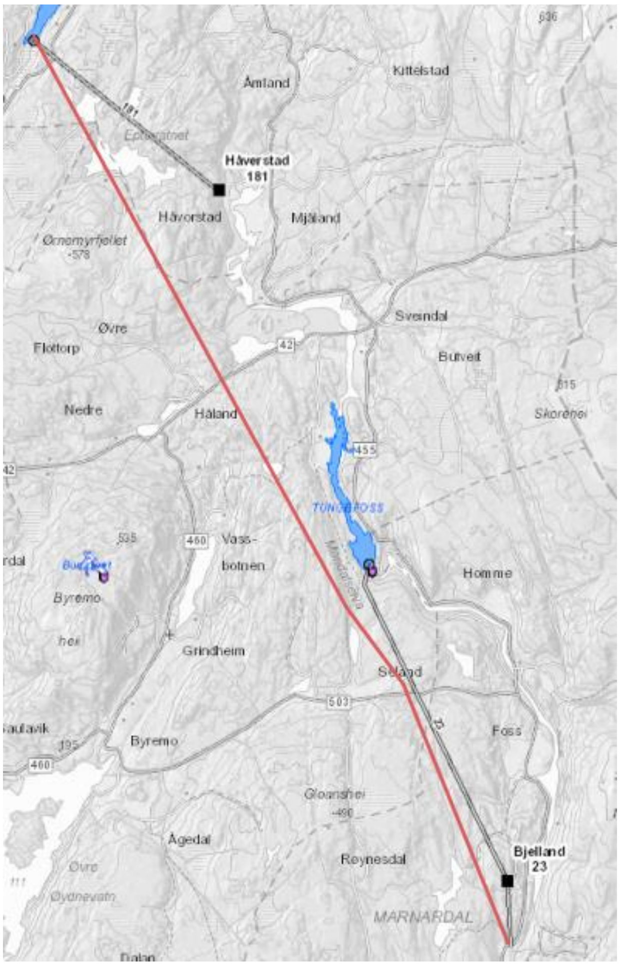
Category A – Conventional Power Plants

A.3
Ørevatn - Bjelland

Design principle: Triple installed capacity

Construction costs: 1050 MNOK
Power: $P = 206$ MW — Turbine type: Vertical Francis
Gross head: $H_0 = 180$ m — Units: 1x240 MVA
Discharge: $Q_{prod.} = 130\ m^3/s$ — Frequency converter: 1x67 MVA

Tunnel length: $L = 18$ km — Rotational speed: 200
Tunnel are: $A = 65\ m^2$ — Speed number: 0.52



Tunnel Profile

Variants

<u>Location of outlet:</u> Location of the outlet is crucial to avoid damaging natural spawning areas.

Potential Research Topics

Hydropower outlet close to natural spawning areas

HydroPeaking

Optimum use of frequency converters

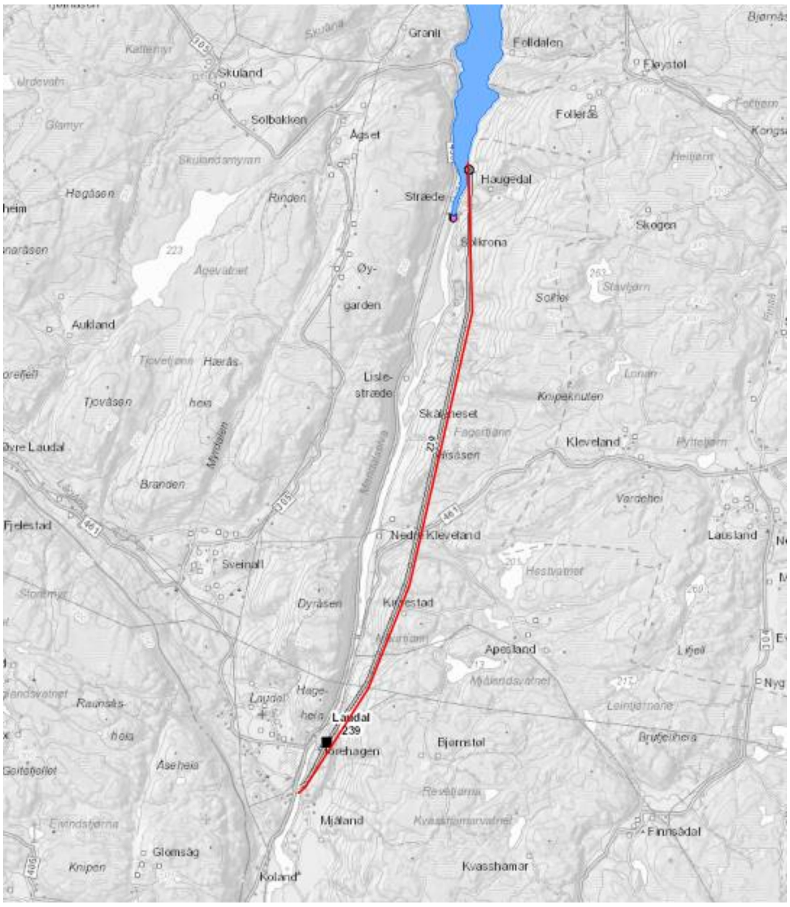
Long tunneling

Replacing two power plants with one new

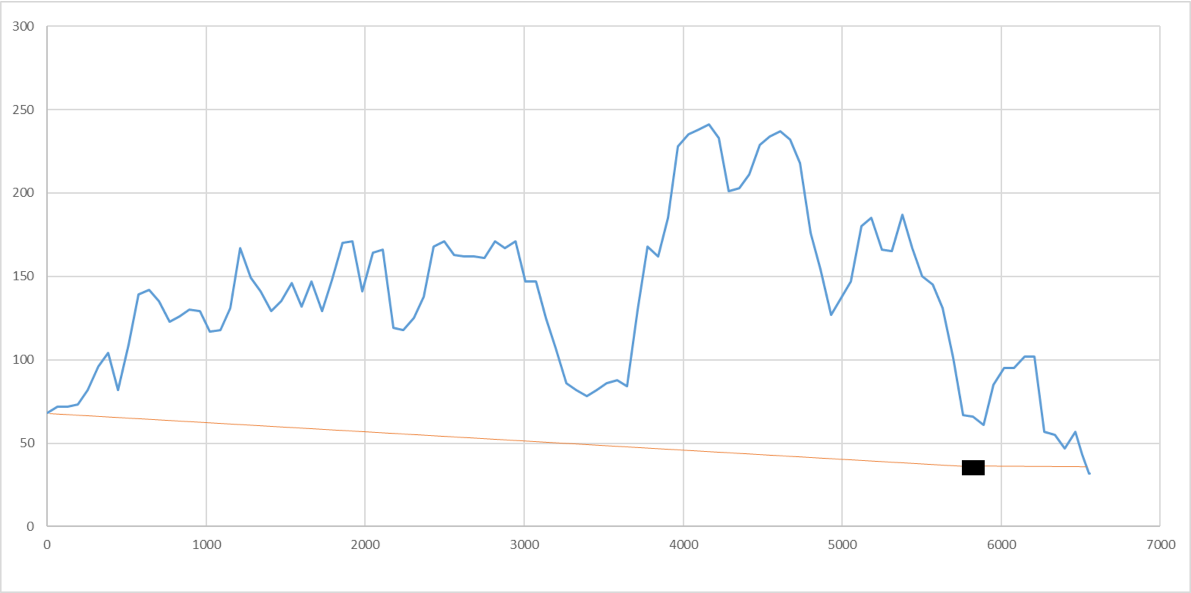
Category A – Conventional Power Plants

A.4
Laudal kraftverk

Design principle:	Triple installed capacity	
Construction costs:	600 MNOK	
Power:	P = 64 MW	Turbine type: Vertical Francis
Gross head:	$H_0 = 36$ m	Units: 1x75 MVA
Discharge:	$Q_{prod.} = 220\ m^3/s$	Frequency converter: 1x21 MVA
Tunnel length:	L = 6 km	Rotational speed: 62.5
Tunnel area:	$A = 110\ m^2$	Speed number: 0.71



Tunnel Profile



Variants

<u>Location of the outlet:</u> Variants of location of the outlet may give a few meter extra head.

Potential research topic

HydroPeaking

Fish friendly intakes

Optimum use of frequency converters

Governing stability for low head power plants

Category B – Pumped Storage Plants

B.1

Storavatn PSP

Design principle: Pumping floodwater

Construction costs: 940 MNOK

Power: $P_{prod.} = 500$ MW, $P_{pump} = 500$ MW

Turbine type: Vertical pump turb.

Gross head: $H_0 = 357$ m

Units: 2x290 MVA

Discharge: $Q_{prod.} = 160\ m^3/s$, $Q_{pump} = 120\ m^3/s$

Frequency converters: 2x290 MVA

Pump start: Frequency converters

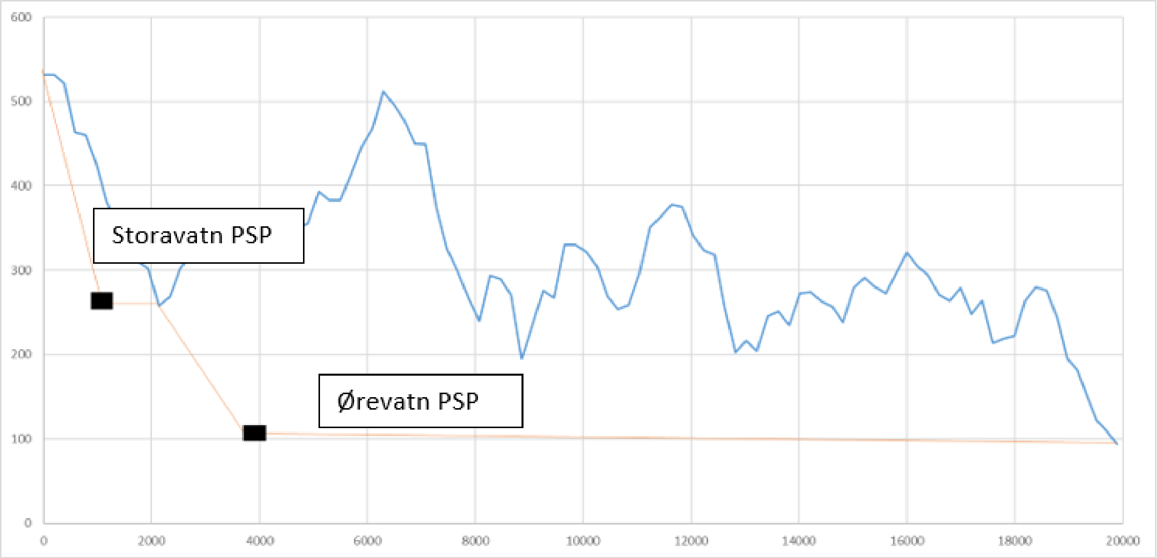
Tunnel length: L = 1.5 km

Rotational speed: 187

Tunnel area: $A = 80\ m^2$

Speed number: 0.33

Tunnel Profile



Varianter

Combined with Ørevatn PSP: Construction together with Ørevatn PSP, which will make it possible to pump and store water from the unregulated Kosåna.

Location of intake: If new Storavatn is not constructed, the intake may be place in Skjerkevatn.

Forskningstema

Flood water pumping plant.

Use of tailrace tunnel as pumping basin

Self-cleaning sandtraps

Variable speed

Category B – Pumped Storage Plants

B.2

Ørevatn PSP

Designprinsipp: Pumping floodwater

Construction costs: 820 MNOK

Power: $P_{prod.} = 120$ MW
$P_{pump} = 120$ MW

Turbine type: Vertical pump turb.

Gross head: $H_0 = 180$ m

Discharge: $Q_{prod.} = 82$ m^3/s
$Q_{pump} = 53$ m^3/s

Units: 1x120 MVA

Frequency converter: 1x120 MVA

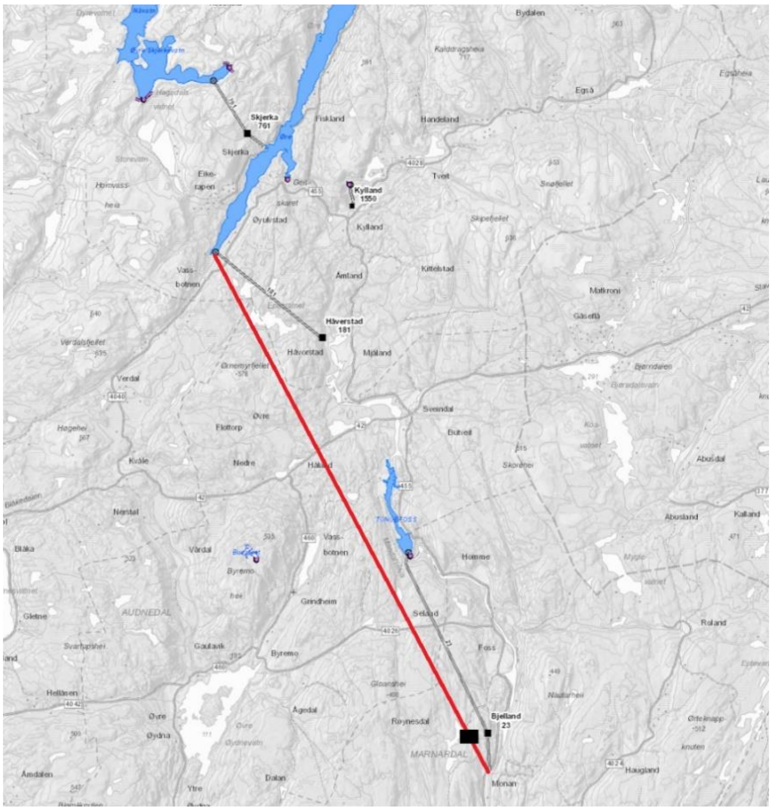
Pump start: Frequency converters

Tunnel length: L = 18 km

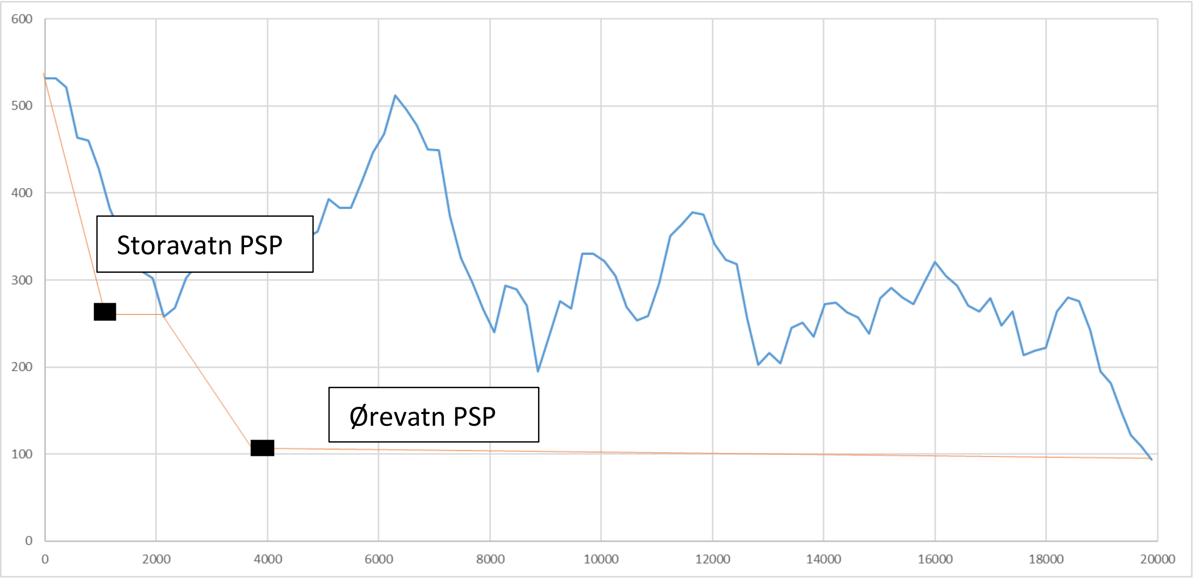
Tunnel area: A = 40 m^2

Rotational speed: 250

Speed number: 0.52



Tunnel profile



Variants

Combined with Ørevatn PSP: Construction together with Ørevatn PSP, which will make it possible to pump and store water from the unregulated Kosåna.

Location of outlet: The location of the outlet is crictical to avoid natural spawning areas. At the same time it is necessary to place the outlet downstream of the existing Bjelland HPP to have access to the water from that power plant.

Potential Research Topics

Flood water pumped plants

Tailrace tunnels as pumping basins

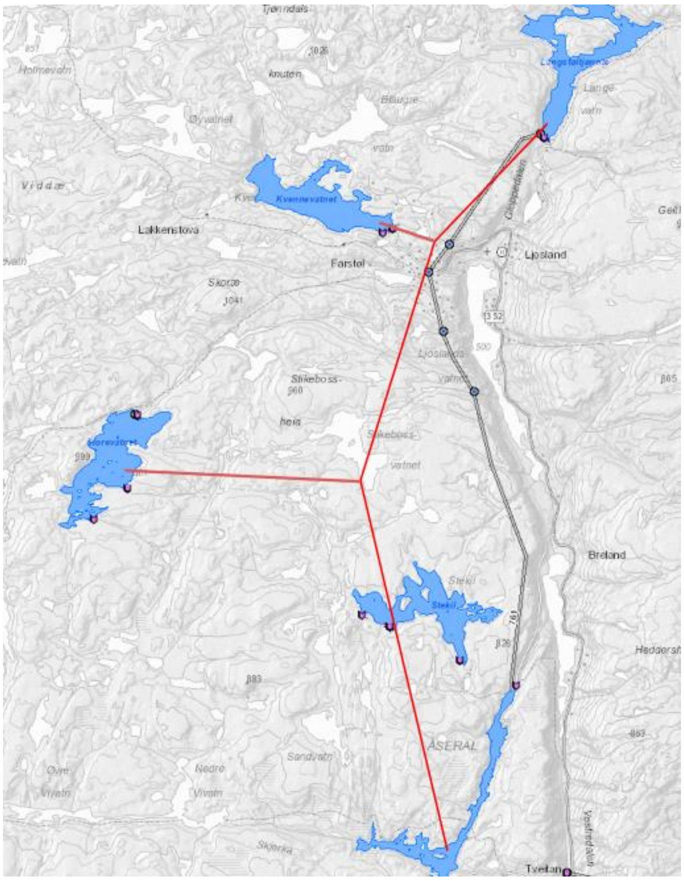
Self-cleaning sandtraps for PSPs

Use of frequency converters in PSPs

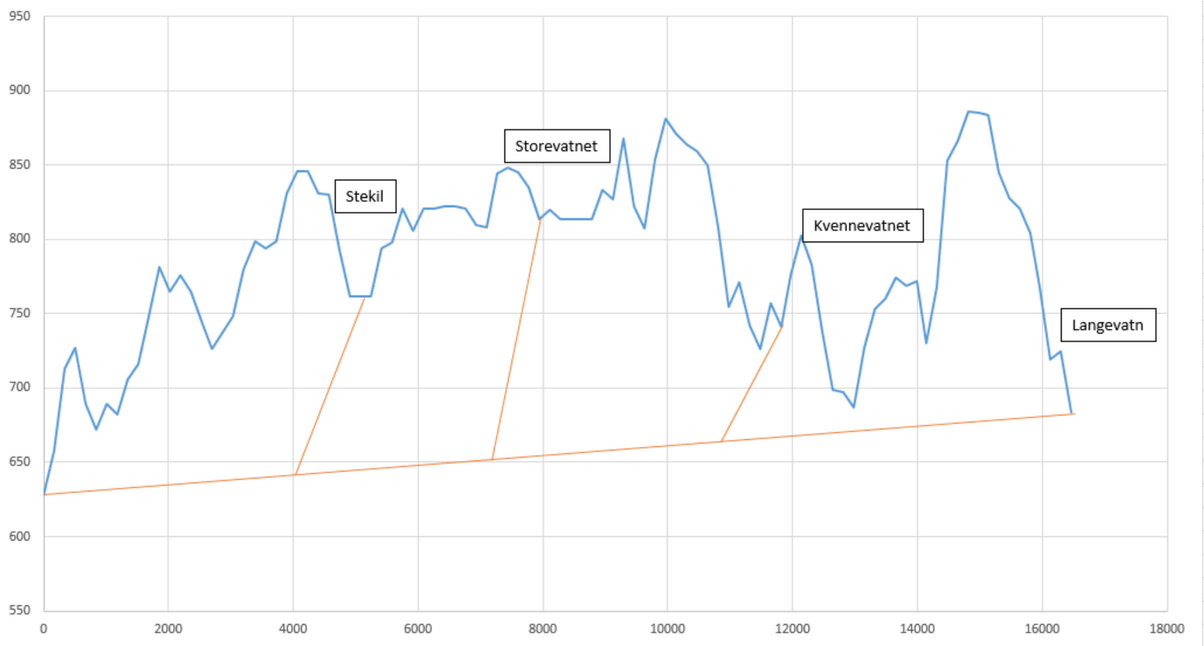
Category B – Pumped Storage Plants

B.3
Nåvatn – Stekilvatn/Kvennevatn/Langvatn/ Storevatnet

Design principle:	Utilize several small reservoirs efficiently	
Construction costs:	930 MNOK	
Power:	$P = 60$ MW	Turbine type: Vertical pump turbine
Gross head:	$H_0 = 70\text{-}250$ m	Units: 1x180 MVA
Discharge:	$Q_{prod.} = 30\text{-}125$ m^3/s	Frequency converter: 1x180 MVA
	$Q_{pump} = 20\text{-}60$ m^3/s	Pump start: Frequency converters
Tunnel length:	$L = 5/10/14/19$ km	Rotational speed: 100 - 300
Tunnel area:	$A = 65$ m^2	Speed number: 0.72-0.45



Tunnel Profile



Variants

Reservoirs: Can skip some of the reservoirs that gives a low value, such as Stekil.

Tunnel alignment: Can upgrade the existing tunnel to allow operation with higher pressure.

Potential Research Topics

Design of turbine, generator and frequency converter to allow a wide range of head and discharge

Frequency converters and use of overspeed (50%) to increase pump capacity.

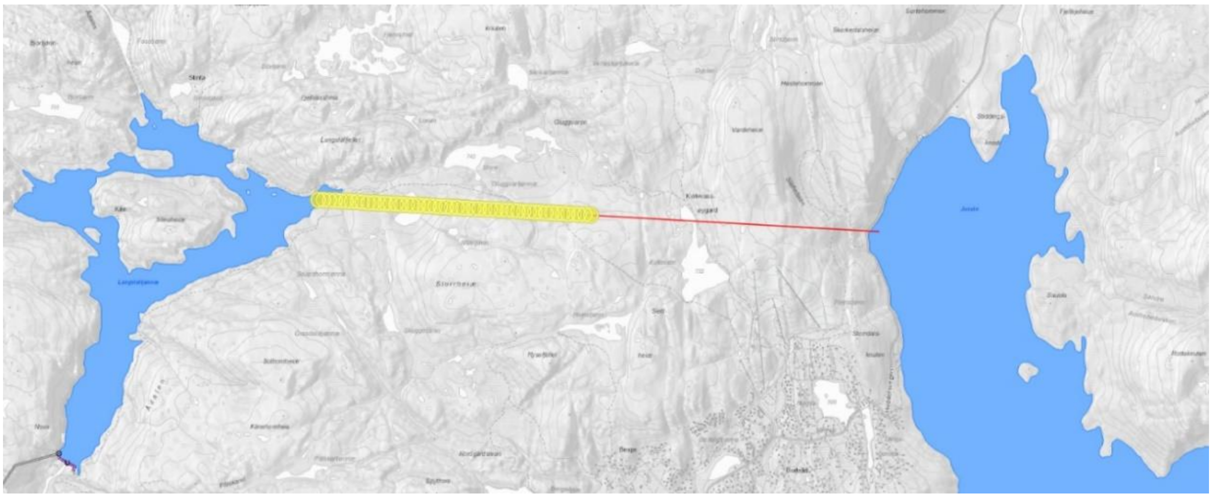
Tunnel system design with closing mechanism

Effect of large pressure variations on tunnel stability

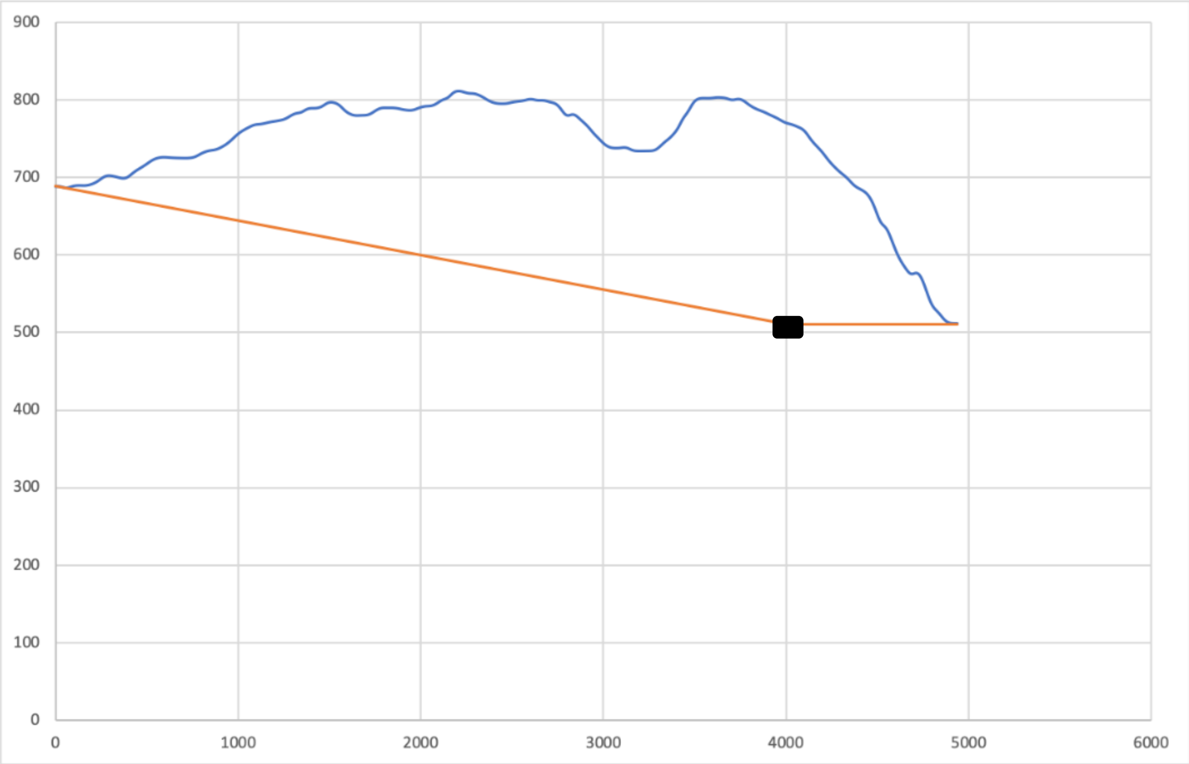
Category B – Pumped Storage Plants

B.4
Langvatn – Juvatn

Design principle:	14 days pumping cycle	
Construction costs:	340 MNOK	
Power:	$P = 70$ MW	Turbine type: Vertical pump turbine
Gross head:	$H_0 = 170$ m	Units: 1x85 MVA
Discharge:	$Q_{prod.} = 45\ m^3/s$	Frequency converter: 1x85 MVA
	$Q_{pump} = 35\ m^3/s$	Pump start: Frequency converters
Tunnel length:	$L = 5$ km	Rotational speed: 375
Tunnel area:	$A = 20\ m^2$	Speed number: 0.6



Tunnel Profile



Variants

<u>Installed capacity:</u> Can consider various size of the installed capacity.

Potential Research Topics

Use of frequency converters in pumped storage plants.

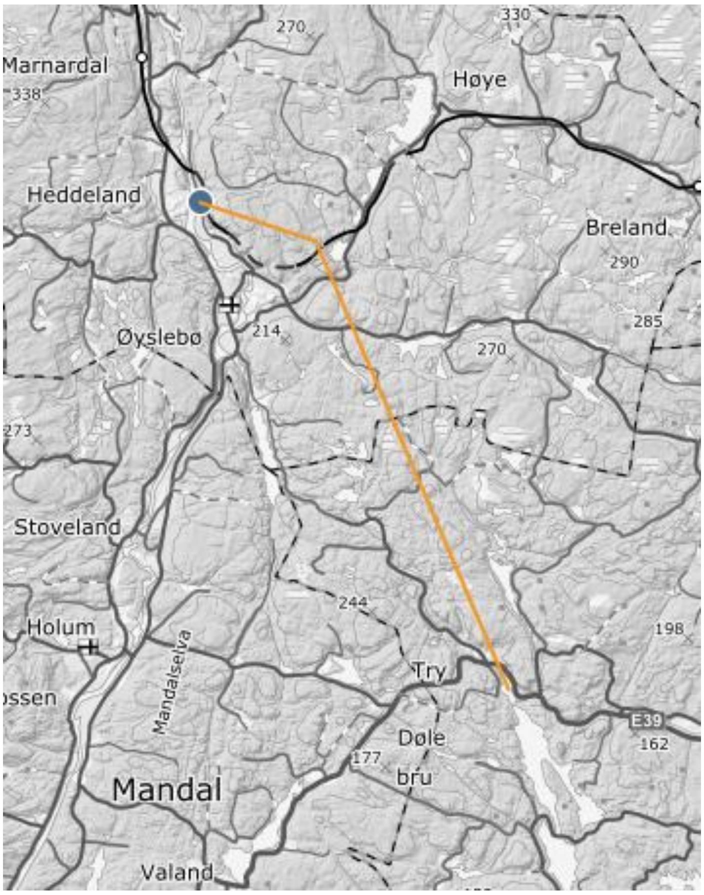
Optimum operation of PSPs between large reservoirs.

Category C – Flood Power Plants

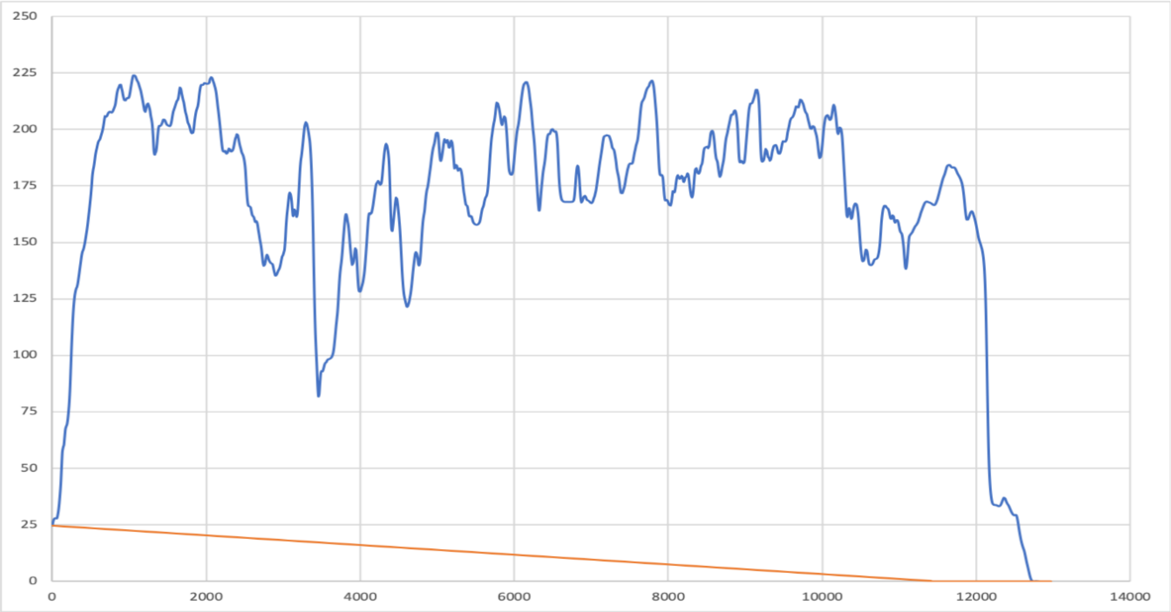
C.1

Øyslebø - Try

Design principle:	Reduce 200-year floods to 20-year floods	
Contruction costs:	800 MNOK	
Power:	P = 20 MW	Turbine type: Vertical Kaplan
Gross head:	$H_0 = 30$ m	Units: 1x25 MVA
Discharge:	$Q = 75$ m^3/s	Frequency converter: 1x5 MVA
Flood bypass:	$Q = 430$ m^3/s	
Tunnel length:	L = 12 km	Rotational speed: 93.75
Tunnel area:	$A = 120$ m^2	Speed number: 0.71



Tunnel Profile



Variants

Size of installed capacity: Can consider other installed capacities for both power production and flood discharge.

Outlet: It is possible to place the outlet in the fjord downstream of Mandal city instead of in Try. But the tunnel will be longer, and it might result in higher water levels in Mandal city during floods.

Potential Research Topics

Flood power plants

Design of fish friendly intakes for flood power plants

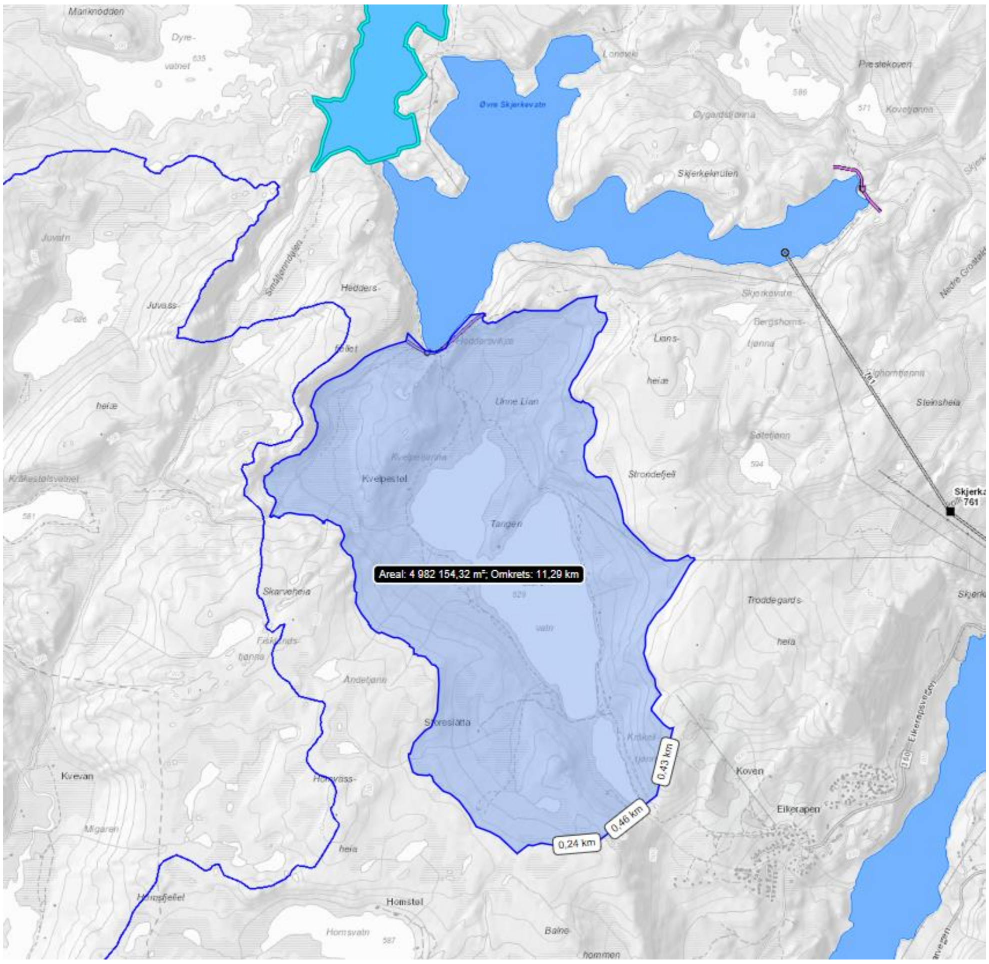
Design of tunnel systems that function both for power production and flood bypass.

Governing stability of hydropower units with long tunnels and low head.

Use of frequency converters for low head power plants.

D.1: Storevatn

Category D – New Reservoirs		
Existing	**Potential**	
Name: Storavatn WL: 529 masl Area = 0.8 km^2 Inflow = 13 mill. m^3	HRW = 580 masl Area = 2.7 km^2 V = 120 Mm^3 Inflow = 13 mill. m^3	HRW = 627 masl Area = 4.9 km^2 V = 280 Mm^3 Inflow = 13 mill. m^3
	Dam	
	Volume: 1.3 Mm^3 Cost: 400 MNOK	Volume: 6.6 Mm^3 Cost: 1600 MNOK



Variants

Size: There is a favourable location for a dam up to 580 masl that gives a reservoir volume of 120 Mm^3. But it is regarded as most realistic to dam up to the same height as the existing Skjerkevatn to combine the two reservoirs.

Potential Research Topics

Consequences of new reservoirs.

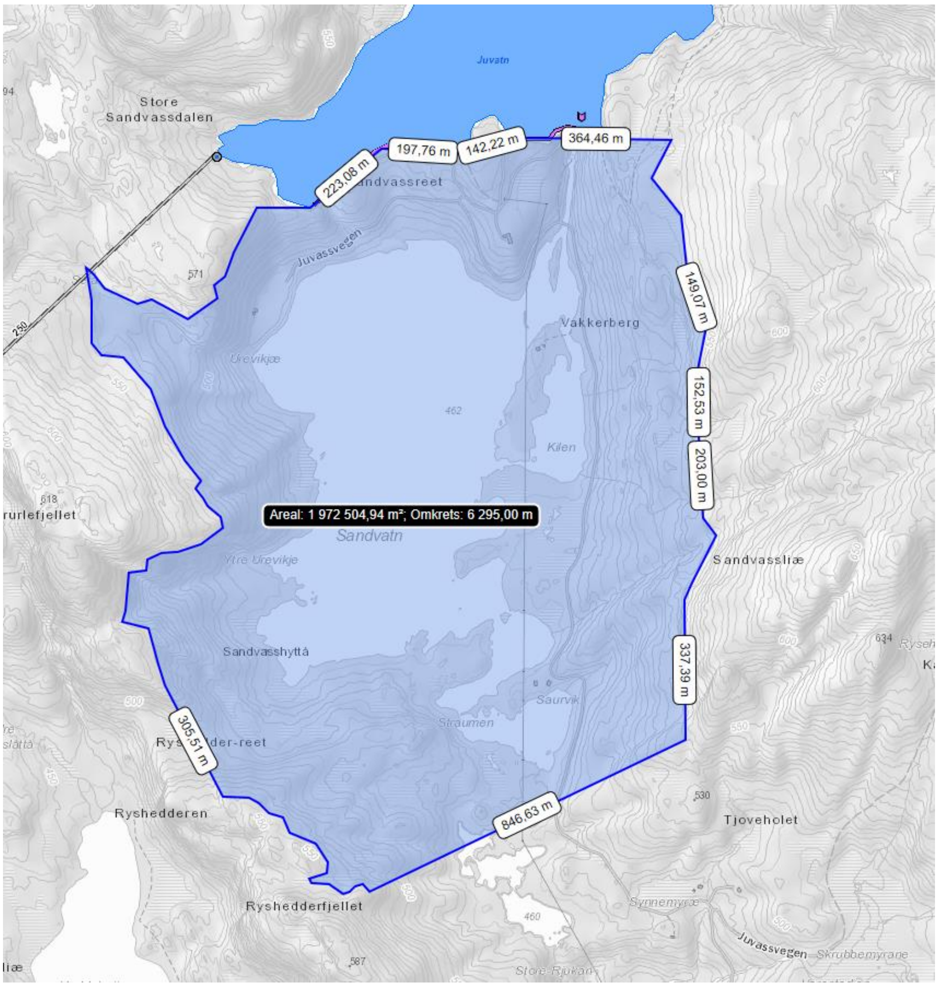
Cost efficient dams with fuseplugs.

Decommisioning of impounded dams.

Construction of large dams.

D.2: New Juvatn

Category D – New Reservoirs		
Existing	**Potential**	
LRW = 489 masl HRW = 513 masl Area = 8.1 km^2 V = 143 Mm^3 Inflow = 360 Mm^3	HRW = 540 masl Area = 14 km^2 V = 520 Mm^3 Inflow = 360 Mm^3 Dam Volume: 1.2 Mm^3 Cost: 400 MNOK	HRW = 540 masl Area = 16 km^2 V = 620 Mm^3 Inflow = 360 Mm^3 Dam Volume: 5 Mm^3 Cost: 1600 MNOK



Variants

Location: The Juvatn reservoir may be heightened by construction a higher dam in the same location, or by constructing a new and higher dam further downstream.

Dam height: The suggested alternatives are based one the use of only one dam. If more dams are used, it is possible to increase the reservoir height further.

Potential Research Topics

Consequences of new reservoir.

Cost efficient dams with fuseplugs.

Construction of large dams.

Environmental design of new reservoirs.

D.3: New Kvennevatnet

Category D – New Reservoirs	
Existing	Potential
LRW = 745 masl HRW = 771 masl Area = 2 km^2 V = 38 Mm^3 Inflow = 63 Mm^3	HRW = 780 masl Area = 2.4 km^2 V = 90 Mm^3 Inflow = 63 Mm^3 Dam: Volume = 0.15 mill. m^3 Cost = 50 MNOK

Variants

Dam height: The suggested alternative is based on only heightening the existing dam. However, the reservoir can be heightened even further if another dam is constructed in the north-east end of the reservoir.

Potential Research Topics

Consequences of heightening existing reservoirs

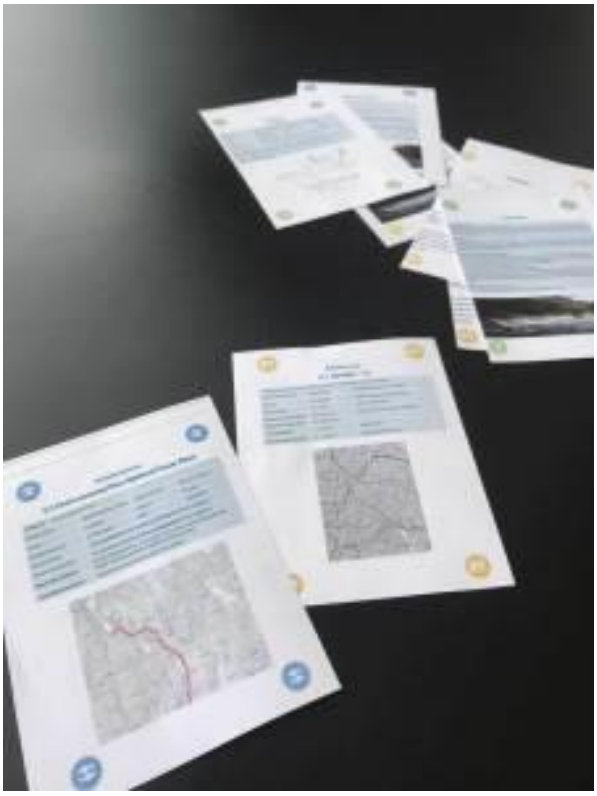
Cost efficient construction of dams with fuseplugs.

Environmental design of new reservoirs.

Innovation Cards

I.1 Deck-of-Cards Method

Category:	**Hydropower Development**		
Case study:	Mandalsvassdraget	Lifetime:	-
Costs:	-	Construction time:	-
Income:	-	NPV:	-
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: A method to map alternatives for environmentally friendly reconstruction of existing hydropower systems. For use in the pre-feasibility phase.			
Overall assessment: A simple and useful tool to obtain an overview of possible combination of hydropower projects and environmental projects, and select scenarios based on a set of design criteria.			



Case study

Scope
Find the best alternatives for environmentally friendly reconstruction of an existing hydropower system.

Requirements
A multidisciplinary work group, maps, site visits, hydrology data, hydropower production data, available previous studies and reports from the hydropower system.

Method and costs
Map and describe all possible hydropower projects on two-page "hydropower cards". Map and describe all possible environmental projects on two-page "environmental cards". Gather the multidisciplinary group and discuss all possible combinations and select the optimal combinations. Conduct production simulations and assess the results.

Consequences for power production and income
Higher probability of detecting and selecting the optimal alternatives.

Environmental consequences
Higher probability of selecting the most environmentally friendly alternatives.

I.2 SediSluicer for Brook Intakes

Category:	**Operation and maintenance**		
Case study:	Stekil brook intake	Lifetime:	20 years
Costs:	1 MNOK	Construction time:	2 weeks
Income:	0.1 MNOK/year	NPV:	0.2 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Install Sedisluicers in brook intakes to avoid deposition of sand, gravel and debris that might cause clogging.			
Overall assessment: Cost-effective measure for brook intakes with sediment accumulation problems. Only profitable for brook intakes that have such challenges, which are of a limited number in Norway.			

Case study

Design criteria
Allow the brook intake to operate without interruption and water losses caused by sediments and debris.

Dimensions
Pipes with D = 0.3 m and L = 30 m installed in the brook intake basin.

Construction method and costs
Fix the pipes with bolts. Drill a hole through the concrete weir and mount a pipe through to the downstream side of the weir for flushing. The driving force is gravity.

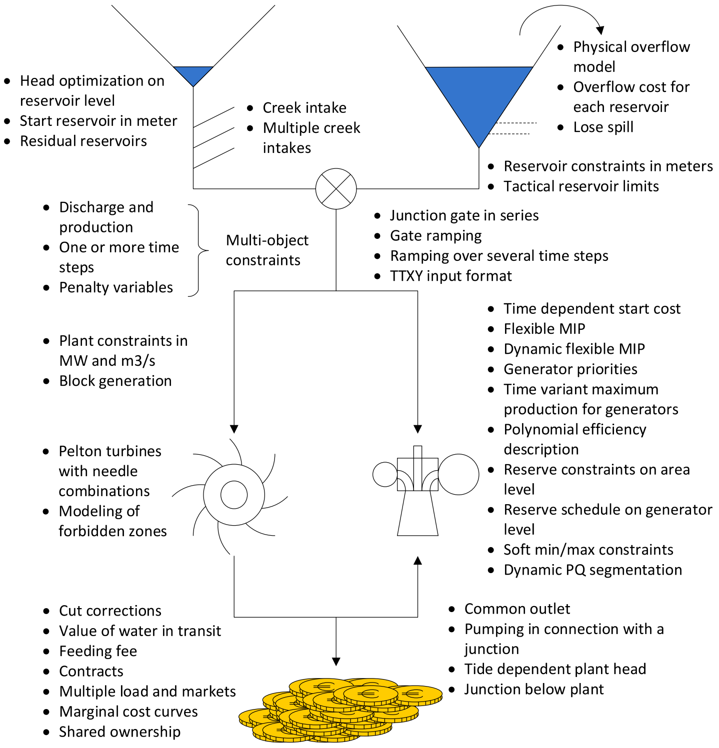
Consequence for power production and income
Will reduce the flood loss as clogging problems will be reduced.

Environmental consequence
May have a negative environmental consequence as when the water is diverted into the tunnels, while the sediments are bypassed to the river. The amount of sediments may be to high compared to the low environmental flow left in the river.

Innovation Cards

I.3 SHOP-ProdRisk Simulator

Category:	**Production simulations**		
Case study:	New Skjerka HPP	Lifetime:	-
Costs:	0.5 MNOK	Commissioning time:	6 months
Income:	8 MNOK	NPV:	7.5 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: A new tool adapted to analyses of future hydro upgrading and refurbishment projects. The tool includes a new coupling of long-term models with short term models.			
Overall assessment: Valuable tool that will improve investment decisions at a limited cost.			



Design criteria
The model simulates optimal operation of a given hydro system for a sequence of inflow and market price scenarios.

Dimensions
A software to be installed and made available for the persons that do production simulation studies in relation to investment decisions.

Construction method and costs
Costs for installing the system including training of the users are estimated to 0.5 MNOK.

Consequence for power production and income
Main benefit of the tool will be improved decision support for investment decisions. For the New Skjerka HPP it is assumed that the tool will improve the decision making and generate 1% more profit from the project.

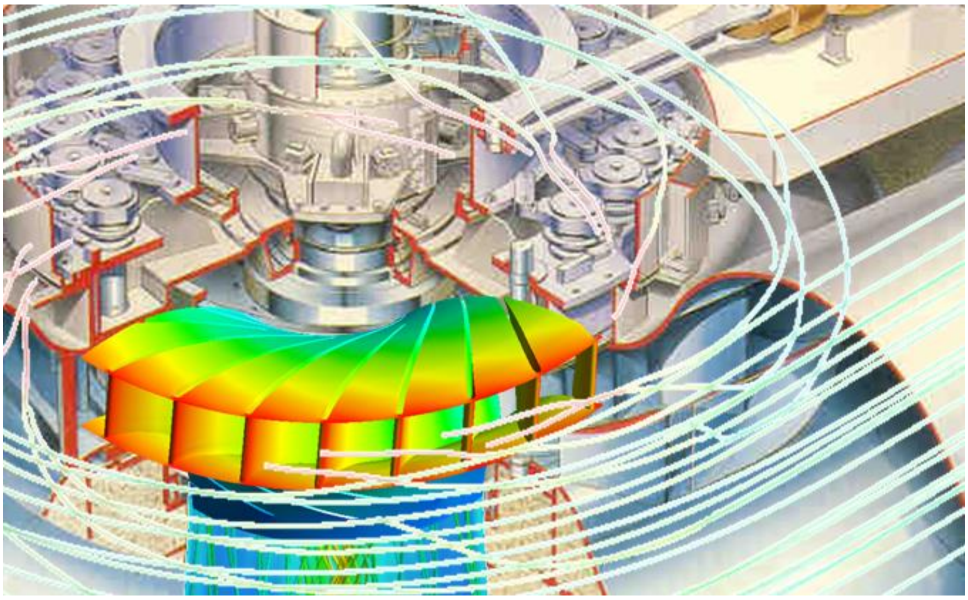
Environmental consequence
There is no consequence.

Case study

Innovation Cards

I.15 OMGvanes

Category:	**Turbine technology**		
Case study:	Skjerka HPP	Lifetime:	20 years
Costs:	1 MNOK	Construction time:	2 years
Income:	0.2 MNOK/year	NPV:	1 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Design of turbine runners, stay vanes and guide vanes with optimized profiles. Will reduce the headlosses and increase turbine efficiency, reduce the risk of dynamic loads leading to undesired phenomena because the loads are the cause of less dynamics. May also be used on propellers and other hydraulic vanes.			
Overall assessment: Good effect at a limited cost. Vast potential in various hydraulic components.			



Case study

Design criteria
Reduce effect of dynamic loads and thereby making possible a slimmer design enabling a reduction of hydraulic losses.

Dimensions
Not affecting the main dimension criteria of the unit.

Construction method and costs
Construct with optimized profiles. Added production costs for turbine runner, stayvanes and guidevanes estimated to 1 MNOK for the case study.

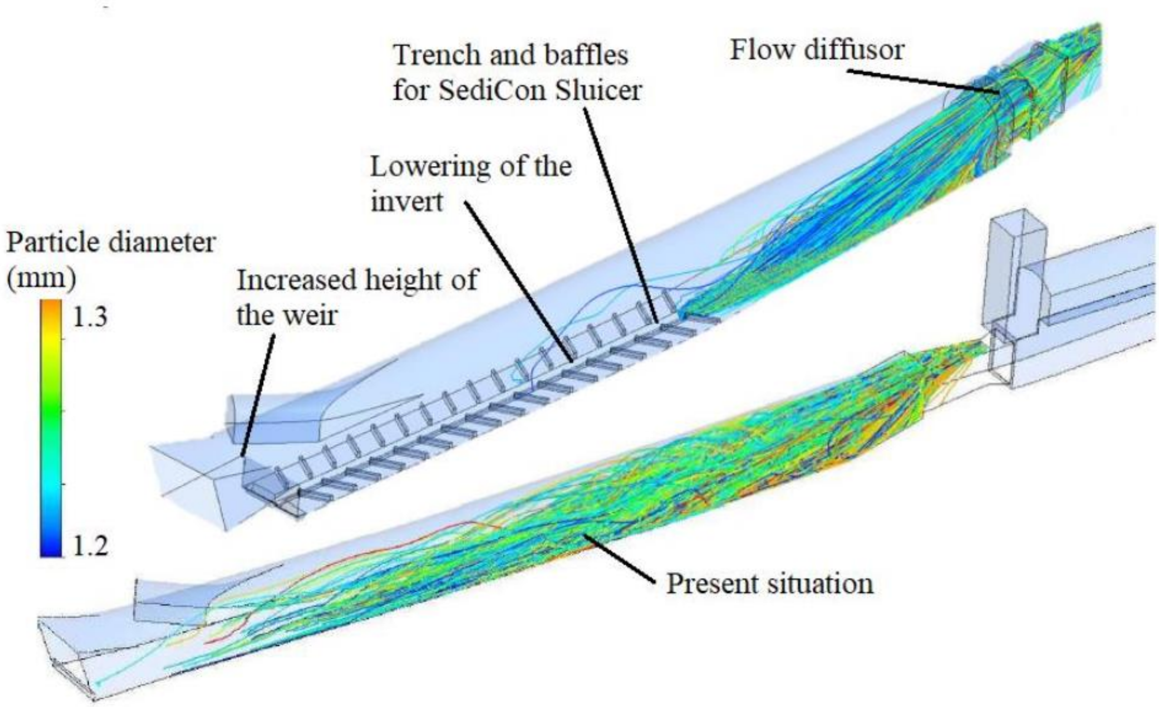
Consequence for power production and income
The increase of turbine efficiency is assumed to be 0.1%. For Skjerka HPP this equals 0.6 GWh/year. Reduced risk of failure and fatigue.

Environmental consequence
More production of renewable energy without using more water.

Innovation Cards

I.5 Flexible Sandtraps

Category:	**Sediment handling**		
Case study:	Skjerka HPP	Lifetime:	100 years
Costs:	4 MNOK	Construction time:	6 mnd
Income:	0.1 MNOK/year	NPV:	-3 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Reconstruction of existing sandtraps, to allow upgrade of the installed capacity.			
Overall assessment: Good effect and limited costs. Only profitable if the sandtrap does not perform properly, or if the installed capacity is being increased. There are no recorded problems with sandtraps in Mandalsvassdraget and hence no profitability.			



Case study

Design criteria

Improve the trap efficiency of the sandtrap and allow a 10% power upgrade.

Dimensions

The sandtrap does not need to be expanded in size, and only structural components inside are necessary. A flow conditioner, shear plates and a sediment flushing arrangement are installed.

Construction method and costs

The flow conditioner and flushing arrangement are prefabricated and can be bolted together during a short dewatering period. Costs are estimated to 4 MNOK for the case study.

Consequence for power production and income

The improved trap efficiency will result in less turbine wear. Installation of a sediment sluicing system will reduce operational costs and need for dewatering. Estimated income caused by less turbine wear and dewatering is 0.1 MNOK per year for the case-study. The possible power upgrade will yield increase power production revenues.

Environmental consequence

No environmental consequence.

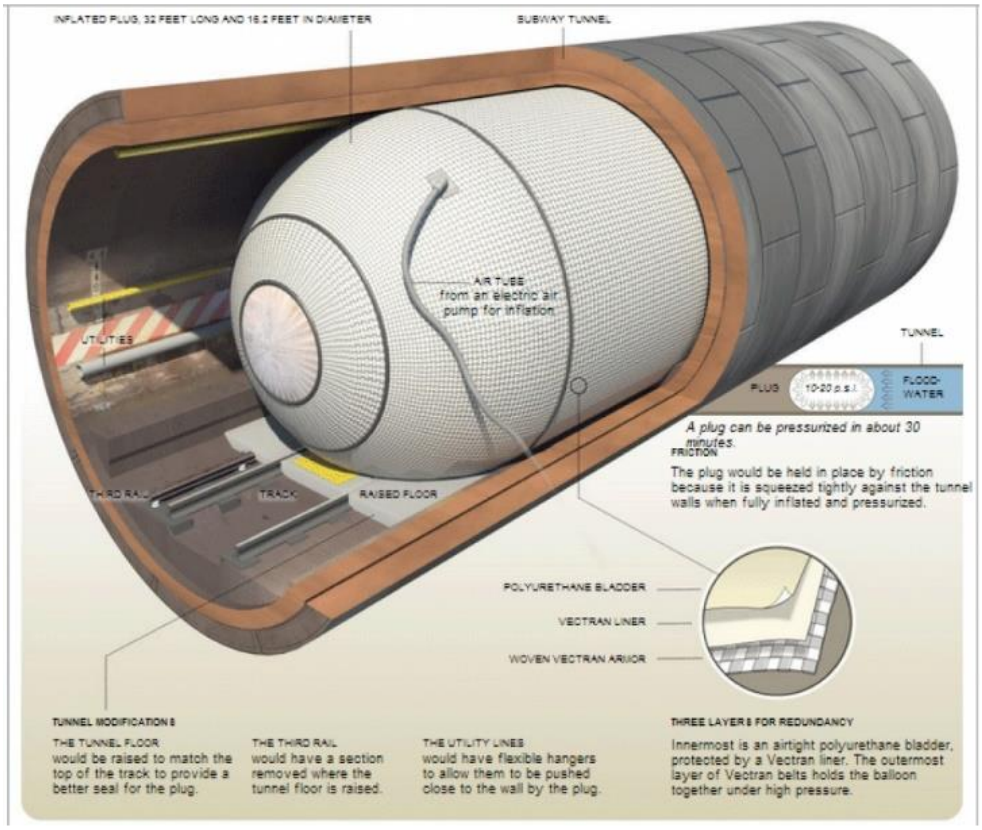
Innovation Cards

I.6 Tunnel Balloon Plug

Category:	**Power plant O/M**		
Case study:	Ørevatn PSP	Lifetime:	20 years
Costs:	10 MNOK	Construction time:	1 mnd.
Income:	14 MNOK	NPV:	4 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/Positive/**Neutral**/Negative/Very negative		

Short description: Use of inflatable plugs for dewatering of hydropower tunnels.

Overall assessment: Low cost and flexible solution that can be used in addition or as an alternative to permanent gates or valves. Promising, but needs validation for the size and pressures relevant for hydropower plants.



A plug can be pressurized in about 30 minutes.

FRICTION

The plug would be held in place by friction because it is squeezed tightly against the tunnel walls when fully inflated and pressurized.

TUNNEL MODIFICATIONS

THE TUNNEL FLOOR would be raised to match the top of the track to provide a better seal for the plug.

THE THIRD RAIL would have a section removed where the tunnel floor is raised.

THE UTILITY LINES would have flexible hangers to allow them to be pushed close to the wall by the plug.

THREE LAYERS FOR REDUNDANCY

Innermost is an airtight polyurethane bladder, protected by a Vectran liner. The outermost layer of Vectran belts holds the balloon together under high pressure.

Case study

Design criteria

Plug the intake tunnel for Bjelland PSP when dewatering is necessary. Shall be an alternative to constructing a normal intake gate.

Dimensions

Circular plug with a diameter of 7 m. Assuming a cross-sectional area of 40 m^3 and pressure P = 100 mVS.

Construction method and costs

Concrete foundation for placing the plug to reduce leakage and provide additional stability: 0.5 MNOK. The cost for a plug with diameter of 5 m is assumed by the manufacturer to be in the range of 4 MNOK. For this case a plug with D = 7 m is needed and the costs are assumed to be 8 million MNOK. Compressor and auxiliary equipment estimated to 1 MNOK.

Consequence for power production and income

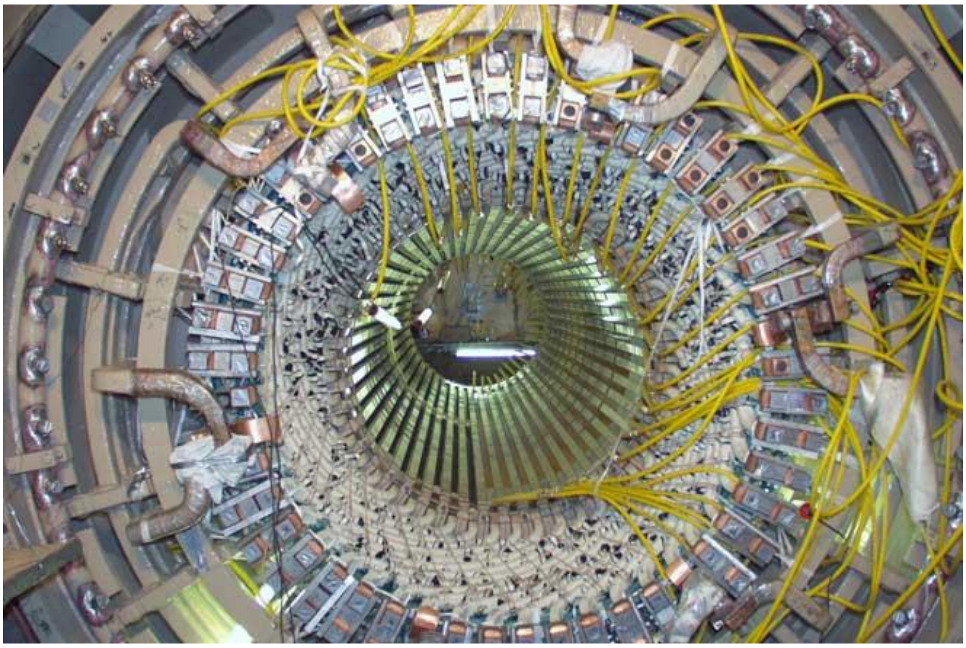
No consequence for power production. Makes repair and maintenance of existing gates and valves possible and may eliminates the cost of permanent gates for new hydropower projects. A complete intake structure for the Ørevatn PSP is estimated to be 14 MNOK. The costs savings if a tunnel balloon plug can be used instead is 4 MNOK.

Environmental consequence

Slightly positive because the use of moveable plugs eliminates the need for above ground intake structures.

I.7 Fault Detection in Generators

Category:	**Operation and maintenance**		
Case study:	Skjerka HPP	Lifetime:	20 years
Costs:	2 MNOK	Construction time:	2 months
Income:	7 MNOK	NPV:	5 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Improved methods for early stage fault detection in generators. Will result in avoided generator failures.			
Overall assessment: Good effect and a limited cost.			



Case study

Design criteria
Reduce unexpected generator failures during the lifetime of the component.

Dimensions
Measuring equipment, a data acquisition unit and data processing tools.

Construction method and costs
Installing measuring equipment during outage of the unit. Costs estimated to 2 MNOK.

Consequence for power production and income
Will have a positive effect on power production as outage is reduced. Maintenance costs will be reduced as faults can be detected at an earlier stage. Assumed a fault with a repair and outage cost of 10 MNOK is avoided after 5 years of operation.

Environmental consequence
No environmental consequence.

I.8 Snorkel for Large Coanda Screen Intakes

Category:	**Intakes**		
Case study:	Stekil brook intake	Lifetime:	20 years
Costs:	0.2 MNOK	Construction time:	1 mnd
Income:	0.05 MNOK/year	NPV:	0.3 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		

Short description: Use of a large-scale snorkel to reduce water loss caused by icing on Coanda intakes. This innovation is a modification of an existing concept.

Overall assessment: Very good effect and limited costs.

Case study

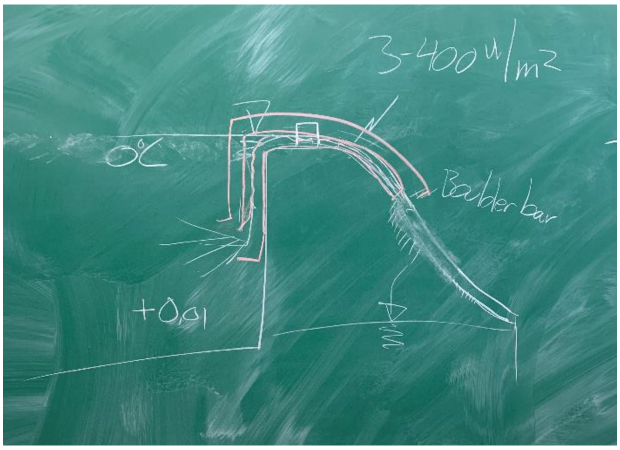
Design criteria
Reduce icing problems on coanda screen intakes. Design for half the intake discharge capacity.

Dimensions
Several PE pipe 2 m long and 200 mm in diameter.

Construction method and costs
Removable pipe clamped on the intake during winter.

Consequence for power production and income
Will reduce clogging of the intake due to ice. Will reduce spill-losses. Assumed annual profit from the extra power production is 0.05 MNOK for the case-study.

Environmental consequence
Less water loss from the intake during winter.

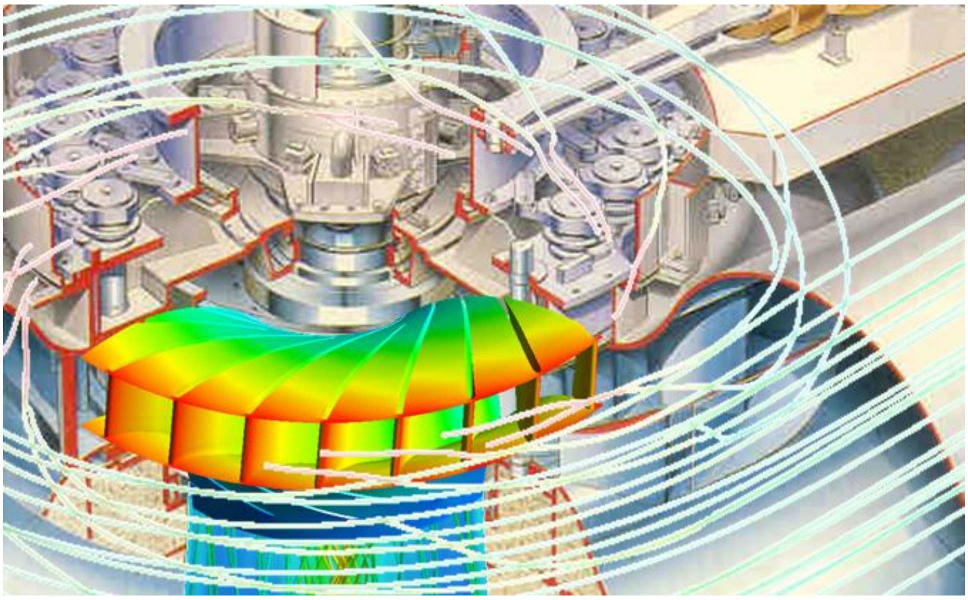


I.9 Guideless Francis Turbine to Reduce Sediment Abrasion

Category:	**Turbine technology and sediment handling**		
Case study:	Skjerka HPP	Lifetime:	20 years
Costs:	100 MNOK	Construction time:	24 mnd.
Income:	14 MNOK	NPV:	-86 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		

Short description: Francis turbine design without guide vanes. No guide vanes will yield higher best-point efficiency but will not give the possibility to operate at different flow. Will require the use of multiple units to operate at different flow. No guide vanes will reduce the sediment erosion challenges for the turbine and reduce the manufacturing cost for the turbine.

Overall assessment: Good effect on sediment handling. Increases the overall efficiency and operating range of the power plant but increases the costs.



Case study

Design criteria
Use three units of 50 MW, 100 MW and 250 MW without guidevanes instead of one unit of 400 MW with guidevanes. The three units will have different installed capacity to have maximum flexibility.

Dimensions
The head of the power plant is 360 m and the maximum discharge is 120 m3/s. The runner diameter will increase to lower the velocity and hence the sediment erosion. The overall turbine diameter will be decreased as there are no guide vanes. The power house length will increase as there is three units instead of only one.

Construction method and costs
The guideless turbine is produced with only stay vanes reducing the cost of the turbine in the range of 20-30%. The cost of one 400 MW unit with guidevanes is estimated to 360 MNOK. The cost of the three smaller units are estimated to 410 MNOK[1]. The extra power plant civil costs are estimated to 50 MNOK.

Consequence for power production and income
The turbine efficiency in the best point will increase owing to less friction. The three smaller units will always run on best point. The operational range of the 400 MW in combination with the existing plant will be in the range 61 to 667 MW, while the three smaller turbines can operate in the range 45 MW to 667 MW with a flatter combined efficiency curve.

Environmental consequence
The turbine design allows more sediments to pass through the turbine with reduced O&M consequences thereby allowing more nutrients to be carried downstream giving a positive environmental impact compared to traditional design.

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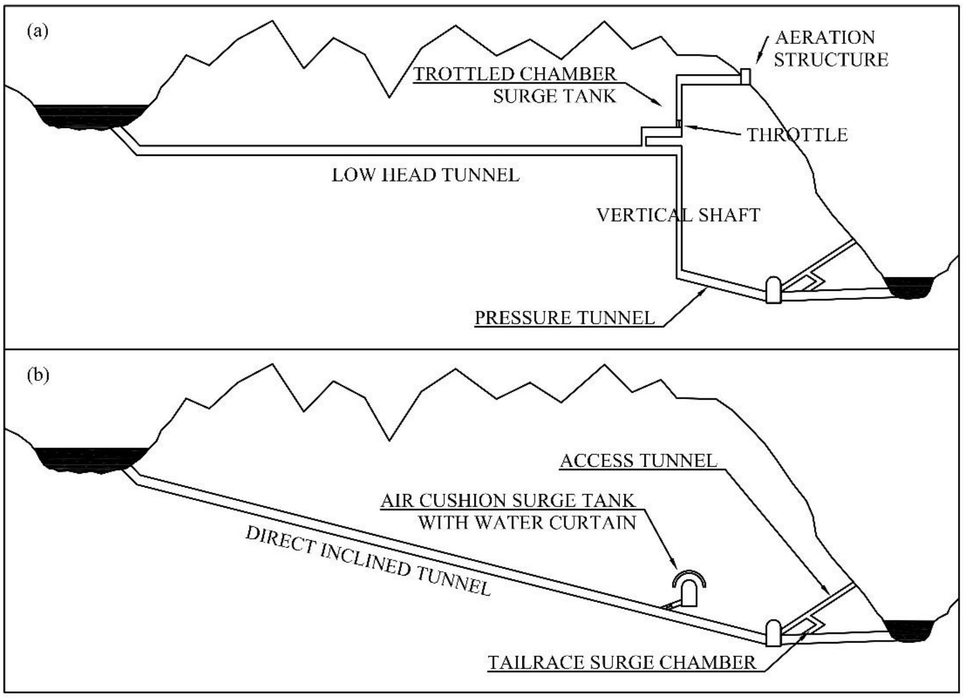
[1] Based on NVE's «Kostnadsgrunnlag for vannkraft» January 2015. cost excluding transformators and lines.

I.10 Improved Design of Air Cushion Surge Chamber

Category:	**Civil and Geotechnical Engineering**		
Case study:	Bjelland PSP	Lifetime:	100 years
Costs:	-20 MNOK	Construction time:	2 mnd
Income:	0 MNOK/year	NPV:	20 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/Positive/**Neutral**/Negative/Very negative		

Short description: New design of air cushion surge chamber (ACSC) to reduce risk of problematic air leakages and allow easier dewatering of the tunnel system. The new design includes pregrouting and optimized cross-section to reduce air leakages, and a closing mechanism to allow dewatering of the main tunnel without having to empty and refill the air in the ACSC.

Overall assessment: Good effect at limited costs. May render the ACSC more attractive than conventional surge tanks for more hydropower projects.



Case study

Design criteria

Use an ACSC instead of a conventional surge tank. Direct inclined tunneling when using ACSC compared with low-head headrace tunnel and vertical shaft for conventional surge tank. The ACSC shall have a closing mechanics that allow dewatering of the main tunnel without emptying the air from the ACSC.

Dimensions

The headrace tunnel with ACSC is 10% shorter and do not require an expensive pressure shaft. The ACSC is 500% larger than the conventional surge tank. In sum the total excavation is rock is 5% less for the design with ACSC.

Construction method and costs

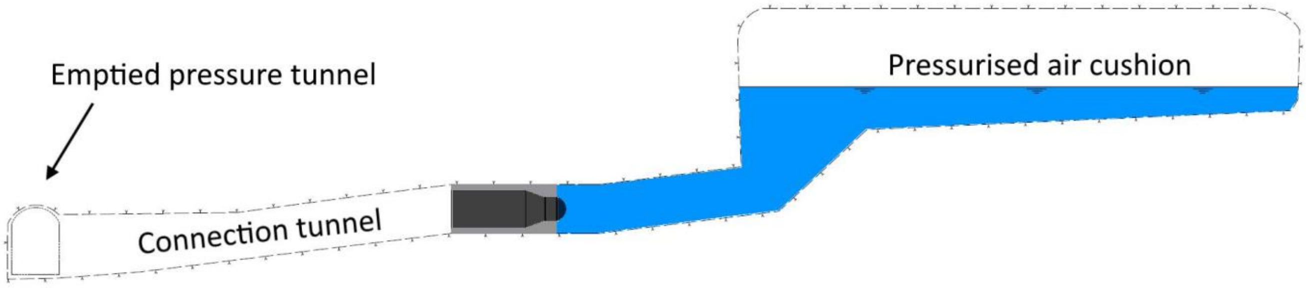
The tunnel system with ACSC can be constructed without a surface access and with a direct inclined tunnel without a pressure shaft. The ACSC is constructed with pregrouting and optimized profile to improve the permeability of the rock mass. The ACSC is constructed with a concrete plug and a closing mechanism to allow dewatering of the tunnel without emptying the ACSC. The ACSC is constructed as two individual chambers to reduce risk of leakages and to reduce downtime if one has to be emptied. The power plant with ACC is estimated to be 20 MNOK less expensive.

Consequence for power production and income

The ACC will allow a more flexible operation of the hydropower plant as the surge facility can be placed closer to the turbine and reduce the acceleration time and water hammer. However, the risk of operational challenges is higher with an ACSC.

Environmental consequence

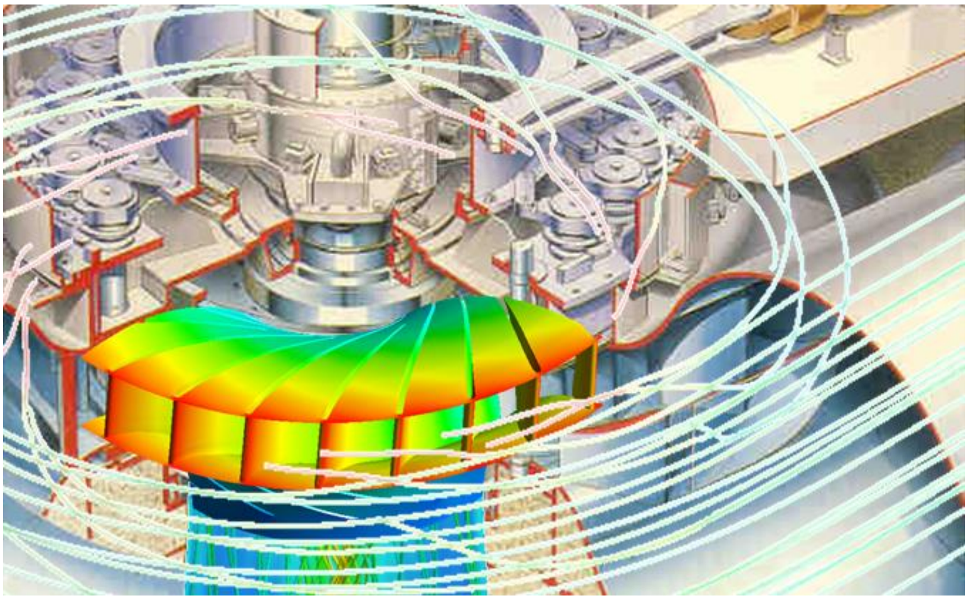
Will reduce the negative impacts of the hydropower plant construction as no surface road is necessary as compared with a conventional surge tank.



Innovation Cards

I.11 LeakReg

Category:	**Turbine technology**		
Case study:	Skjerka HPP	Lifetime:	20 years
Costs:	2 MNOK	Construction time:	2 mnd.
Income:	0.5 MNOK/year	NPV:	5 MNOK
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Confidential			
Overall assessment: Confidential			



Case study

Design criteria

Dimensions

Construction method and costs

Consequence for power production and income

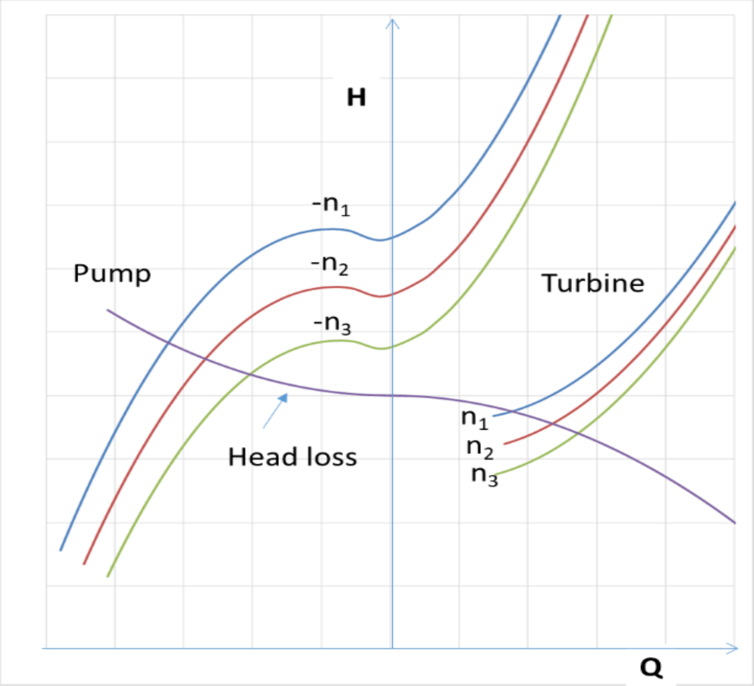
Environmental consequence

I.12 VarSpeed Pumping to Multiple Reservoirs

Category:	**Pumped Storage**		
Case study:	Langevatn PSP	Lifetime:	20 years
Costs:	-	Construction time:	24 months
Income:	-	NPV:	-
Environment:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		

Short description: Full frequency converter to allow turbine operation and pumping to reservoirs at different head, as an alternative to having multiple units.

Overall assessment: The estimated costs may be significantly reduced compared to installed four conventional units. But higher risk of outage as there is only one generator. The concept will become more profitable if the prices of power electronics are reduced over time.



Case study

Design criteria

Allow pumping from Nåvatn to Langavatn (70 m), Stekil (150 m), Kvennevatn (153 m) and Storevatn (250 m) with only one generator-motor. 160 MW installed capacity, giving turbine discharges in the range 50 m^3/s to 125 m^3/s.

Dimensions

The unit will require two runners, one for the head 150-250 m and one for the low head 70 m. A full-size converter and transformers are necessary. The rotational speed of the unit will be in the range 300 rpm ± 50%.

Construction method and costs

Compared with four separate synchronous units, the VarSpeed solution requires additional space in the powerhouse for the power electronics. However, in sum the powerhouse is reduced in size owing to one instead of four units.

Consequence for power production and income

The turbine and pump efficiency will increase, and it will be possible to regulate in pumping mode, compared with synchronous units. The number of hours allowed in harmful operating zones will greatly increase (2-3 times more in both upper and lower limit compared to a synchronous machine). The O/M costs are assumed similar as the frequency converter gives less mechanical strain, while only one generator gives higher costs of outage.

Environmental consequence

Positive impact as the water value will increase and less variations in the reservoir level. Locally negative impact if the technology results is more reservoirs being used for pumped storage. Globally positive impact if more pumped storage can result in more renewable energy production.

Innovation Cards

I.13 Anti-Diving Sickness

Category:	**Fish friendly hydropower**		
Case study:	Skjerka HPP	Lifetime:	20 years
Costs:	1 MNOK	Construction time:	2 mnd
Income:	0 MNOK	NPV:	-1 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Short description: Use of ultrasound to avoid supersaturated water from turbines by inducing cavitation in the draft tube. Will reduce fish mortality caused by supersaturated water.			
Overall assessment: Good environmental effect, at a limited cost. Recommendable for hydropower plants with supersaturation problems. Costs is very roughly estimated and will depend on both equipment cost and power consumption where the uncertainty is still high.			

Case study

Design criteria

Fully avoid fish mortality caused by supersaturated water.

Dimensions

Ultrasound speakers connected to the draft tube. Further research is required before dimensions can be specified.

Construction method and costs

Ultrasonic speakers are clamped onto the draft tube. The control units are placed in a dry area nearby. Further research is required to identify suitable equipment.

Consequence for power production and income

Highly dependent on required power. Research so far indicates that a substantial amount of power is required to obtain required effect.

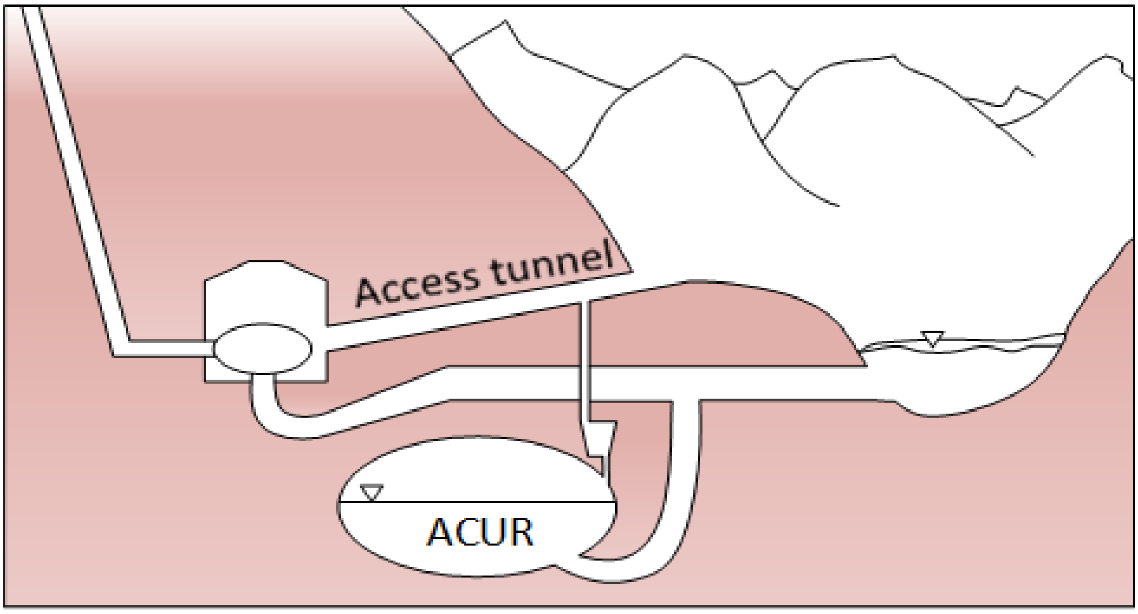
Environmental consequence

There is no problem with supersaturation in the Mandal river. As the solution does not have any identified negative impacts, and increases resilience the consequence is set to positive.

Innovation Cards

I.14 AcurLE

Category:	**Mitigating HydroPeaking**		
Case study:	Håverstad HPP	Lifetime:	100 years
Costs:	55 MNOK	Construction time:	12 mnd
Income:	5 MNOK/year	NPV:	5 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Construction of an underground rock cavern with pressurized air to control the water outflow from hydropower plants to mitigate hydropeaking.			
Overall assessment: Good effect but only economically feasible for hydropower plants with operational restrictions that significantly reduce the potential economical profit. Highly uncertain costs and income and must be investigated further.			



Case study

Design criteria
Volume to allow downramping in 12 minutes instead of 60 minutes (similar as for Brattsberg HPP). Operation with two full cycles per day (two startup and two shutdown).

Dimensions
Rock cavern with volume = 110 000 m3. Compressor capacity of 8 MW that can deliver air volume equal to 2/3 of the turbine discharge of 75 m3/s.

Construction method and costs
Unlined drill and blast tunneling to excavate the underground cavern. Cost 300 kr/m3 excavation of rock and 5 MNOK per 1500 kW compressor system (largest on the market).

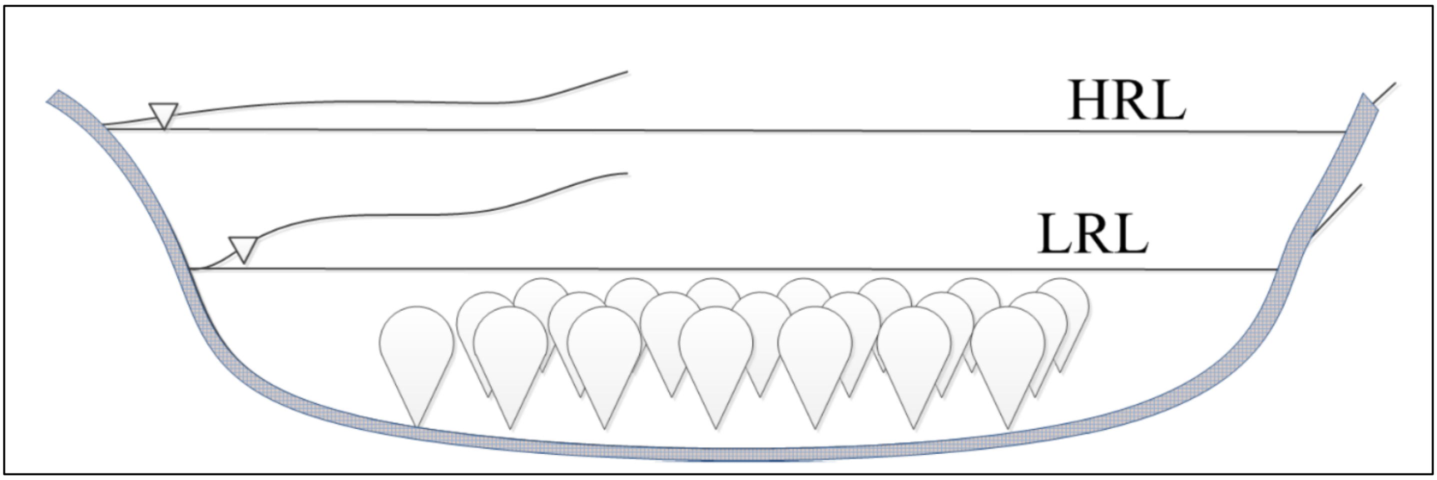
Consequence for power production and income
Will make it possible to run the power plant with hydropeaking without environmental effects. Assumed a quality factor increase of 0.05 equal to 5% increase of revenue from power sales. The system is a net consumer of energy and will reduce the annual energy production from the power plant.

Environmental consequence
Will have a positive environmental impact due to control of the flow in the river.

Innovation Cards

I.4b AcurHE – Underwater balloons

Category:	**Reservoir optimization**		
Case study:	Håverstad HPP	Lifetime:	20 years
Costs:	1000 MNOK	Construction time:	10 Years
Income:	50 MNOK/year	NPV:	- 400 MNOK
Environment:	Very Positive/Positive/Neutral/Negative/**Very negative**		
Power production:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Short description: Use compressed air to inflate underwater bags/balloons to displace water and manipulate water level. Profit from allowing a higher reservoir level (increase the head) and reducing flood loss.			
Overall assessment: New technology with potential to increase the flexibility of hydropower plant. However, not profitable with current technology.			



Case study

Design criteria

Compressed air delivery in and out of the underground cavern is assumed equal to 2/3 of the turbine discharge to Håverstad power plant. The total volume of the cavern is equal to the reservoir volume of 2 m regulation height. The tops of the balloons are at the same level as LRL.

Dimensions

Approx. 10 000 underwater lift bags (V = 750 m^3) are needed to displace the required volume of 7 mill. m3 equal to two meters of regulation. Total compressor capacity of P = 5 MW is needed.

Construction method and costs

The balloons are connected to a large grid of interconnected pipes underwater, which again is connected with compressors and generators on land. Construction costs are taken from a similar concept with energy storage in air balloons under the sea. The costs include compressors, generators, and balloons in the region of > 1 billion NOK.

Consequence for power production and income

AcurHE will increase production by keeping the water level at Ørevatn always at HRL (assumed 2 m increase from the current situation). This gives an annual extra energy production of 7 GWh. The annual energy loss of operating the balloons is assumed to be 2 GWh (50 filling/emptying cycles at 80% efficiency).

Another potential benefit is reduction of flood water loss. If assumed that the reduced loss is equal to the balloon volume for every flood event, and that this volume increases the production for all power plants downstream, each flood event will generate an extra income of approximately 6 GWh.

Environmental consequence

AcurLE will have a significant negative impact on the environment on the bottom of Ørevatn. AcurLE will impact the entire surface area and will affect the temperature in Ørevatn. The system will also need large land-based structures for compressors and generators.

Innovation Cards

I.16 Fish Friendly Hydropower Tunnels

Category:	**Fish friendly hydropower**		
Case study:	New Bjelland PSP	Lifetime:	100 years
Costs:	5 MNOK	Construction time:	2 months
Income:	0 MNOK	NPV:	-5 MNOK
Environment:	Very Positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very Positive/Positive/**Neutral**/Negative/Very negative		
Short description: Norwegian hydropower tunnels are mostly unlined and with gravel and sand remaining on the invert after the construction period. By installing lights and making rest areas they may be adapted to become fish habitats. This is especially interesting if Atlantic salmon may find such habitats attractive.			
Overall assessment: Unexplored field of research. Large potential as there are about 4000 kilometers of hydropower tunnels in Norway, giving a large potential for such solutions.			

Case study

Design criteria

Make the hydropower tunnel system attractive for Atlantic salmon as habitat and spawning area. Avoid restrictions on hydropower operation and increased hydraulic losses.

Dimensions

The Bjelland PSP can be constructed with a 16 km long tailrace tunnel with cross-section 40 m^2. The tunnel will be unlined drill and blast tunnel with gravel and sand from the construction period remaining on the invert after commissioning. The water velocity will be maximum 1 m/s.

Construction method and costs

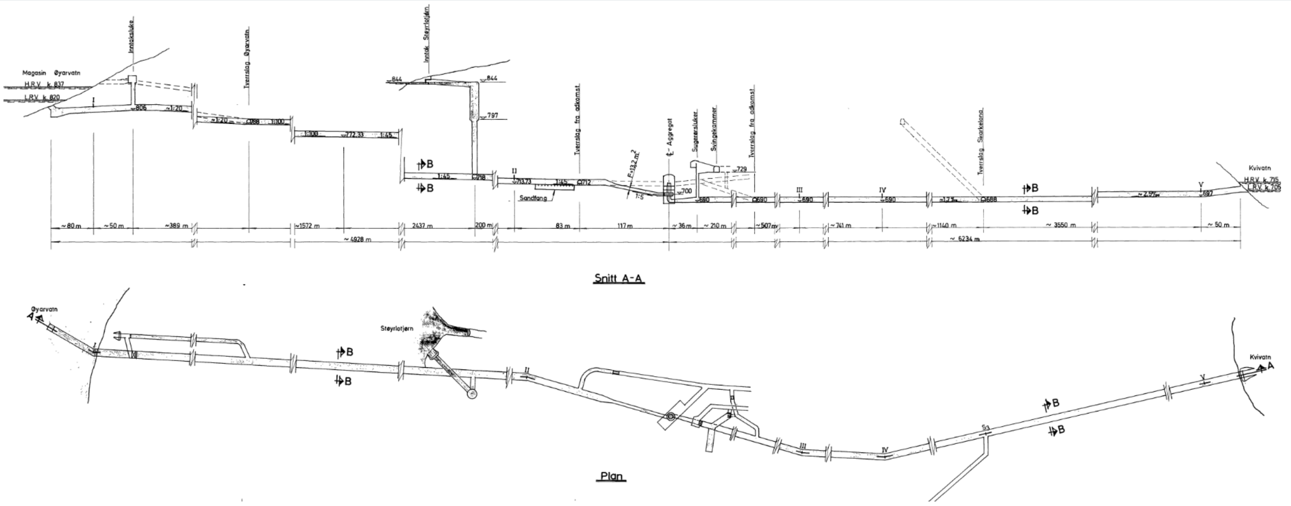
Install lights with seasonal and daily variation. Make resting areas in niches from the construction period. Place fish screens in the upstream end of the tunnel at the entrance to the draft tube. Lay spawning gravel on the tunnel invert (if not existing gravel is good enough).

Consequence for power production and income

The effect on power production may be negative if the adaptation to fish causes the need for operational restrictions.

Environmental consequence

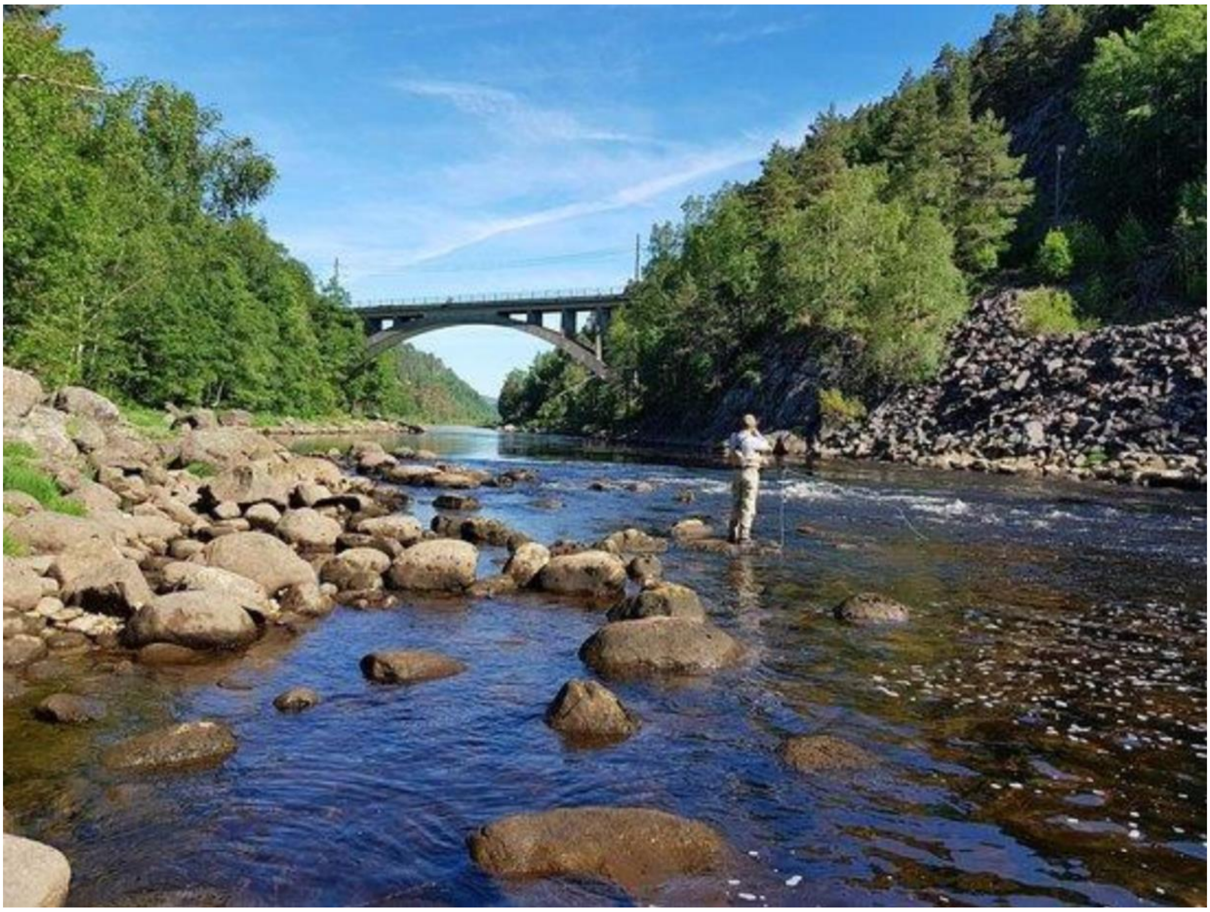
The environmental effect is potentially very positive if the fish finds the hydropower tunnel to be an attractive habitat.



Research Project Cards

RP.1 The Value of Hydropower Flexibility

Relevance:	All HPP	Previous research:	Available
Necessary funding:	20 MNOK	Discipline	Multidisciplinary
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Quantify the value of hydropower flexibility and flood dampening		
Overall assessment:	Existing research is available but needs to be reviewed and complemented.		



Detailed description

Problem

Both hydropower operators, third parties and the government do not presently have good tools or information on how to assess the value of hydropower flexibility and flood dampening. This may lead to underestimation and suboptimal utilization of the potential.

Possible solution

Conduct research to demonstrate and quantify the value of hydropower flexibility and flood dampening. Needs to be evaluated both for the present and future power market.

Effect on power production, the environment and the society

More knowledge may lead to optimum use of the hydropower flexibility, both in terms of production, environment and the society.

Research topics

Literature review and mapping of knowledge gaps. Complementary research, and proposal to further research.

Necessary funding and cooperation partners

20 MNOK funding for a four-year KPN project including NTNU, SINTEF and NINA.

Research Project Cards

RP.2 Flood Power Plants

Relevance:	Try FPP	Previous research:	Limited
Necessary funding:	20 MNOK	Discipline:	All
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Reduce flood damage and increase hydropower production. Make combined hydropower plant and bypass tunnels.		
Overall assessment:	Unexplored field of research. Potential for new innovations.		

Detailed description

Problem

Many rivers have large floods causing damage to nearby infrastructure and urban areas. In Norway the largest cities are located close to rivers.

Possible solution

Make a combined hydropower plant and flood bypass tunnel.

Effect on power production, environment and society

The flood protection may finance construction of new hydropower schemes that would otherwise not be feasible. Flood power plants may have a negative environmental impact, but a large positive impact on society.

Research topics

Design of flood power plant concepts.

Necessary funding and cooperation partners

A funding of 20 MNOK for a four-year KPN research project. The project will be conducted by a multidisciplinary group from NTNU, NINA and SINTEF.

Research Project Cards

RP.3 Fish Friendly Intakes for Pumping

Relevance:	Bjelland PSP	Previous research:	Limited
Necessary funding:	4 MNOK	Discipline:	Fish/hydraulics
Environment:	Very positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/Neutral/**Negative**/Very negative		
Short description:	Avoid spreading species when pumping water. Develop a fish friendly intake for pumping plants and pumped storage plants		
Overall assessment:	Unexplored field of research. Potential for new innovations.		

Detailed description

Problem
Allow construction of pumped storage plants without spreading species through the pumped water. For Bjelland PSP there is a potential to pump salmon up to reservoirs where there is no natural population of salmon.

Possible solution
Use a large scale modified coanda screen intake to prevent salmon from entering the pumped storage plant tunnel system.

Effect on power production, environment and society
The environmental effect is to avoid a negative effect of spreading species. There might be a small negative effect on power production owing to increased headloss. There is no effect on the society.

Research topics
Design of the fish friendly intake. Fieldwork, CFD and laboratory scale model testing.

Necessary funding and cooperation partners
A funding of 5 MNOK to employ a PhD candidate is assumed necessary. The project must be conducted as a cooperation between fish experts, civil and hydraulic engineering.

Research Project Cards

RP.4 Fish Friendly Intakes for Flood Power Plants

Relevance:	Try FPP	Previous research:	Limited
Necessary funding:	5 MNOK	Discipline:	Fish/hydraulics
Environment:	Very positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/Neutral/**Negative**/Very negative		
Short description:	Allow safe downstream migration for migratory fish. Develop a fish friendly intake for flood power plants.		
Overall assessment:	Unexplored field of research. Potential for new innovations.		

Detailed description

Problem

Allow construction of flood power plants without allowing fish to enter the turbines. For Try FPP there is a potential for salmon to enter the turbines and be killed. Shall have six times more water through the intake in flood bypass mode. Have very low head in power plant mode and need to have minimum headloss in the intake.

Possible solution

Design a fish friendly intake with a separate intake for power plant mode and flood diversion mode. The fish can be allowed to enter the flood diversion intake.

Effect on power production, environment and society

The environmental effect is to avoid a negative effect of killing migratory species. There might be a small negative effect on power production owing to increased headloss. There is no effect on the society.

Research topics

Design of the fish friendly intake. Fieldwork, CFD and laboratory scale model testing.

Necessary funding and cooperation partners

A funding of 5 MNOK to employ a PhD candidate is assumed necessary. The project must be conducted as a cooperation between fish experts, civil and hydraulic engineering.

RP.5 Generator Capability

Relevance:	All HPP	Previous research:	Limited
Necessary funding:	5 MNOK	Discipline:	Electro
Environment:	Very positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Utilize more of the capability of the generator		
Overall assessment:	May gain higher efficiency for generators in hydropower plants at a limited cost.		

Detailed description

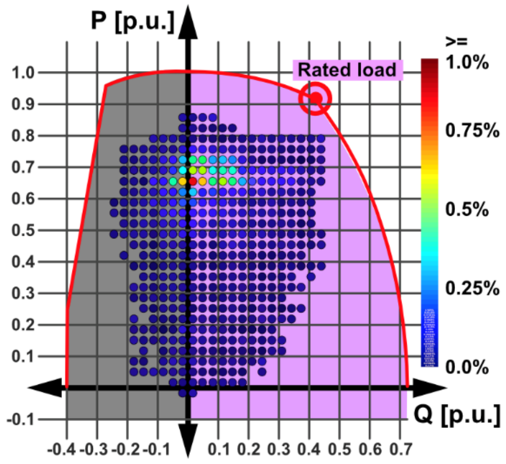
Problem
The design codes for generators do not account for the full capability when allowing time-limited operation outside the normal steady-state range.

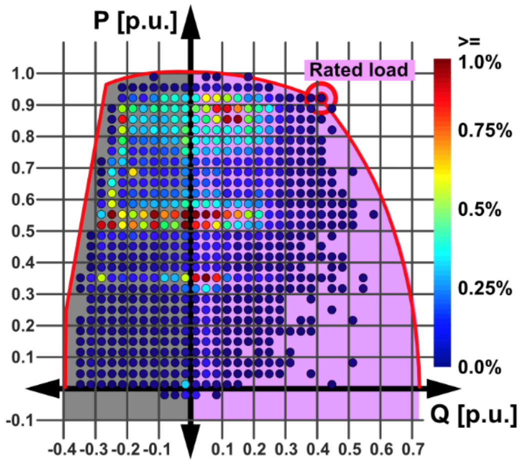
Possible solution
Study the possibilities and make new design codes and allow an extended range of operation. Design new generators to further utilize the possibilities.

Effect on power production, environment and society
A positive effect power production owing to higher flexibility and operational range.

Research topics
Capability of generators. Design of generators with extended capability diagrams.

Necessary funding and cooperation partners
A funding of 5 MNOK to employ a PhD candidate is assumed necessary. The project will be conducted by electro engineers.





Research Project Cards

RP.6 Temperature-Controlled Water Release

Relevance:	All HPP	Previous research:	Available
Necessary funding:	5 MNOK	Discipline	Fish/Hydraulics
Environment:	**Very positive**/Positive/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/**Neutral**/Negative/Very negative		
Short description:	Develop new technical solutions to retrofit existing intakes and dam to enable temperature-controlled water release.		
Overall assessment:	Potential good effect at a limited cost.		

Detailed description

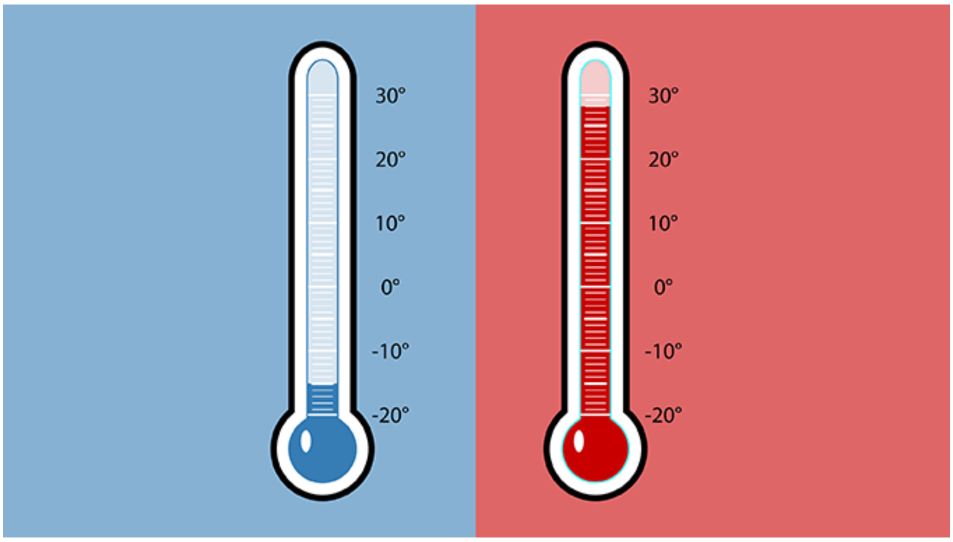
Problem
Regulation of rivers results in a shift of the natural temperature. During winter the temperature may increase, and during summer the temperature may drop. This may cause problems for water organisms.

Possible solution
Make the inexpensive water release arrangement to control which level in the reservoir water is released from. Should be able to retrofit existing intakes.

Effect on power production, the environment and the society
No impact on power production as the same water amount is released, it is only taken from different levels in the reservoir. Potentially very high positive effect on the environment.

Research topics
Technical solutions. Simulation of water temperature in the river. Water temperature and the impact on water organisms.

Necessary funding and cooperation partners
A funding of 5 MNOK to employ a PhD candidate is assumed necessary. The project must be conducted as a cooperation between fish experts and hydraulic engineers.



Research Project Cards

RP.7 Draught Period Water Release

Relevance:	All HPPs	Previous research:	Limited
Necessary funding:	20 MNOK	Discipline:	Fish/Hydraulics
Environment:	**Very positive**/Positive/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/Neutral/**Negative**/Very negative		
Short description:	Avoid severe fish death events during draught periods. Establish guidelines for water release during draught periods in regulated rivers.		
Overall assessment:	Unexplored field of research. High potential for improvements of the current situation.		

Detailed description

Problem
The minimum environmental flow in regulated river may not be sufficient in extreme draught periods. The temperature in the water becomes too high and the oxygen content decreases below the need of fish and other water organisms.

Possible solution
Establish guidelines for when there is need for extra water release. Suggest a regulatory framework for such release.

Effect on power production, environment and society
The water release will have a small negative effect on power production. However, the positive effect on the river is potentially very high.

Research topics
Mapping river with draught problems. Simulation of temperature in the river during water release. Study the tolerance of fish and water organism to temperature. Regulatory framework for water release.

Necessary funding and cooperation partners
A funding of 20 MNOK for a four-year KPN-project. The project must be conducted as a cooperation between fish experts and hydraulic engineers.

RP.8 Cell Weirs in Reservoirs

Relevance:	All reservoirs	Previous research:	Limited
Necessary funding:	4 MNOK	Discipline:	Fish/hydraulics
Environment:	Very positive		
Power production:	Neutral to positive		
Short description:	Allow fish to enter spawning streams even with high regulation of the water level in reservoirs. Design of cell weirs in inlet streams of reservoirs		
Overall assessment:	Largely unexplored field of research. Innovation potential.		

Detailed description

Problem
Trout and other similar fish species that spawn in reservoir tributaries frequently struggle to access streams due to low reservoir water levels creating migration barriers. Recruitment is then a common problem in reservoirs.

Possible solution
Construction of cell weir structures that allow fish to ascend streams at different water levels in the reservoir. The structures may simultaneously act as a structural refuge for return migrating offspring (juvenile fish).

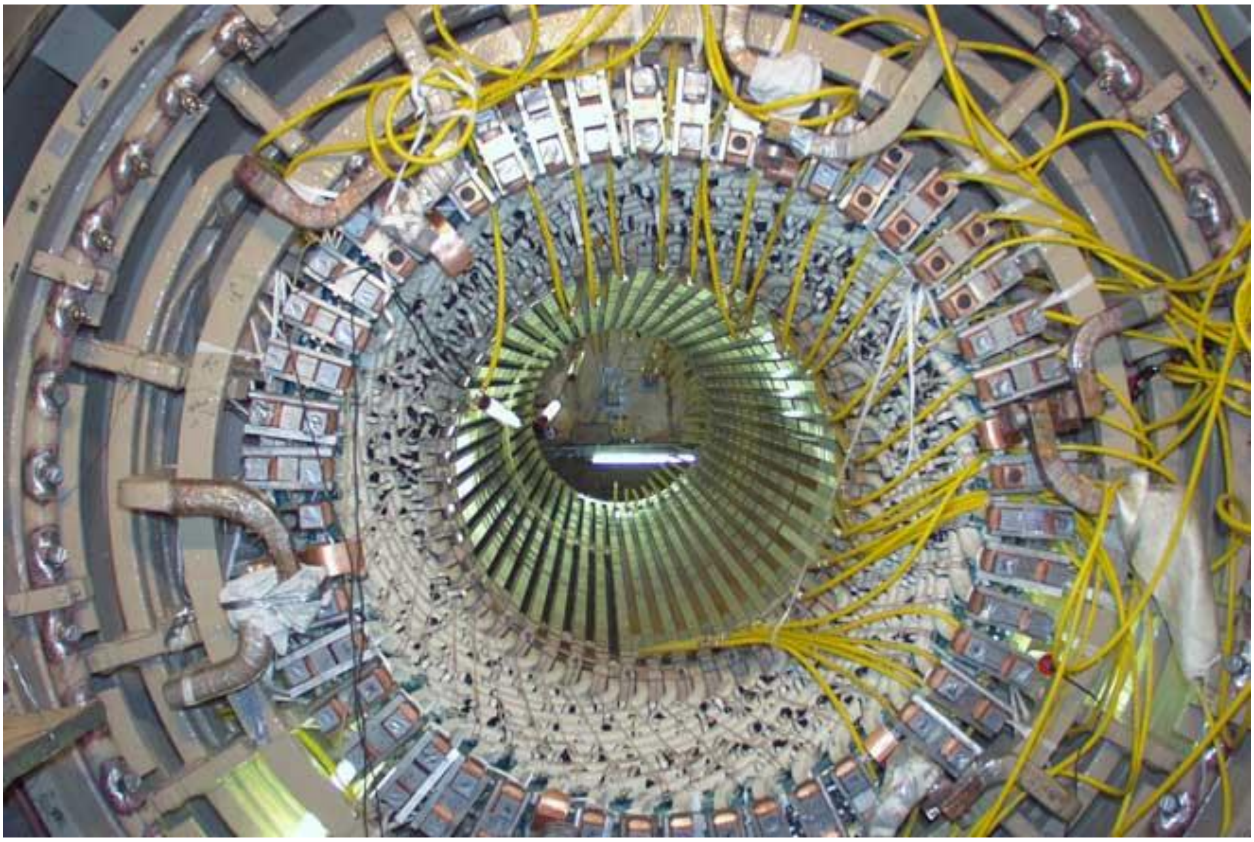
Effect on power production, environment and society
May restore natural recruitment of fish, allow termination of stocking programs and potentially impact power production as less restrictions are necessary.

Research topics
Design of a generalized concept for cell weirs in reservoirs.

Necessary funding and cooperation partners
A funding of 4 MNOK to employ a PhD candidate is assumed necessary. The project depend on cooperation between fish ecologist and engineers

RP.9 Thermic Inertia for Reactive Power

Relevance:	All HPP	Previous research:	Limited
Necessary funding:	5 MNOK	Discipline	Electro
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/Positive/**Neutral**/Negative/Very negative		
Short description:	Use the thermic inertia of generators to allow short periods of large delivery or consumption of reactive power during emergency in the grid.		
Overall assessment:	Good effect at a limited cost. Technically feasible. Requires new control systems and regulatory framework.		



Detailed description

Problem
Extreme events may require large production or consumption of reactive power in the grid for short periods. Conventional solutions to secure this demand are expensive.

Possible solution
Use the existing hydropower generators to deliver short term large amounts of reactive power, by allowing the temperature to rise above the normal boundary for limited amount of time.

Effect on power production, the environment and the society
No effect on normal power production or the environment. Positive effect for the society as existing infrastructure can be utilized instead of constructing new and expensive facilities.

Research topics
Short term thermic tolerance in hydropower generators. Control systems. Regulatory framework. Pole angle stability.

Necessary funding and cooperation partners
5 MNOK for a four-year PhD project. One or more of the generator and control system producers should be included as partner.

Research Project Cards

RP.10 Heat Energy in Hydropower Plants

Relevance:	All HPPs	Previous research:	Limited
Necessary funding:	20 MNOK	Discipline:	Electro
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Maintain a constant low temperature in the powerhouse and improve generator cooling. Use excess heat for heat storage to nearby household or industry. Avoid temperature strain in generators and increase efficiency.		
Overall assessment:	Potential for improved energy efficiency and new innovations.		

Detailed description

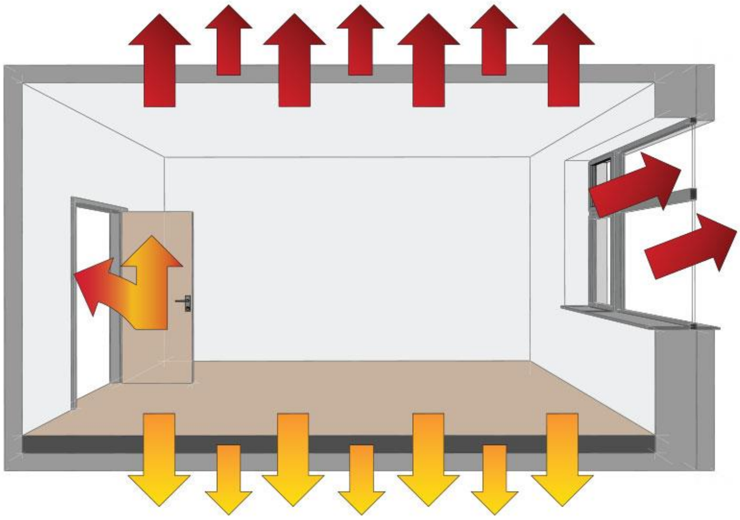
Problem
All generators experience large temperature changes during startup, shutdown and various other operation of the hydropower plant. Such temperature changes will over time cause wear. In addition, the generator has the highest efficiency when the temperature is low.

Possible solution
Make a large-scale air condition system to maintain a constant and low temperature in the powerhouse. Any excess heat can be transported out of the powerhouse for use elsewhere.

Effect on power production, environment and society
Positive environmental impact owing to higher degree of energy utilization for hydropower plants. The society may have a reduced cost for heating. The power production will in sum increase marginally owing to higher efficiency and reduced maintenance.

Research topics
Design of generalized concepts for large scale climate control and heat storage from hydropower plants.

Necessary funding and cooperation partners
A funding of 20 MNOK to conduct a four-year IPN-project. The project will be conducted by electro, mechanical and civil engineers.



Research Project Cards

RP.11 Fish Friendly Hydropower Tunnels

Relevance:	All HPPs	Previous research:	None
Necessary funding:	10 MNOK	Discipline:	Fish/hydraulics
Environment:	**Very positive**/Positive/Neutral/Negative/Very negative		
Power production:	Very positive/Positive/Neutral/**Negative**/Very negative		
Short description:	Norwegian hydropower tunnels are mostly unlined and with gravel and sand remaining on the invert remaining from the construction period. By installing lights and making rest areas they may be adapted to become fish habitats. This is especially interesting if Atlantic salmon may find such habitats attractive.		
Overall assessment:	Unexplored field of research. Large potential as there are about 4000 kilometers of hydropower tunnels in Norway, giving a large potential for such solutions.		

Detailed description

Problem

Hydropower plant reduce the quality of natural fish habitats as they bypass most of the water from the natural river. To compensate, it is interesting to see if the tunnels in the hydropower plant can be adapted to become new alternative habitats.

Possible solution

Install lights with seasonal and daily variation. Make resting areas. Place fish screens in the end of the tunnel towards the turbine. Lay spawning gravel on the tunnel invert (if not existing gravel is good enough). Design the tunnel cross-section size so that the maximum velocity is adapted to the fish.

Effect on power production, environment and society

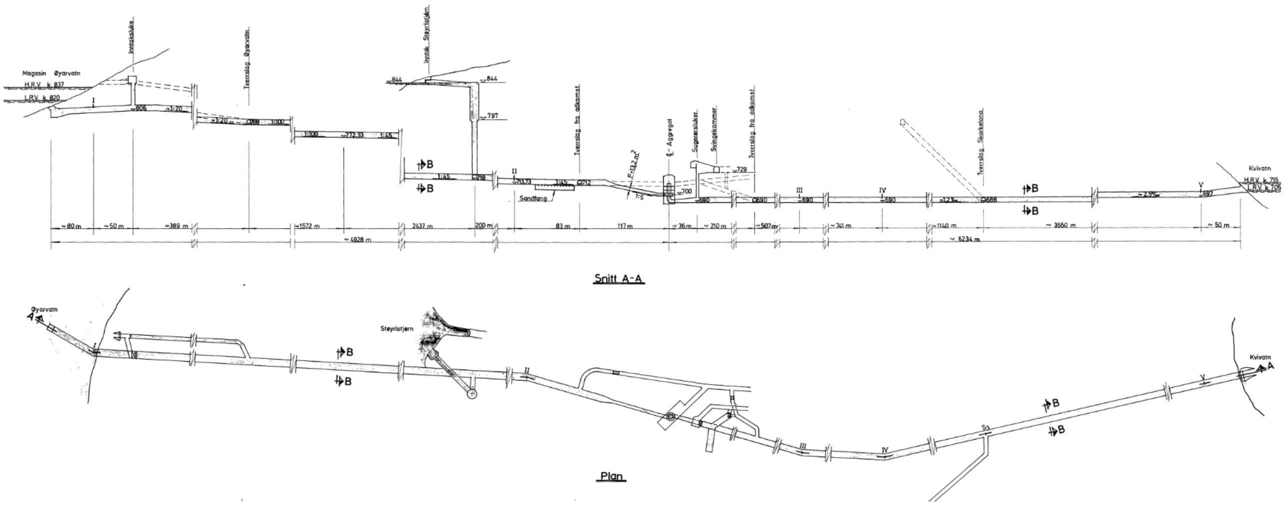
The environmental effect is potentially very positive. The effect on power production may be negative if the adaptation to fish causes the need for operational restrictions.

Research topics

Design of the fish friendly tunnels. Lab-experiments with fish, testing of various measures and operational scenarios.

Necessary funding and cooperation partners

A funding of 10 MNOK to employ two PhD candidate is assumed necessary. The project must be conducted as a cooperation between fish experts, civil and hydraulic engineering.



RP.12 Tunnels as Reservoirs

Relevance:	All HPPs	Previous research:	Available
Necessary funding:	5 MNOK	Discipline:	Hydraulic/Eng. Geo.
Environment:	Very positive/**Positive**/Neutral/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Utilize the tunnel system as reservoirs. The tunnel system may be adapted to also function as a reservoir		
Overall assessment:	Some research available, but there is still potential for further development of the technology.		

Detailed description

Problem

Reservoirs for hydropower plants are expensive and have a large environmental consequence.

Possible solution

For hydropower plants with tunnel systems, the tunnel may be adapted to function also as a reservoir for water storage.

Effect on power production, environment and society

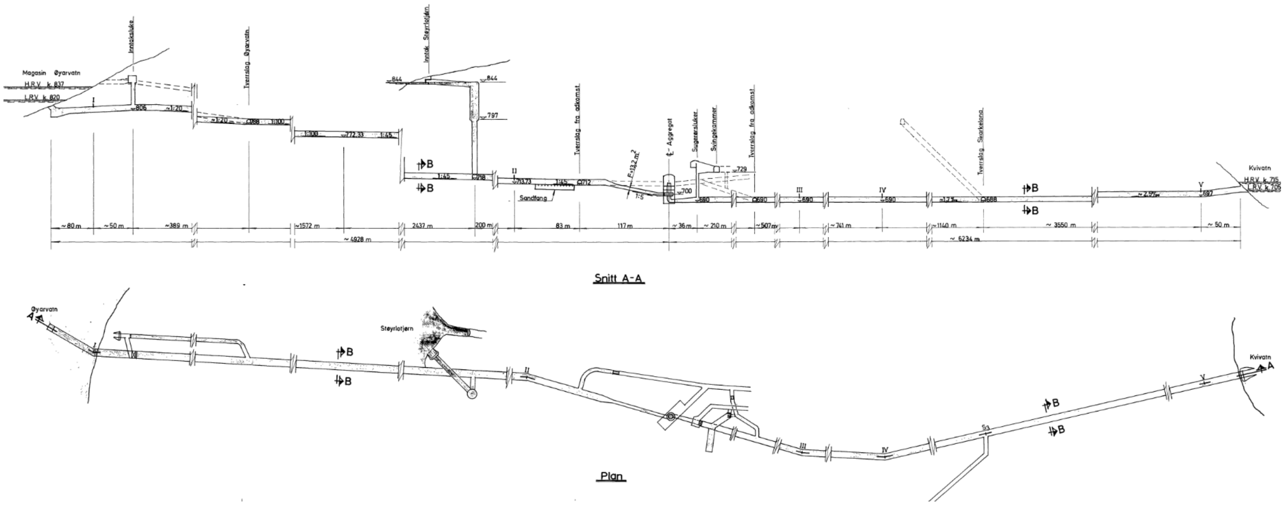
The environmental effect is potentially very positive. The effect on power production is also positive as a reservoir is made available. The reservoir may also be closer to the turbine, reducing the total friction loss.

Research topics

Design of reservoirs in tunnels. Investigate various different design.

Necessary funding and cooperation partners

A funding of 4 MNOK to employ a PhD candidate is assumed necessary. The project must be conducted as a cooperation between hydraulic engineers and engineering geologist.



RP.13 Cost Reduction 50% for Hydropower

Relevance:	All HPPs	Previous research:	Limited
Necessary funding:	20 MNOK	Discipline	Multidisciplinary
Environment:	Very positive/Positive/Neutral/**Negative**/Very negative		
Power production:	**Very positive**/Positive/Neutral/Negative/Very negative		
Short description:	Investigate potential cost reduction for hydropower development.		
Overall assessment:	Uncertain if the scope is realistic, but limited similar efforts is currently being undertaken.		

Detailed description

Problem
Hydropower development have high and increasing costs, while wind and solar power have decreasing costs. An initiative to study potential cost reductions is warranted.

Possible solution
Study the major costs of hydropower development and the potential for costs reductions.

Effect on power production, the environment and the society
Lower costs may enable more development of hydropower, which is positive for power production and the society but negative for the environment.

Research topics
Civil, mechanical, electro, regulatory, construction management, regulatory framework.

Necessary funding and cooperation partners
A funding of 20 MNOK for a four-year IPN project at NTNU, SINTEF and NINA with industry partners.

RP.14 Virtual Inertia

Relevance:	All HPPs	Previous research:	Available
Necessary funding:	5 MNOK	Discipline	Electro/Mech.
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Use frequency converters to exploit the rotational inertia of hydropower units to govern the frequency in the grid.		
Overall assessment:	High potential but ongoing research also elsewhere.		

Detailed description

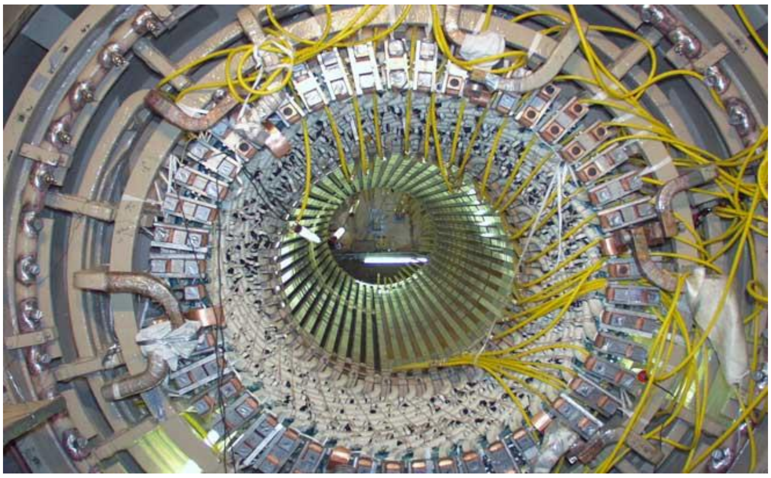
Problem
The frequency in the grid is becoming less stable owing to intrusion of more wind and solar power.

Possible solution
Hydropower plants with frequency converters may provide system services by utilizing the rotational inertia of the units.

Effect on power production, the environment and the society
Positive effect on power production as more system services can be delivered. Positive effect on the society owing to more stable grid frequency. No effect on the environment.

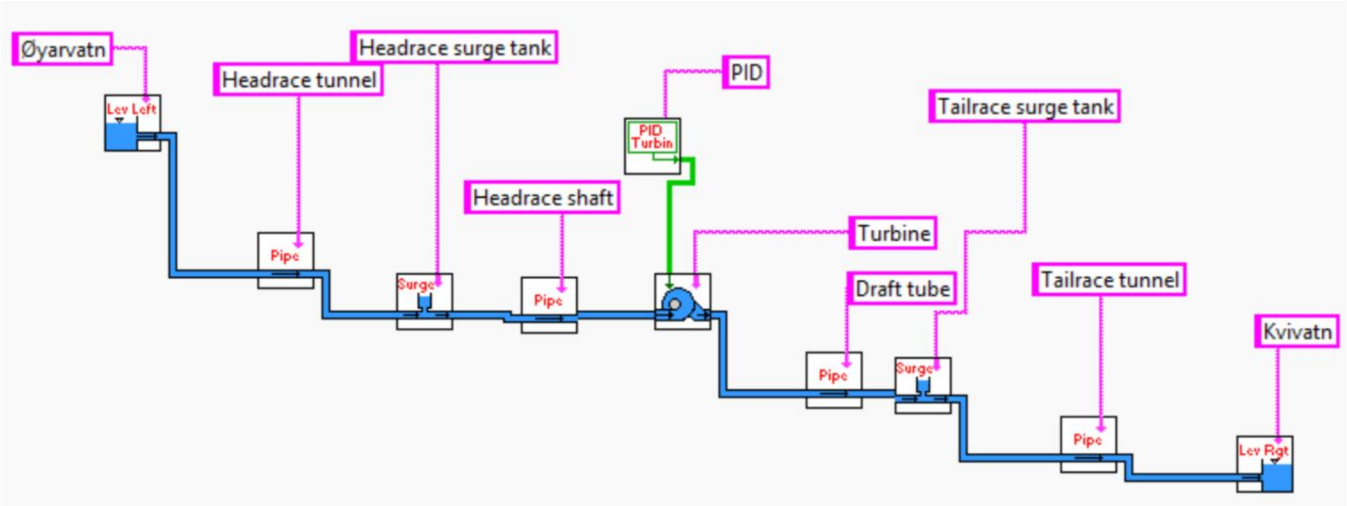
Research topics
Control systems. Optimum use of virtual inertia. Technical solutions. Simulation of the power grid and optimum operation of the hydropower plant.

Necessary funding and cooperation partners
A funding of 5 MNOK to employ a PhD candidate is assumed necessary. The project will be conducted by the electro and mechanical groups at NTNU.



RP.15 Digital Twin Turbine Governors

Relevance:	Try FPP	Previous research:	Available
Necessary funding:	20 MNOK	Discipline	Machine
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Develop DTTG to enable stable turbine governing in low head hydropower plants.		
Overall assessment:	Recent development enable new possibilities. Potential for new innovation, but assumed ongoing research at other institutions.		



Detailed description

Problem

There is a need for more frequency governing in the grid owing to more wind and solar power. Many hydropower plants are not able to deliver frequency governing with standard governors.

Possible solution

Apply digital twin to develope a new type of turbine governor.

Effect on power production, the environment and the society

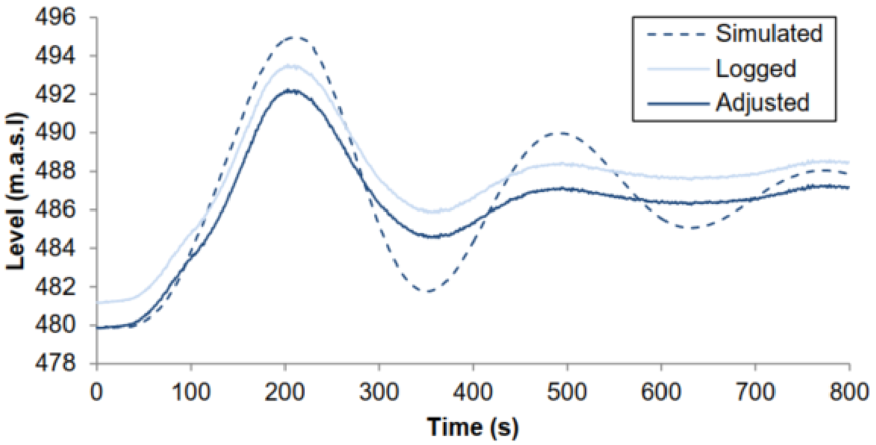
Positive effect on power production. No impact on the environment. Positive impact on the society as the power grid becomes more stable.

Research topics

Digital twins and turbine governors. Numerical simulation. Laboratory experiments.

Necessary funding and cooperation partners

A funding of 20 MNOK for a four-year IPN project. The project will be conducted in the machinery group at NTNU with industry partners.



RP.16 Social Acceptance for Hydropower

Relevance:	All HPPs	Previous research:	Available
Necessary funding:	20 MNOK	Discipline	Social Science
Environment:	Very positive/Positive/**Neutral**/Negative/Very negative		
Power production:	Very positive/Positive/**Neutral**/Negative/Very negative		
Short description:	Review research on social acceptance. Reconsider and update the knowledge based on recent world development.		
Overall assessment:	An important subject to enable more and sustainable development of hydropower.		

Detailed description

Problem

Social acceptance for hydropower may be crucial for development of new schemes. The public opinion on hydropower has shifted in recent year owing to the transition into more renewable power production and more extreme weather. New methods have been made available in other fields of research that may be applied.

Possible solution

Review existing research and complement with new developments in other fields. Update the current state-of-the art.

Effect on power production, the environment and the society

May enable more development of hydropower which is positive for power production and the society but negative for the environment.

Research topics

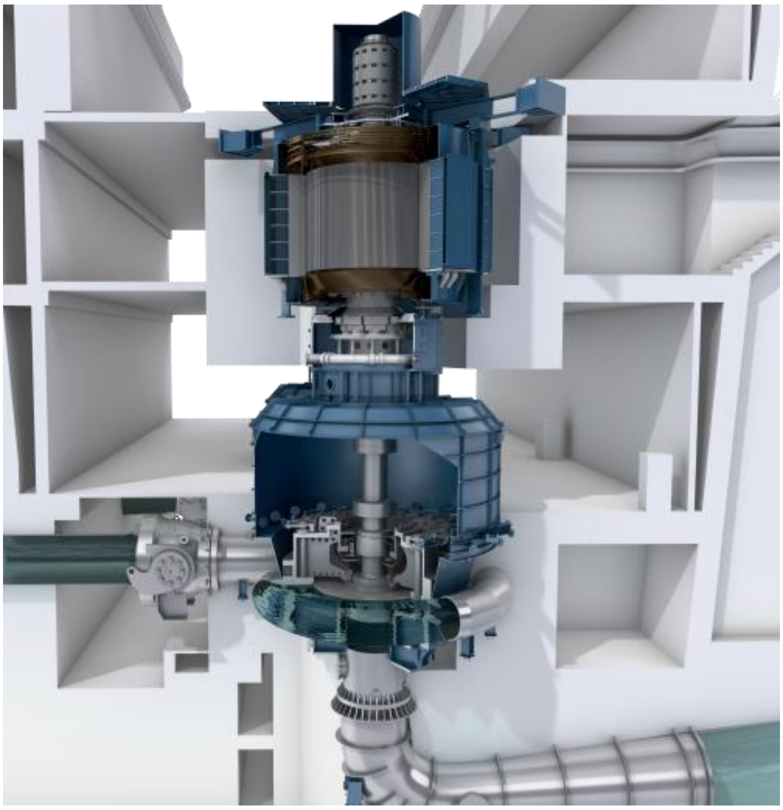
Review of existing literature. Review of relevant development in other fields of research. Further develop methods for mitigation of social challenges in hydropower.

Necessary funding and cooperation partners

A funding of 20 MNOK for a four-year IPN project with social scientists at SINTEF and NINA together with industry partners.

RP.17 Pumped Storage with Multiple Reservoirs

Relevance:	Langevatn PSP	Previous research:	Available
Necessary funding:	20 MNOK	Discipline	Multidisciplinary
Environment:	Very positive/Positive/Neutral/**Negative**/Very negative		
Power production:	Very positive/**Positive**/Neutral/Negative/Very negative		
Short description:	Develop technology for reversible units that may pump to a large variable range of head.		
Overall assessment:	Potential for innovation but assumed limited number of projects where it is relevant.		



Detailed description

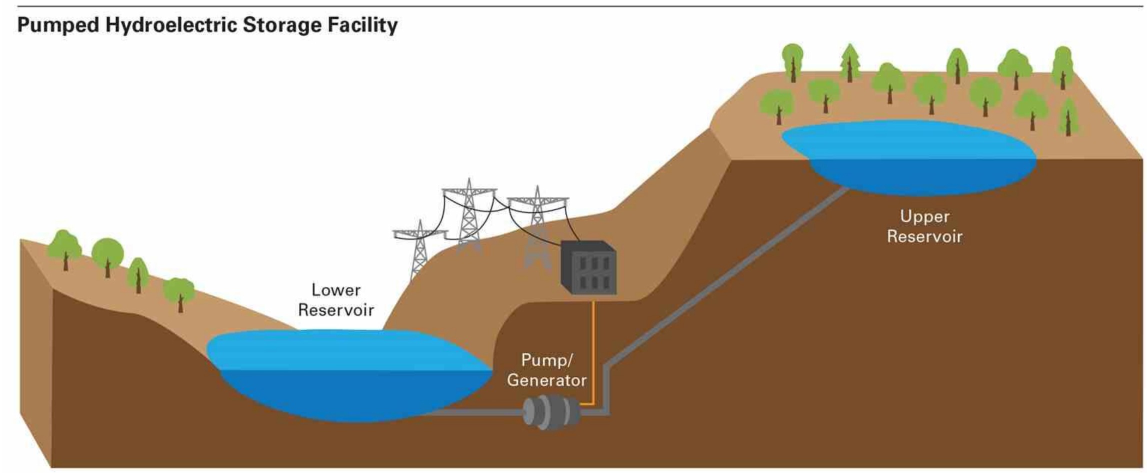
Problem
High costs of installing pumped storage plants with pumping to multiple reservoir at different elevations with large range of head.

Possible solution
Full frequency converter to allow turbining and pumping to reservoirs at different head, as an alternative to having multiple units.

Effect on power production, the environment and the society
May allow development of new pumped storage plants. Positive effect on power production and the society. Negative effect on the environment.

Research topics
Design of reversible units. Application of frequency converters and variable speed. Tunnel system and gate-controlled reservoirs.

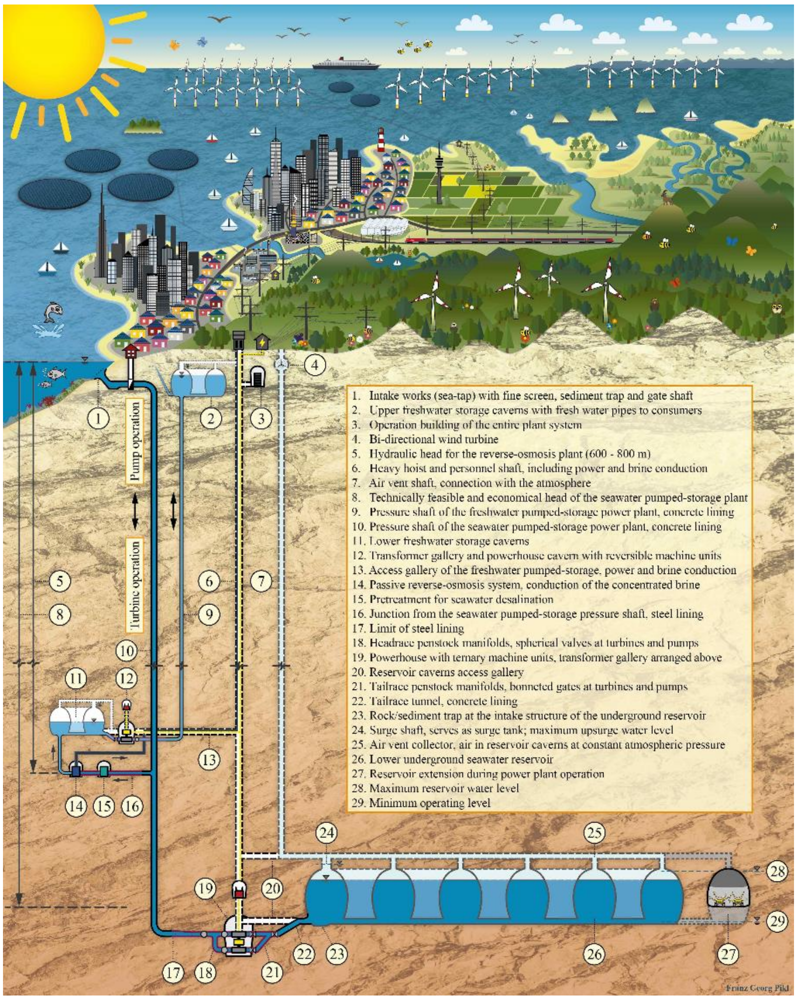
Necessary funding and cooperation partners
A funding of 20 MNOK for a four-year IPN-project. The project will be conducted by a multidisciplinary group from NTNU together with industry partners.



Research Project Cards

RP.18 Underground Pumped Storage Plants

Relevance:	All HPP	Previous research:	Available
Necessary funding:	20 MNOK	Discipline:	Multidisciplinary
Environment:	**Very positive**/Positive/Neutral/Negative/Very negative		
Power production:	**Very positive**/Positive/Neutral/Negative/Very negative		
Short description:	Develop technology to enable economically feasible underground pumped storage.		
Overall assessment:	Potential to solve the energy storage crisis.		



Detailed description

Problem
There is a need for energy storage to allow the transition to the renewable energy age. Pumped storage is the current largest energy storage technology, but feasible locations are limited. Underground pumped storage has been known for a long time but has not been realized because of risk, costs and untested technology.

Possible solution
Validate the feasibility and further develop the technology. Underground construction of pumped storage plants is possible in many locations. Variants include combination with seasonal heat storage and using the sea as upper reservoir including drinking water desalination.

Effect on power production, environment and society
The environmental effect is very positive as limited surface habitat is affected. The technology has the potential to enable the transition to renewable energy.

Research topics
Design and operation of underground PSP. Requirement for suitable location. Economic assessment. Comparison with alternative technologies.

Necessary funding and cooperation partners
A funding of 20 MNOK for a four-year KPN-project. The project must be conducted as a part of a multidisciplinary group with industry partners.