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Livia Ioana Pitorac

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Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
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Department of Civil and Environmental
Engineering

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Preface

This thesis is submitted to Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of Philosophiae Doctor (PhD).

The work was conducted at the Hydraulic Engineering Group, from the Department of Civil and Environmental Engineering, NTNU, Trondheim, with Professor Leif Lia as the main supervisor and Associate Professor Kaspar Vereide as co-supervisor. Professor Michel J. Cervantes from Luleå University of Technology was external co-supervisor.

The work in this thesis was financed through a three year and seven months PhD position by the Norwegian Research Center for Hydropower Technology (HydroCen), out of which, three years and three months were allocated to research and the rest allocated to teaching. The focus of HydroCen is research on upgrading existing hydropower plants to pumped storage plants by using the existing tunnel system. The research center has been covering multiple research topics such as reversible pump turbines (RPTs), generator-motor, sand transport, geology, rock engineering, waterway hydraulics, ecohydraulics, river hydraulics. The teaching duty included the supervision of four master students and assisting in lecturing- and organizing of the courses: TVM4106 Hydrological Modelling, TVM5132 Prefeasibility Study of Hydropower Development, TVM5160 Headworks and Sedimentation Engineering, and TVM5171 Modelling Water Resources. Additional volunteering teaching was done for the last year master students on the topic of Scientific Writing.

In accordance with the guidelines of the Faculty of Engineering Science and Technology, the thesis comprises an introduction to research that has resulted in three scientific papers.

Abstract

Energy storage is needed to enable the transition from fossil to renewable electrical energy sources. As wind and solar power are unregulated and volatile, energy storage is necessary. Pumped hydro can deliver both short- and long-term electrical energy storage. The motivation of this work is to enable cost-efficient and more environmentally friendly construction of pumped storage plants, by finding solutions to the technical challenges.

This thesis presents research on hydropower tunnels for pumped storage plants with multiple surge tanks that resulted in three journal papers. This thesis is organized to answer the following four research objectives: (1) Review of existing Norwegian pumped hydro: design challenges, technological solutions, and operational experience. (2) Verify hydraulic scale modelling for investigations of reconstruction of HPPs to PSPs. Demonstrate on a case-study. (3) Identify main challenges associated with the upgrade in terms of tunnel system design and provide solution alternatives. (4) Assess the effect of brook intakes on mass oscillations stability, and its implications for upgrading of hydropower plants with brook intakes.

The three research methods applied to answer the research objectives are: field measurements, 1D numerical simulations, and hydraulic scale modelling. Much of the work is conducted based on a case-study, namely the 50 MW Roskrepp hydropower plant located in southern Norway. A feasibility study for reconstructing this HPP to a PSP is currently undertaken by the power plant owner Sira-Kvina kraftselskap, making it an ideal case-study for the work. The power plant owner granted access to conduct field measurement during operation, a 3D scanning of the tunnel system, and available documentation and reports.

The work results in three journal papers, presented in this thesis. In addition, four secondary papers are published. The main contributions from this work are:

1. A technical review of currently existing Norwegian PSPs. This review provides a foundation for future development of PSPs.
2. A new method for determining the distribution of head loss factors in hydropower tunnel systems with multiple surge shafts.
3. Identification of the main limitations for upgrading HPP to PSP and provided solution alternatives.
4. An investigation of the effect of brook intakes on the stability of mass oscillations in existing hydropower plants.

It is concluded that it is possible to upgrade existing hydropower plants to pumped storage plants by using the existing tunnel system infrastructure with minor modifications. Suggestions for future work are included at the end of this thesis.

List of papers

Selected papers

1. Pitorac, L.; Vereide, K.; and Lia, L. Technical Review of Existing Norwegian Pumped Storage Plants, *Energies*. 2020; 13(18):4918. DOI: 10.3390/en13184918 *(Open Access)*
2. Pitorac, L.; Vereide, K.; Lia, L., and Cervantes, M. Hydraulic Scale Modelling of Mass Oscillations in Pumped Storage Plants with Multiple Surge Tanks. 2021; *(In review: Journal of Hydraulic Engineering)*
3. Pitorac, L.; Vereide, K.; Svingen, B., and Lia, L. Stability of Mass Oscillations in Hydropower Plants with Brook Intakes. 2021 *(In review: Journal of Hydraulic Research)*

Secondary papers

1. Pitorac, L.; Bardini, D., Vereide, K.; and Lia, L. The Effect of Brook Intakes, Downstream Surge Tanks and Reservoir Levels on Surge Tank Stability. *13th International Conference on Pressure Surges*. *Hydro power*. 2018; p. 521-534; Bordeaux, France, 14-16 November 2018.
2. Pitorac, L.; Vereide, K.; and Lia, L. Upgrading Hydropower Plants to Pumped Storage Plants: A Hydraulic Scale Model of the Tunnel System. *8th IAHR International Symposium on Hydraulic Structures*. 2020. Santiago, Chile, 12-15 May 2020. DOI: 10.14264/uql.2020.602.
3. Pace, D., Vereide, K., De Cesare, G., Pitorac, L., Lia, L. (2020). *Case Study of Rotor Lifting in a Pumped Storage Hydropower Plant in Norway*. Hydro 2020. Online. 26-28 October 2020.
4. Saha, S., Vereide, K., Pitorac, L. (2020). *An Innovative Tunnel System and Surge Sank Design for the 1300 MW Kuli Pump Storage Plant.* Hydro 2020. Online. 26-28 October 2020.

Master theses

1. Debora Bardini (2018). *Direct Simulation of Surge Tank Stability*. Supervisors: Kaspar Vereide (NTNU), Stefano Malavasi (Politecnico di Milano), Livia Pitorac (NTNU).
2. Daniel Pace (2019). *Numerical Simulation of Long Tailrace Tunnels in Hydropower Pumped Storage Plants*. Supervisors: Leif Lia (NTNU), Giovanni De Cesare (EPFL), Kaspar Vereide (NTNU), Livia Pitorac (NTNU).
3. Sanjoy Saha (2019). *Tunnel System Design for the Kuli Pumped Hydro Storage Project*. Supervisors: Kaspar Vereide (NTNU), Livia Pitorac (NTNU).
4. Alexandru Milca. *Physical Modelling of Mass Oscillations in Roskrepp Hydropower Plant*. (2020). Supervisors: Leif Lia (NTNU), Bogdan Popa (Politehnica University of Bucharest), Livia Pitorac (NTNU).

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Thanks to all my PhD colleagues and friends at the Department of Civil and Environmental Engineering. To the PhDs in the foregoing generation, especially Ana and Noemi, you have been a very welcoming group and helped me integrate and accommodate very well, so thank you. To the PhDs in the following generation, thank you for the lunch conversations, which ranged from deep to funny, and for the fruitful share of knowledge in our PhD talks. Thank you to my students, with special thanks for Debora and Ana Juarez for being open and giving me real feedback on how to improve my supervision skills. You have been a pleasure to work with. Thank you to the technical personnel in the lab, with special thanks to Thai for being a good friend, and for always saying yes to any help I would ask for, and to Geir and Eirik for good conversations and advice during the hydraulic model construction period.

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My dear friends, I would like to thank you for the good times we have had together. Donata, thank you for being a real friend, for always telling me what I don’t want to hear because it’s the truth. I value your help and support, and despite the short time that we know each other for, I value you and your friendship a lot. To Christa, you have been there for me to laugh and cry together, you gave me a hug and a giggle when I needed it most, you will always have a special place in my heart, thank you for being my family in Norway for the past six years. Adelina, I am blessed to have you as my best friend, even if we have been far from each other, you have always been there for me. Our long phone conversations have always been a pleasure. I love you! To the Covid gang, thank you for the good times and delicious dinners we shared together. Without you, the Covid period would have been much harder, I am thankful for having you around. I also want to thank my Oslo friends and my salsa friends for the good times we shared together, for the fun dances, and for proving to be a solid group of friends for me.

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List of symbols

1D - one dimensional
2D - two dimensional
3D - three dimensional
a - celerity
A - tunnel cross section area
A_{r} - cross section area of the riser
A_{st} - cross section area of the surge tank
A_{Th} - Thoma cross section area
D - tunnel diameter
D_{h} - hydraulic diameter
f - friction factor
g - gravitational acceleration
h - non-dimensional head
h_{f} - friction loss
h_{r} - height of water level in the riser above the reservoir
h_{s} - singular loss
h_{st} - height of the water level in the outer tank above the reservoir
H - turbine gross head
k_0 - throttle loss parameter at Q_0
L - length
n - speed of rotation
n_{ref} - reference speed of rotation
Δn - difference between n and n_{ref}
p - pressure
P_{h} - hydraulic power
P_{e} - electric power
ΔP - difference between P_{e} and P_{h}
q - non-dimensional discharge
Q - discharge
Q_{BI} - brook intake external inflow
Q_{T} - tunnel discharge
Q_{t} - turbine discharge
Q_0 - turbine design discharge
Q_{over} - overflow over the riser crest
v - velocity
s - tunnel slope
t - time
x - distance
y - non-dimensional guide vane opening
α - guide vane opening
ζ - singular head loss factor
ρ - water density
μ - dynamic viscosity
$\partial H/\partial t$ - change in head over time
$\partial v/\partial x$ - change in velocity
$\partial v/\partial t$ - velocity variation in time

List of abbreviations

BI - brook intake
DST - downstream surge tank
ESD - emergency shutdown
FM - flow meter
HPP - hydropower plant
HRWL - highest regulated water level
LRWL - lowest regulated water level
MOC - method of characteristics
NVE - Norwegian Water Resources and Energy Directorate
PID - partial-integral-differential (governor)
PS - pressure sensor
PSP - pumped storage plant
RPM - rotations per minute
RPT - reservable pump turbine
UA - unplugged adit
US - ultrasonic sensor
UST - upstream surge tank

1 Introduction

This chapter presents an introduction to the work in this thesis. It provides brief account on the background of the study followed by the motivation and scope of the thesis.

The energy system is being altered due to the international effort to combat climate change. Consequently, more renewable energy sources are included. Some of the renewable energy sources such as wind and solar are unregulated and result in imbalance between the supply and demand within the energy system. To provide balance in the system, there is a need for more energy storage (Staffell & Pfenninger, 2018). The short-term energy storage may be covered by batteries, but these do not provide long-term energy storage. Long-term storage may currently only be covered by fossil sources, hydrogen, or pumped hydro (Schaber, et al., 2004). Due to the CO2 emissions, fossil sources are undesirable. Hydrogen energy storage has an advantage for large scale energy storage but has a low roundtrip efficiency, below 50% (Steilen & Jorissen, 2015), it is relatively expensive, and still under development. Pumped hydro is a mature technology, flexible, and can provide both long- and short-term storage (Deane, et al., 2010; Hunt, et al., 2020; Rogner & Troja, 2018; IHA, 2021). Pumped hydro is currently the dominant solution for electric energy storage, with 160 GW installed capacity worldwide in 2020 (IHA, 2021). However, developing new large pumped-hydro projects is capital intensive and may be regarded as risky for potential investors (Deane, et al., 2010). In addition, resistance due to environmental and social concerns may block the development of new projects (Thaulow, et al., 2016). For these reasons, a more cost-efficient and environmentally friendly solution is to upgrade existing hydropower plants (HPPs) to pumped storge plants (PSPs), as the projects would be developed using already existing reservoirs, and the tunnel system can, to a large extent, remain unchanged. This is the broad topic covered in the current study.

The hydraulic transients can be separated into two different phenomena, water hammer and mass oscillations (Chaudhry, 2014). Water hammer is a pressure transient encountered during any turbine operation in a power plant. In HPPs with long tunnel systems, a severe water hammer can occur during a shutdown or startup, as the entire water column is decelerated or accelerated, respectively. A way to reduce the water hammer is to implement surge tanks (Jaeger, 1977). Surge tanks have a long history, with the concept first being introduced by Michaud (1878). The concept got well-developed along years, with significant contributions from Johnson (1908), Thoma (1910), Jaeger (1958; 1977), Svee (1972), Anderson (1984), and Chaudhry (2014). By including a surge tank along the tunnel system, an additional free water surface is included where the water hammer pressure is released. However, by introducing a surge tank, U-tube oscillations are introduced between the surge tank and the reservoir. These are called mass oscillations and they occur in the form of a sine wave around the steady-state water level.

In addition to surge tanks, brook intakes (BIs) are extensively studied in this work. Brook intakes are secondary intakes that have the role of transporting water from brooks to the tunnel through an intake and a shaft. They are, in practice, surge tanks with inflow. The inflow in the brook intake is usually unregulated and they are more common in regions with a certain type of topography. If the brook intake can be placed in a beneficial location, it can be used as a primary surge tank. A brook intake included in the system adds to the complexity of hydraulic transients. Surge tanks are designed with a minimum size to avoid instability of the mass oscillations. When a tunnel system with surge tanks is upgraded to a higher installed capacity or a pumped hydro, stability issues with surge tank may occur. Surge tank stability is extensively studied in previous literature; however, the effects of brook intakes on the hydraulic transients received limited attention.

1.1 Scope of work and contributions

The motivation for this thesis is to determine how the behavior of the tunnel system in a hydropower plant is changing in the case of an upgrade to a pumped storage. The focus is the hydraulic transients, mainly looking into surge tanks, brook intakes and mass oscillations. When a HPP is upgraded to a PSP by using the already existing tunnel system, the hydraulic transients become more severe, thus there is a need for verification of the tunnel system hydraulics and consider necessary measures to allow the upgrade. The surge tank is of particular interest in this work since it is the main component in the waterway controlling both water hammer and mass oscillations. When the direction of the water flow is reversed from turbining to pumping, the hydraulic grade line significantly changes, thus the water levels in the surge tanks are different during steady-state operation. In addition, pumping operations include more and different system behavior in terms of transients. These are important to be investigated when an upgrade is to be implemented, as the current tunnel system and surge tanks are designed only for turbining mode, thus constituting another reason for investigating the topic. For reconstruction of HPPs to PSPs it is also necessary to investigate the effects of the brook intakes on the hydraulic transients and stability of the mass oscillations. In Alpine areas, there are many BIs in systems where a conversion from HPP to PSP is likely. It is thus important to assess their influence, to determine if they could be a bottleneck for an upgrade or on the contrary if they would have a positive effect and be in general useful for an upgrade.

The larger scope of this work is to enable the upgrading of existing hydropower plants to pumped-storage plants, in order to provide a reliable storage solution for the renewable energy transition. The focus is to overcome the limitations of using already existing tunnel infrastructure. The research objectives of this work are presented in the following.

Objective 1: Review of existing Norwegian pumped hydro: design challenges, technological solutions, and operational experience.
Objective 2: Verify hydraulic scale modelling for investigations of reconstruction of HPPs to PSPs. Demonstrate on a case study.
Objective 3: Identify the main challenges associated with the upgrade in terms of tunnel system design and provide solution alternatives.
Objective 4: Assess the effect of brook intakes on mass oscillations stability, and its implications for upgrading of hydropower plants with brook intakes.

The first objective is to get an overview of the existing design of pumped storage plants in Norway. The focus of the review is to obtain information about the tunnel system and surge tank design, as well as the electro-mechanical installation and operational experience. Another point within the objective is to get information about possible challenges that can be encountered when operating pumped storage plants directly from the owner and operators. The review shall provide a foundation for the design and construction of new PSPs.

The second objective is to verify a potential research method that can be applied to study the possibility to modify a complex hydropower system to a pumped storage. Hydraulic scale modelling is a commonly used method in hydraulic engineering. However, mass oscillations in hydropower tunnels with multiple surge tanks have not been verified with field measurements before. A hydraulic scale model shall be constructed and verified using a case study, determining whether the method may be useful for the design of the future reconstruction of HPP to PSP.

The third objective is to identify what potential challenges can be encountered during tunnel system design for reconstruction to PSP and provide possible solution alternatives. The solutions are intended to be specific to the case study, but at the same time, they should provide generally applicable engineering knowledge. The case study shall incorporate typical features such as headrace and tailrace surge tanks, as well as adit tunnels and brook intakes along the headrace and tailrace tunnels.

The fourth objective is to assess the effect of brook intakes on mass oscillations stability. There are several brook intake variables that can have an influence. The variables which are to be investigated are the number of brook intakes, the cross-section, the throttling, and the inflow in the brook intake. The study shall be conducted using a generalized model of a typical hydropower tunnel system.

The main contributions from this work are presented in the following. (1) A review of the existing and operational PSPs in Norway with a focus on the tunnel system. This review provides a foundation for the future development of PSPs. (2) Verification and demonstration of a new method for determining the distribution of head loss factors in hydropower tunnel systems with multiple surge shafts using hydraulic scale modelling as a tool. (3) Identify the main limitations for upgrading HPP to PSP using hydraulic scale modelling and provide solution alternatives with specific recommendations for reconstruction of the 50 MW Roskrepp HPP in southern Norway. The results, based on a comparison between model tests and field measurements, verify that hydraulic scale modelling can be used with reasonable accuracy also for complex hydropower tunnel systems. (4) An investigation of the effect of brook intakes on the stability of mass oscillations in existing hydropower plants, and an assessment of whether brook intakes may allow an upgrade of existing hydropower plants without significant reconstruction. The results show that brook intakes have a stabilizing effect on the mass oscillations, but that the effect of the brook intake inflow must be accounted for. The effect of several variables of the brook intake design is quantified.

1.2 Thesis structure

In Chapter 1, the work done in this project is introduced. Chapter 2 describes the research methodology. The results are presented in Chapter 3, together with the contributions resulted from the work. A discussion about potential applications and limitations of the work is included in Chapter 4, and Chapter 5 presents the conclusions. The selected papers are included in full in Appendix A. Appendix B contains the co-author statements for the published papers and the work under the publishing process.

2 Research methods

For the review of technological solutions, a combination of publicly available data sources, questionaries and interviews for each PSP owner and operator are used. Three different research methods are applied in this study: field measurements, hydraulic scale modelling, and 1D numerical modelling. Each method has different benefits and challenges, and often a combination of the three is necessary for obtaining accurate and reliable results. The three research methods and their application for complex hydropower tunnel system are described in this chapter, together with the benefits and the limitations for each of them. A detailed description of the selected case study is included.

2.1 Questionary and interview

The review of current existing technological solutions applied in Norwegian PSPs is conducted using a combination of questionary, documentation, and interview. Confidentiality agreements are signed before gaining access to the information. In the initial stage, a questionary with ten questions about the mechanical equipment, four questions about the electrical equipment, six questions about the civil works, and three questions about the production is sent to each PSP owner. In addition to the questions, technical drawings are also requested. In the second stage, the collected data are centralized, analyzed, and compared. In the third stage, the PSP operators are interviewed over the phone about their operational experience.

2.2 Case study

Roskrepp HPP is selected as the case study out of six evaluated alternatives for several reasons: (a) the HPP is very likely to be converted to a PSP in the future; (b) it contains four shafts, two along the headrace and two along the tailrace, which are possible issues for the upgrade; (c) it has a high head design, a common design for the HPPs that are most likely to be converted; (d) data availability and facilitated access to the power plant. Roskrepp power plant is located in southwest Norway, and it is owned by Sira-Kvina kraftselskap. A longitudinal view of the tunnel system in Roskrepp HPP is shown in Figure 1. The hydropower plant is equipped with one 50 MW high head Francis turbine, it has an 83 m head, and 70 m^3/s nominal discharge. The power plant has two reservoirs, an upper reservoir (UR), Roskreppfjorden, regulated between 890 and 929 masl, and a lower reservoir (LR), Øyarvatn, regulated between 820 and 837 masl. Along the tunnel system, there are located two surge shafts, three adit tunnels, and a brook intake. Roskrepp hydropower plant has a headrace tunnel of 3.5 km, along which there are located a brook intake (BI) and an upstream surge tank (UST). The tailrace tunnel is 300 m long, with a downstream surge tank (DST) and an unplugged adit (UA). Other adit tunnels also exist, but these are plugged with gated concrete plugs and do not influence the hydraulic transients. The BI is an inclined shaft transporting water from lake Skjerevatn to the headrace tunnel. The UST is located right before the penstock, and it has a lower and an upper expansion chamber. The DST is in fact the shaft for the draft tube gates, but expended to supersede the minimum stability criteria, which is typical in Norwegian design. The UA is an adit tunnel to the tailrace. The special characteristic of the UA is that it has the outlet into the LR at an elevation between the highest regulated water level (HRWL) and lowest regulated water level (LRWL). This means that the adit is filled with water when the water level is high, and it acts as surge tank when the water level is low in the lower reservoir. The tunnels are constructed using the drill and blast method, and left unlined, with only few lining sections along weakness zones. In drill and blast tunnels, the risk of fallen rocks is higher, thus a rock trap is built at the downstream end of the headrace, placed before the fine trash rack and the transition to the steel lined penstock. A special aspect of this hydropower plant is that the headrace tunnel invert is covered with asphalt, protecting the underlying rock material from erosion. This specific hydropower plant is selected as it presents all the characteristics of interest for the current study, namely typical design, reservoirs both upstream and downstream, and multiple surge shafts located along both the headrace and the tailrace tunnels.

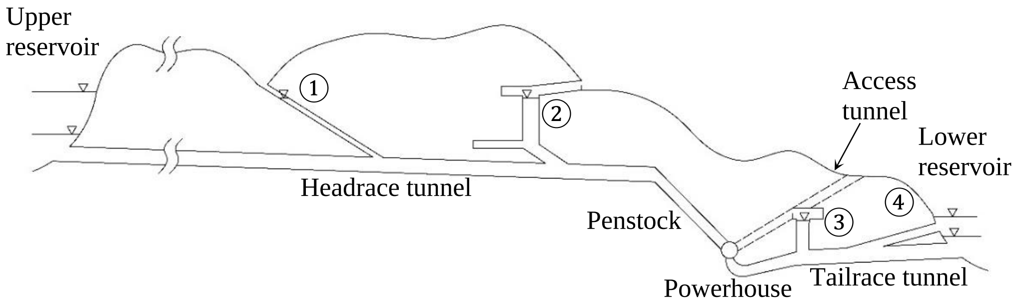


Figure 1. Longitudinal view of Roskrepp hydropower plant: ① brook intake, ② upstream surge tank, ③ downstream surge tank, ④ unplugged adit

2.2.1 Tunnel inspection during Roskrepp HPP dewatering

The headrace tunnel system in Roskrepp hydropower plant is dewatered during the summer of 2018, and some photos from the field visit are show in Figure 2. During the dewatering, inspection is done of the tunnel, lining, gates, plugs, penstock, turbine inlet valve, and turbine (photo 6 in Figure 2). The occasion is used also for 3D scanning of the headrace tunnel including the brook intake, upstream surge tank, and powerhouse (Figure 1). During the inspection of the tunnel, some rockfall is noticed (photo 3 in Figure 2), as well as scalping of the asphalt paving (photo 2 in Figure 2) in some areas. Water seepage from the rock is noticed in some areas (photo 4 in Figure 2). In photo 5 from Figure 2 the shaft of the upstream surge tank is shown, and there are no obvious issues. In general, the tunnel does not present significant issues that could result in problems for the upgrade. However, one concern that is raised is that the headrace tunnel has asphalt lined invert from the upstream reservoir to the upstream surge tank. During the inspection, no significant problems is observed with this, apart from a few areas where the lining is scalped. After the upgrade to PSP, more issues might encounter both because of reversed flow and because of change of the pressure line.

Figure 2. Field visit during dewatering of Roskrepp headrace tunnel (1 - asphalt lining; 2 - scalped asphalt section; 3 - rock fall; 4 - possible weakness zone; 5 - UST shaft (see figure 1); 5 - adit plug before penstock (see figure 1))

2.3 Field measurements

Field measurements are an important part of the research work. Field measurements campaigns are conducted at the 50 MW Roskrepp HPP, to collect both operational data (September 2017) and conduct a full 3D scan of the headrace tunnel system (June 2018). The field measurements are used to construct, calibrate, and validate a physical and a numerical model.

2.3.1 Three-dimensional tunnel scanning

The tunnel scan part of the field measurements is a 3D scan of the waterway, using a Leica Scan Station P20 with a point density of 25 mm, for points at 10 m distance from the scanner. The measurements are performed with approximately 20 m distance between each setup, at a measuring rate of 1 million points per second, creating a point cloud. The site preparation for measurements includes marking the locations and placing the rock bolts at regular intervals (pictures 1 and 2 in Figure 3). It is only possible to measure the exact location of the bolts outside the tunnel, so the final scan has to be adjusted based on position of the bolts at the start and finish of the tunnel stretch. After the site is prepared, the actual scanning takes place (pictures 3 and 4 in Figure 3), with operations in the following order: targets placed on the bolts, set the scan station location, place two reflective prisms before and after the laser scanner, respectively, start scanning, redo operations while advancing along tunnel.

Figure 3. 3D scanning step-by-step process and resulted scan (1 - bolt location marking; 2 - drill for bolt placement; 3 - scanning target placement; 4 - laser scanning)

The areas covered in the 3D scan measurements are the headrace tunnel, the penstock, the powerhouse, the brook intake, the UST, the expansion chamber of the DST, the access tunnels (Figure 4). The tailrace tunnel, together with the DST shaft and the adit are not included as the tailrace tunnel is not dewatered. The measurements are performed by a team of five people from the Scan Survey company. The 3D scanning of the tunnel system is considered relevant to obtain for improving the knowledge about the tunnel design and to ensure good correlations between the geometry of the prototype and the models. This proves to be valuable information, as significant discrepancies are found in some areas. Details about this can be found in the *Results* chapter as well as in the *Paper 2*.

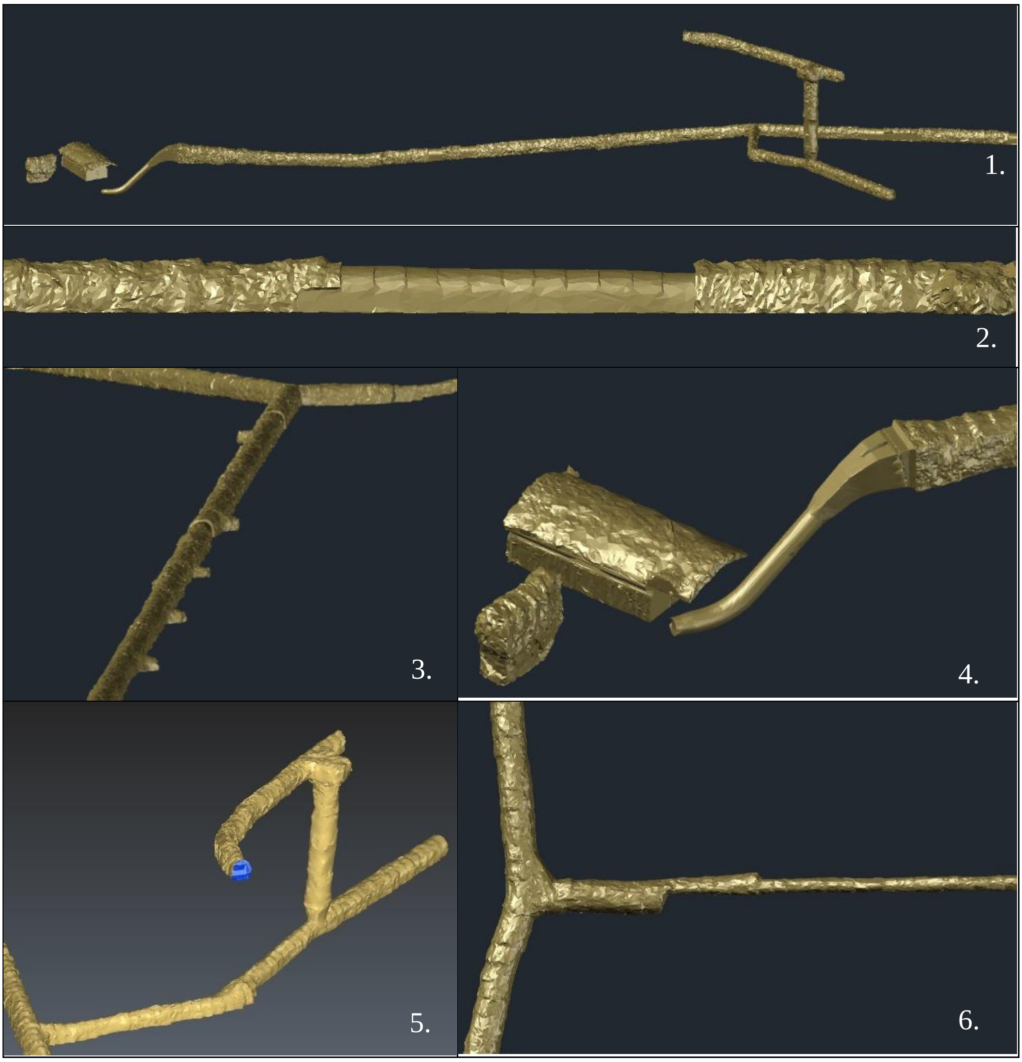


Figure 4. Three-dimensional scan of the headrace tunnel in Roskrepp HPP (1 - headrace from UST to powerhouse; 2 - lined section; 3 - section showing niches along the tunnel; 4 - penstock, power house and DST; 5 - UST; 6 - BI entrance and BI section)

2.3.2 *Measurements of hydropower plant operation*

In September 2017, field measurements of hydraulic transients in Roskrepp HPP are carried out during a period of 3 hours. The HPP is operated according to a planned schedule including startup to full load, load decrease and increase of 20, 40, 60%, and emergency shutdown from full load, shown in the graph from Figure 5. The water levels in the two reservoirs are relatively stable, with no water level decrease in the upstream reservoir and less than 10 cm variation of the water level in the lower reservoir, during the entire measurements period.

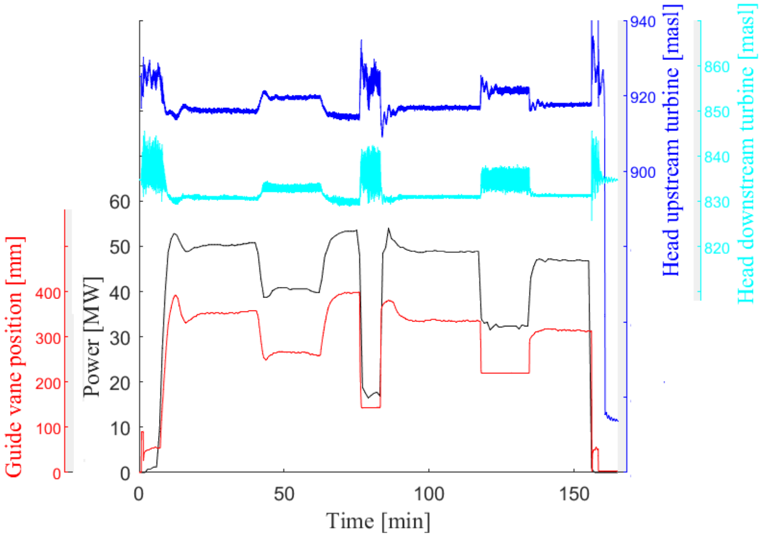


Figure 5. Field measurements performed at Roskrepp hydropower plant

For the pressure measurements, a 50 bars sealed-gauge pressure transducer is collecting data from the turbine inlet, and a 25 bars sealed-gauge pressure transducer is connected to the draft tube. The guide vane position is determined using a linear potentiometer, which measures the displacement of the guide vane servo. The rotational speed of the turbine is measured using a tachometer with a nominal range of 6x10^7 counts per minute. All sensors are recording at 50 Hz frequency and have a Bessel lowpass filter. The water levels in the two reservoirs are recorded at one-hour intervals. Data about power production during the measurements are provided by the power plant operator, and they are recorded at a minute-by-minute rate. The field measurements are performed as a collaboration between personnel from Sira-Kvina kraftselskap, PhD candidates and master students from NTNU, and hydropower plant measurement specialists from Flow Design Bureau (FDB).

Only measurements of the pressure variation at turbine inlet and outlet are collected, and no information about the pressure variation in each separate surge shafts is collected. This means that no information about the mass oscillations in the brook intake and the unplugged adit are available which represents a limitation of the collected data. Another limitation comes from the fact that the discharge in the brook intake is unknown during the measurements. The brook intake inflow is though considered to be relatively low and have minimal influence, considering that the weather during the measurements is stable with little to no rainfall in the region. A calculation of the assumed water inflow to the brook intake is presented in *Chapter 3.1.3*.

2.4 Numerical modelling

One-dimensional (1D) numerical modelling is a common technique applied in hydraulic engineering and research. There are various numerical models that can be used for mass oscillations analysis, and the one selected for this study is the Method of Characteristics (MOC) as presented in Wylie and Streeter (1993). The MOC is based on the equation of continuity (conservation of mass) and the equation of motion (conservation of momentum):

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial v}{\partial x} = 0 \qquad [1]$$

$$g\frac{\partial H}{\partial t} + \frac{\partial v}{\partial t} + f\frac{v|v|}{2D_h} = 0 \qquad [2]$$

where $\partial H/\partial t$ is the change in head over time, a is the celerity, g is the gravitational acceleration, $\partial v/\partial x$ is the change of velocity, $\partial v/\partial t$ is the velocity variation in time, f is the friction factor, v is the velocity, D_h is the hydraulic diameter.

The two partial differential equations [1] and [2] have two dependent variables (velocity v and head H) and two independent variables (distance along pipe x and time t). With certain assumptions, the two partial differential equations can be transformed into four ordinary differential equations, thus solvable using a 1D numerical model.

There are several limitations to MOC, and 1D numerical modelling in general. One limitation would be that such models do a 1D representation of 2D and 3D objects through empirical values and simplifications. Linearization of the differential equations is another simplification. Variation in cross section, niches, sand trap are simplified into a 1D representation, their effect on the head loss being included in the head loss factor. The cross-section averaging can lead to unaccounted velocity and pressure variation. In general, empirical 1D friction models are good in steady state, but they get more inaccurate during transient flow, and they are not accurate for unsteady friction, which in some special cases can be significant (Brekke, 1984). In the case of transient flow, the flow may also change from the turbulent to laminar regime (Moody, 1944) which is not represented in the friction modelling. Other limitations can be air unaccounted for in the prototype, and the fact that the turbine model used in LVTrans does not represent its exact characteristics, but rather uses the generalized turbine model by (Nilsen, 1990).

Despite its limitations and uncertainties, 1D numerical modelling is chosen for the study as it is considered to provide sufficiently reliable and accurate results with limited time and effort. Using 2D or 3D numerical models for a large and complex systems with water hammer and mass oscillations is challenging because of the high computational requirements. Even though 1D numerical models do not capture the 3D effects, it is considered that when the length to diameter ratio is above 10, the 1D numerical model is not only acceptable, but also the main representation of the physical phenomena (Wylie, 1996).

The simulations in this study are conducted using the LVTrans 1.11.8 (2014) and 02.11.14 (2018) freeware (Svingen, 2014), which is developed in LabView. Different modules such as pipes, surge tanks, reservoirs, turbines, governors, and pumps are implemented in LVTrans to model all the components of a hydropower plant. Figure 6 shows the block diagram of the governor system implemented in LVTrans, where n_{ref} is the reference speed of rotation, n is the speed of rotation, Δn is the difference between the actual speed of rotation and the reference speed of rotation, P_h is the hydraulic power, P_e is the electric power, ΔP is the difference between the electric and the hydraulic power.

One reason for choosing LVTrans as the numerical modelling tool used in this study is the freeware characteristic of the package. Commercial software programs are taken into consideration such as OpenFlows HAMMER by Bentley, Pipe by KYPIPE or SIMSEN by Power Vision Engineering, but they do not provide additional possibilities compared with LVTrans. Another reason for choosing LVTrans is the available expertise at NTNU and the turbine manufacturer Rainpower in Trondheim. This is valuable for reducing the learning time and for receiving fast technical support when necessary.

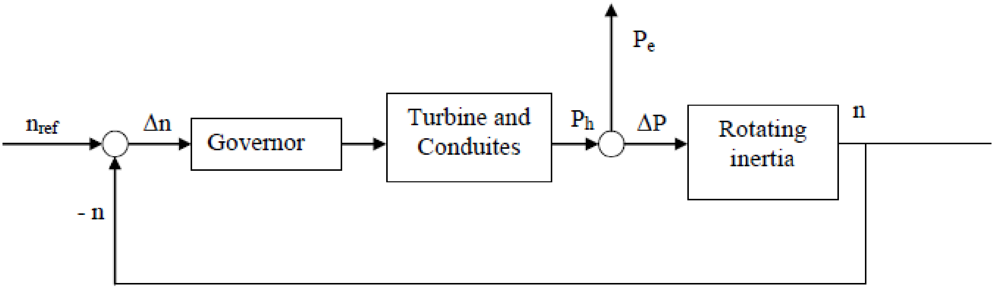


Figure 6. Block diagram describing the governing process

The numerical models developed in this study is calibrated and validated based on the field measurements. The models allow for testing of how the existing case-study hydropower plant may be upgraded, and the effect on the hydraulic transients.

2.4.1 Frequency-response analysis

In the frequency-response analysis, y is the non-dimensional excitation and hq is the non-dimensional response, which means that the guide vane position α gets an imposed oscillation and the response on the turbine inlet pressure and turbine discharge HQ is measured. In the analysis, four oscillation periods are implemented for stabilizing the system, and four more for collecting the data. The oscillations are induced around 0.8 and 1.1 α guide vane opening, with an amplitude of 0.001 (small amplitudes), 200 sample frequencies, 100 samples between 0.001 and 0.01 Hz and 100 samples between 0.01 and 0.1 Hz, logarithmically distributed. The frequency response analysis is the method of choice because it can analyze and quantify the stability of the system. From the different possibilities of excitations and responses, the hq/y is chosen, because, unlike h/y, the hq/y can quantify the stability of a system, and not only provide a comparative analysis. Even though hq/y is not a feasible method for implementing in real hydropower plant, like n/n_{ref} or n/p, the two can only be implemented in island mode, which makes them theoretical methods. Another reason for using hq/y is that the PID does not have an influence on the results, eliminating the PID as a possible error source due to poor tunning. The hq/y is in fact nearly proportional to p/y apart from the efficiency curve, which means that it is reasonable to assume that the results are reliable in terms of system stability.

2.5 Hydraulic scale modelling

Hydraulic scale modelling is a commonly used method in hydraulic engineering. The accuracy of a hydraulic model depends on scaling law that is applied, the scaling factor, what simplifications are implemented, as well as the boundary conditions. In hydraulic scaling, a prototype is chosen and scaled down to a laboratory size, abiding by the hydraulic scaling laws. Hydraulic similarity is grouped in geometric similarity (ratio between geometric parameters), kinematic similarity (ratio between velocities), and dynamic similarity (ratio between forces). The dynamic similarity is desired since this includes the kinematic and geometric similitude as well, but it is only possible if using 1:1 scale model, since all forces cannot be downscaled correctly at the same time. As a result, the scaling is performed to keep dynamic similarity of only the most influential forces and the scaling law that is applied need to be selected to keep the similarity of phenomena of interest (Kobus, 1978). Three main similarity laws are used in hydraulic engineering: Reynolds (inertia to viscous forces), Froude (inertia to gravity forces), and Euler (pressure to inertia forces).

In this work, a dimensional analysis is done using Buckingham-π theorem (Buckingham, 1914) to ensure that the correct scaling law is chosen. The method involves assuming m physical variables and o fundamental dimensions, that are used to formulate m-o independent dimensionless parameters π. The conditions for correct implementation of the method are: (1) each o dimension should appear in at least one m variable; (2) two variables cannot be chosen together in a recurring set if they can form a dimensionless parameter by themselves. The dimensionless parameters for the model used in this study are presented in Table 1 Where D is tunnel diameter, L is the tunnel length, s is the tunnel slope, f is the friction factor, ρ is the water density, μ is the dynamic viscosity, p is the pressure. The dimensionless parameters are in accordance with the Euler scaling law. When assuming rigid water with constant water density, the Euler scaling law is in practice the same as the Froude scaling law.

Table 1. Dimensionless parameters from Buckingham-π method

	Expression	Name
π_1	$\frac{v}{\sqrt{g\,D}}$	Froude number
π_2	$\frac{H}{D}$	Head factor
π_3	$\frac{L}{D}$	Length factor
π_4	s	Tunnel slope
π_5	f	Friction factor
π_6	$\frac{v}{a}$	Mach number
π_7	$\frac{vD\rho}{\mu}$	Reynolds number
π_8	$\frac{vt}{D}$	Keulegan–Carpenter number
π_9	$\frac{p}{\rho v^2}$	Euler number

The tuning and validation of the hydraulic scale model is done using the prototype measurements. The model tuning is necessary to obtain the correct head loss scaling. There are two options for this: (1) scaling of roughness which can be obtained by selecting a material with desired roughness or by creating the desired roughness through implementing loss points along the tunnel system; (2) selecting a material with lower roughness than necessary and include singular loss points along each relevant stretch to sum up to the total head loss. Both friction loss h_f and singular loss h_s are functions of the same variables $f(v^2)$:

$$h_f = f\frac{L}{D}\frac{v^2}{2g} \qquad [3]$$

$$h_s = \zeta\frac{v^2}{2g} \qquad [4]$$

where ζ is the singular head loss parameter. In this study, the second method is used because of the relative simplicity of the method, cost, as well as already available materials.

There are three different types of possible error sources in experimental modeling: systematic, random, and personal. The systematic error sources affect all experiments, and additional data do not compensate for them. Possible systematic error sources can be equipment calibration, instrumentation drift, temperature- and pressure in the environment at certain times during a day, disregarding the effect of a variable that turns out to be important. Random errors are unpredictable variations during the experiment which can be mitigated by a higher sampling rate. Possible random error sources can be equipment accuracy, instrument resolution, temperature- or atmospheric pressure changes in the room, random electric or magnetic noise. Within the study, all these possible error sources are accounted for and measures to mitigate them are taken. The systematic errors that could encounter due to selecting a material with lower roughness than the scaled roughness of the tunnel is compensated with including singular loss points along the relevant tunnel stretches. The method is analytically validated using the minor and major head loss formulas, which for turbulent flow are just $f(v^2)$ as shown in Equations 3 and 4; the head loss during laminar flow, which encounters only for a short period of time during flow reversal, is insignificant comparing to the total head loss. In addition, the method is tested and validated in previous studies (Vereide, 2016). To mitigate some other possible systematic or random error sources, such as equipment calibration, instrumentation drift, or environmental temperature- and pressure changes, following measures are put in place: sensor calibration provided by the producer and verified by the author, sampling is done randomly and at different times of the day, sensors are swapped.

One advantage of hydraulic scale models over numerical models is that they incorporate the 3D effects, which are not fully accounted for in a 1D numerical model. The downside of hydraulic models is that less configurations are possible to be tested because of longer and more expensive construction time. Despite this, hydraulic scale models are still an important tool in hydraulic engineering and research.

2.5.1 Model construction

The hydraulic scale model construction project is divided in six phases: design, components order and construction, assembly, troubleshooting, modifications, model validation. The design phase starts in October 2018 and ends in May 2019, the components construction take place between March and August 2019, followed by model assembly, from August to October 2019. In parallel with the model assembly, the equipment testing takes place in August - September 2019, and the connection and sensor installation is done in October 2019. The troubleshooting process took place between November 2019 and February 2020. The modifications are implemented, and the model is validated in February - March 2020. The total construction and validation time is about 17 months. The total cost of the model is approximately 100 000 €, including materials, equipment, and technical assistance. Some materials and equipment are already available; thus, the cost is reduced.

The system is monitored using six GE UNIK 5000 pressure sensors of 0.3 bars (Figure 7a), with ±0.04% full scale accuracy, two Microsonic ultrasonic level sensors, (Figure 7b) with ±1% uncertainty, and two Siemens SITRANS FM MAG 5100W electromagnetic flow meters (Figure 7c) with ±0.4% uncertainty. The location of each sensor is marked in the sketch from Figure 8. The flow meters are placed in locations where a steady flow can be obtained, keeping a minimal distance of 25 diameters before and 15 diameters after the flowmeter to the closest perturbation. Placing the pressure sensors in sections with unperturbed flow proves more challenging, thus for locations where this is not possible, the specific pressure sensor is collecting data using a multiple wall tap type of connection. The ultrasonic sensors are placed on the upper edge of each reservoir, measuring perpendicular to the water surface, in order to avoid any possible reflections.

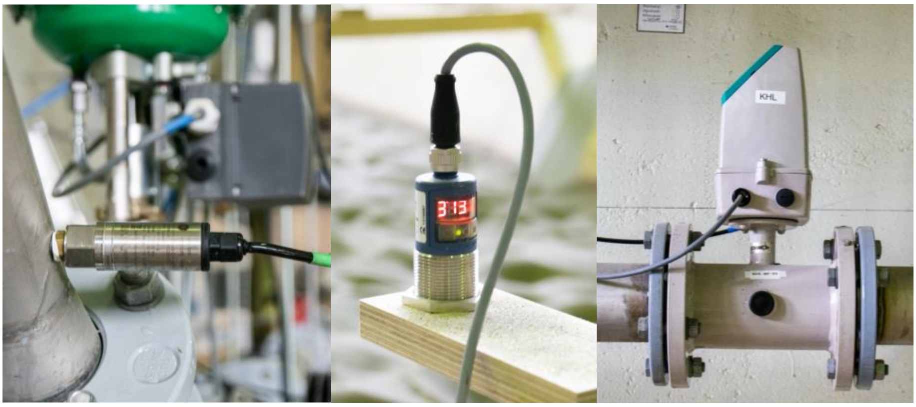


Figure 7. Measuring devices in the model (left to right: pressure sensor, ultrasonic sensor, flow meter)

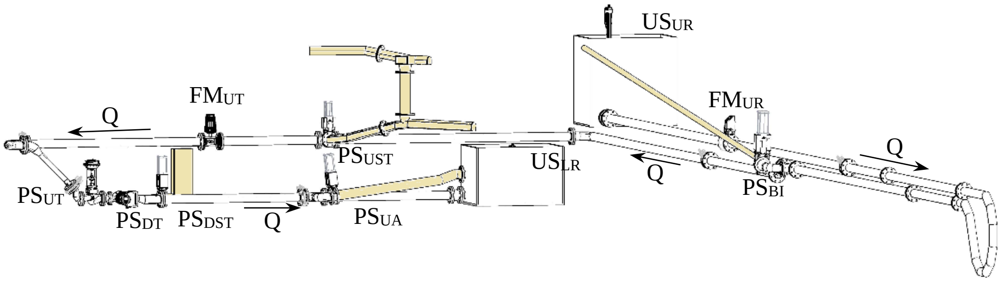


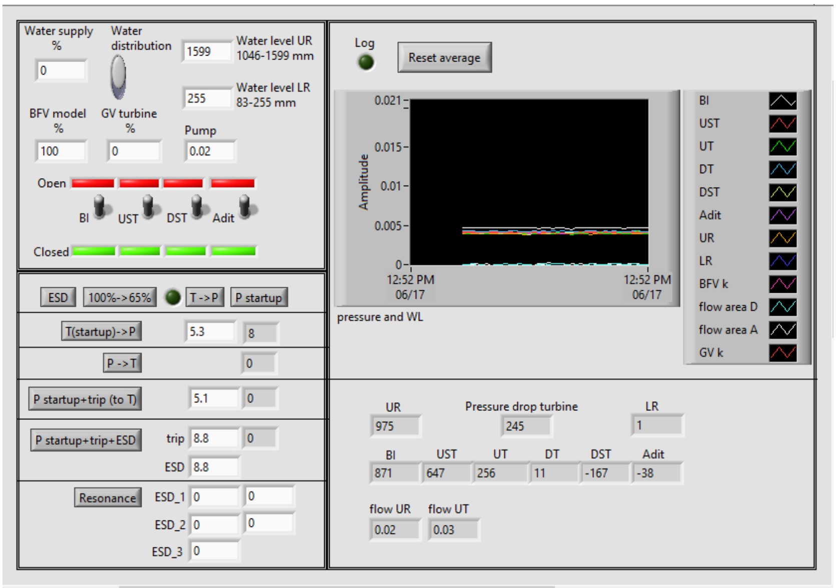
Figure 8. Monitoring sensors placement in the hydraulic scale model (PS - pressure sensor, FM - flowmeter, US - ultrasonic sensor). Parts in acrylic glass are in yellow color.

The model is an open loop system, with water supply coming from the general water supply system of the laboratory, controlled using a butterfly valve and a T-port ball valve which directs the water supply to either of the two reservoirs. The water flow through the model is controlled using a RTK PV6211 Pneumatic Control Globe Valve DN65 with a parabolic plug (representing the turbine), a GEFA HG1 DN65 butterfly valve (for fast closing), and a GRUNDFOS MAGNA3 pump. (Figure 9). The other alternative for the turbine valve would have been a butterfly valve, but the accuracy of flow control is not as performant as for a globe valve. The reason for choosing a parabolic plug for the globe valve is that the valve should accept reversed flow during pumping operations with limited throttling. There are several secondary parameters that can be controlled within the model: disconnection of any of the four shafts (ON/OFF ORBINOX EBN06 knife gate valves), the reservoirs water levels (LINAK LA33 and LA 36 linear actuators). All the mentioned control points are controlled using pneumatic or electric actuators. Other control parameters within the model are manual due to reduced time for control needed. These are the singular loss valves used to obtain the correct total head loss on each relevant tunnel stretch (butterfly valve), the water inflow in shafts, and the air release valves. The system can be fully dewatered using a drainage system that is manually controlled. The sensors in the system, are connected to an I/O cabinet, equipped with a CompactDAQ controller, having seven modules: two analog input modules NI9203, with 16 channels, two analog output modules NI9265 with eight channels, one digital input module NI9375 with 16 channels, and two relay output modules NI9482 with eight channels (Figure 10).

Figure 9. Hydraulic scale model control equipment (left to right: butterfly valve, globe valve, pump)

Figure 10. CompactDAQ and modules installed for hydraulic model control and monitoring

The system is controlled and monitored using a LabVIEW code developed by the author, with the front end shown in Figure 11. The code is separated in three parts: (1) control, (2) automatization, and (3) monitoring. (1) The control part allows the user to control each component in the system individually, to control the water supply to the system, as well as setting the desired position of the valves and the linear actuator in the model. (2) The automatization part is developed to have a good control of the operations to which the system is subjected, and to have good repeatability. In this part of the code, automatization of the control necessary to model the maneuvers from Table 5 is implemented. (3) The monitoring part is collecting both feedback data from the control equipment, as well as data from the pressure sensors and flow meters, at a 10 Hz frequency. This frequency is determined to be more than enough to respect the Nyquist theorem, in such a way that no aliasing encounters in capturing the mass oscillations.



Water supply % 0

Water level UR 1046-1599 mm 1599

Water level LR 83-255 mm 255

BFV model % 100

GV turbine % 0

Pump 0.02

T(startup)->P 5.3 8

P ->T 0

P startup+trip (to T) 5.1 0

P startup+trip+ESD trip 8.8 0

ESD 8.8

Resonance ESD_1 0 0

ESD_2 0 0

ESD_3 0

UR 975

Pressure drop turbine 245

LR 1

BI 871

UST 647

UT 256

DT 11

DST -167

Adit -38

flow UR 0.02

flow UT 0.03

Figure 11. Front end of the applied control and monitoring software

For ensuring a correct system behavior, operation and maintenance procedures are set in place, as follow: (a) air release procedure: the model is run for an extended period of time, alternating between steady state and fast transient states. These operations are run until no air is released through the air release valves and no visual air bubbles are eliminated through the acrylic shafts. (b) pressure and ultrasonic sensor verification procedure: the system is stopped and let to settle to static state (no flow and no oscillations), after which the head indicated by each sensor is verified to be equal to the head imposed in the reservoirs. The procedure is applied minimum two times, once for the maximum and the minimum water level in each reservoir. (c) flow meter verification procedure: the system is run at a constant opening of the turbine valve until steady state is achieved, after which the two flow meters are verified that they indicate the same flow rate. The procedure is applied for a minimum of three flow rates.

For significant amounts of entrapped air, the flow conditions can be changed, the air bubbles acting as an air cushion for the system. The pressure rise in the system can increase up to five times in unfavorable conditions (Pitorac, et al., 2016). The air release procedure is applied after the filling of the system with water or after an extended period which the model. After the air release procedure, the procedures for sensors verification are necessary to be followed as well. Procedures (b) and (c) are applied at the beginning of a new measurements set and anytime it is considered to be necessary. In case the results from the verifications done in the procedures (b) and (c) are not satisfactory, the sensors are disconnected, visually inspected, cleaned if necessary, and in some cases, swapped between each other to check if the error encounters from the sensor itself or from the system.

2.5.2 Hydraulic model configurations and troubleshooting

Several configurations of the model are used for experiments and the model contains several simplifications. The tunnel system is implemented as a circular constant cross section, simplified from the D-shape cross section in the prototype. In addition, the tunnel roughness is not implemented to scale, being included as singular loss along the tunnel. Another simplification to the tunnel is the disregard of the niches and the rock trap. Even though these are not physically implemented, their effect is still accounted for in the total head loss. In the first tested configuration of the model, the brook intake in the hydraulic model is simplified to a vertical shaft with the cross section of the shaft equivalent to the scaled water table cross section from the prototype. The downstream surge tank is also simplified to constant cross section, disregarding the upper expansion chamber from the prototype. A 3D drawing of the first configuration can be seen in Figure 12.

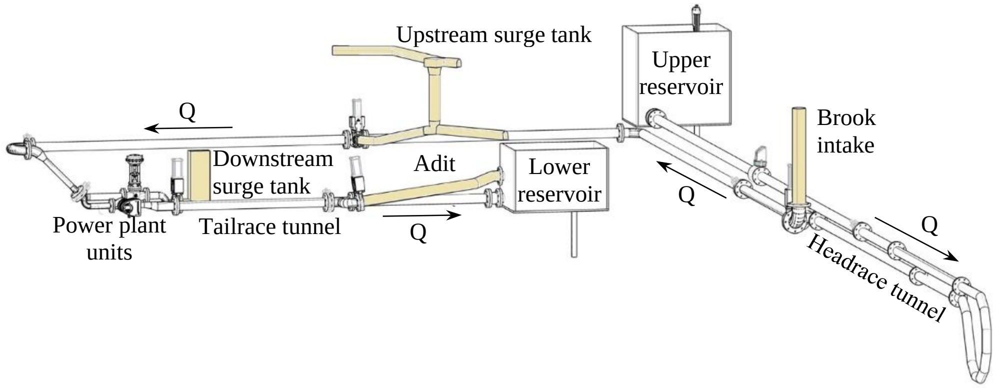


Figure 12. Initial configuration of the hydraulic scale model

Trials of calibration and validation of the model are performed. The steady state calibration of the head loss is implemented for full load steady state of mode. As the head loss is only known as a total between the UR and the turbine, it is implemented in the model as proportional to the length of each relevant stretch, meaning that the head loss on each relevant stretch is the one presented in Table 2.

Table 2. Total head loss on each relevant stretch for initial hydraulic scale model

Stretch	**Prototype**	**Hydraulic model (scaled)**
UR to BI	8.8 m	5.4 m
BI to UST		2.4 m
UST to UT		1 m
DT to LR	2.1 m	2.1 m

The transient state verification is done for the field measurements of start to full load, emergency shut down from full load, load decrease from full load to 60% load, and load increase from 60% load to full load. The validation is unsuccessful; thus, a troubleshooting process is necessary. In the initial troubleshooting phase, all the sensors and control equipment are individually checked for any possible error sources. Pressure sensors, ultrasonic sensors, and flow meters are recalibrated. Next, the possibility of entrapped air is checked. The locations where possible air bubbles could form and get trapped are determined and air release valves are installed. After installing the extra air release valves, the air release procedure presented in subchapter *2.5.1 Model construction* is followed. After this, the model still is not calibrated. Further, the scaling of each parameter and the geometry of the model are verified, but no significant errors are found. The field measurements are rechecked, and discrepancies are found between the actual location of the pressure sensors during the measurements, and the ones assumed in the hydraulic scale model calibration. This is proved to not be the main error factor. Lastly, the simplifications are reconsidered and verified. As the validation troubles are more significant on the upstream section (headrace tunnel), this area is the main focus. The troubleshooting is done using two numerical models in parallel: one for the prototype (1:1 scale) and one for the hydraulic scale model (1:70 scale). The verified simplifications are the brook intake and the head loss distribution, the latter being done using the method presented in the *Results* chapter and in *Paper 2*. The two numerical models are developed in parallel and independent of each other, the configurated parameters being compared between the two when the calibration is achieved. From this, the following changes are implemented to the second configuration of the hydraulic scale model: (a) The brook intake is rebuilt as an inclined shaft, following the original design of the BI from the prototype. (*Note: the simplified vertical shaft previously implemented was replaced, in order to eliminate the errors due to water inertia during mass oscillations*). (b) The head loss along each relevant tunnel stretch is not implemented as proportional to the tunnel length, but rather following the head loss parameters determined from the numerical models, with the values shown in Table 3. (*Note: the head loss on the UST to UT stretch is too high, and it cannot be lowered in the hydraulic scale model. The reason for this discussed in detail in Paper 2*). (c) Valves are included at the bottom of each surge shaft in order to implement the correct head loss during transients. A 3D drawing of the final configuration can be seen in Figure 13.

Table 3. Total head loss on each relevant stretch for final hydraulic scale model

Stretch	Prototype	Hydraulic model (scaled)
UR to BI	7.8 m	3.3 m
BI to UST		1.7 m
UST to UT		4.2 m
DT to LR	1 m	1 m

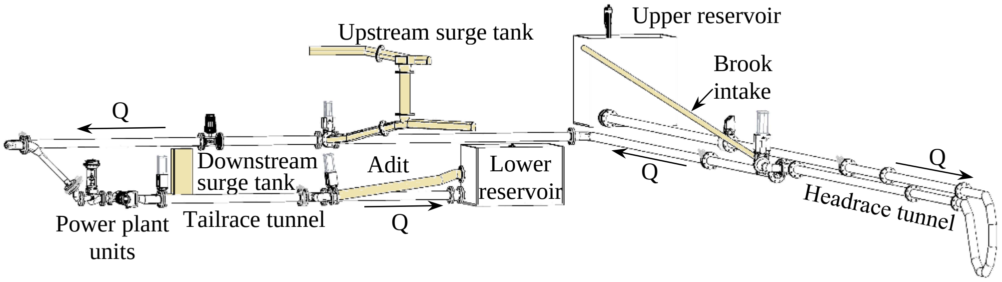


Figure 13. Final configuration of the hydraulic scale model

With this configuration the model is correctly calibrated, and a cross-check of the results from the field measurements, the numerical model, and the hydraulic scale model confirms that the new setup is successful and provides an accurate representation of the physical system. The comparison between field measurements, numerical model results, and hydraulic scale model results is presented in the main findings chapter.

2.5.3 Conducted experiments

The main parameters monitored in experiments are oscillations in the headrace and the tailrace surge tanks, with special interest for the highest and lowest amplitudes at limit operations. The necessary investigations for PSP surge tank design are shown in Table 4. Having these considerations in mind, the investigations shown in Table 5 are performed using the physical model, at both highest and lowest water level in each reservoir.

The measurements are performed in two series, one with the original design of the power plant and one with the modifications done to mitigate the identified main challenges in the system. For each series, four sets are performed. To eliminate some of the possible systematic or random error sources, changes are done to the model and experiment plan:

random sampling order, sampling at different times of the day, sensor switched between each other.

Table 4. Necessary investigations for pumped storage plant surge tank design

Operation	Effect
Headrace surge tank	
ESD from turbine mode	maximum upsurge and maximum pressure at surge tank bottom
ESD from turbine mode	minimum downsurge in surge tank
Pump start failure	minimum pressure at surge tank bottom
Tailrace surge tank	
Pump start failure	maximum upsurge and maximum pressure at surge tank bottom
ESD from turbine mode	minimum downsurge in surge tank
Additional necessary checks	
Resonance case + ESD with guide vane blocking Resonance case + ESD from part load with most adverse characteristics and closing time	water hammer reflection time

Table 5. Investigations performed using the hydraulic scale model

Operation mode	Maneuver
Turbining	startup shutdown emergency shutdown (ESD) change to pumping change to pumping from startup
Pumping	startup shutdown trip with blocked guide vanes startup failure with blocked guide vanes startup failure with ESD

3 Main findings

A summary of the main findings is presented in this chapter. The chapter is divided in two sections, the first section where the main results are presented both from papers and previously unpublished results. In the second section, the contributions to the objectives set for this thesis are presented.

3.1 Introduction to main findings

3.1.1 Pumped storage plant review

The results in this section are obtained using a combination of methods. The first set of results presented in a review article (*Paper 1*) is obtained by gathering publicly available information, from the pumped hydro owners, the Statistisk sentralbyrå, the NVE Atlas, Norgeskart, as well as other publications, such as papers and reports. The Statistisk sentralbyrå is the Norwegian governmental statistics bureau. The NVE Atlas is a map tool by NVE (Norges vassdrags- og energidirektorat - Norwegian Water Resources and Energy Directorate) that provides geographical data, aerial images, and an updated map of buildings, water courses, glaciers, hydrological data, hydropower plants, wind farms, power network, protected areas, natural hazard areas, and topography data. Sensitive information such as tunnel alignment included in the map are distorted on purpose, in order to ensure the security of the locations. The Norgeskart is a map service providing maps, landmarks, and other information from the database of the Norwegian Mapping Authority. Overall, general information about the units, the reservoirs, the production is gathered, but detailed information about the units, the tunnel system, as well as detailed production data are missing, thus the publicly available information is complemented using questionaries and interviews with the power plant owners and operators. Confidential data, such as unit efficiency curves, are nondimensionalized and normalized to be presented in a comparative manner and to avoid disclosure of sensitive information. Data about the access tunnels to the underground powerhouses are not included for the same reason. The elevation profiles are drawn using the technical drawings provided by the plant owners, together with the two mapping services publicly available (NVE Atlas and Norgeskart). The review article is verified and approved by all the power plant owners before publishing. The result provides a knowledge base of detailed design of pumped storage plants, as well as the challenges encountered in the past, and what solutions were then implemented, in general and with focus in the tunnel system.

3.1.2 Field measurements

The results based on field measurements are from the measurements campaign from September 2017. Before the measurements campaign started, the power plant is shut down and let to stabilize for a longer period of time. This is done to ensure that no transients already existing in the system would influence the tunnel system response to the operations done during the measurements. By doing this, the accuracy of the response is ensured, and in the end the quality of the data is ensured. First, the sensors are installed for measuring the pressure at the turbine inlet and outlet, the guide vane position, and the RPM. Next, the actual measurements take place. Before and after the measurements, the zero readings are performed for a period of 30 minutes with the power plant shut down, to verify the calibration. The pressure variation at turbine inlet and outlet is recorded as relative pressure in kPa, relative to the location of each sensor. The guide vane position is recorded in mm, for both guide-vane acting arms. The rest of necessary data, i.e., the power production, the water levels in the upper and lower reservoirs, as well as efficiency curves for the unit are provided by the power plant operator and owner, respectively. These results are used for calibration and validation purpose of the numerical and hydraulic scale models developed in this thesis work. Ensuring a good correspondence between the behavior of the models and the prototype is important for providing accurate, reliable, and valuable data generated from the models.

3.1.3 Hydraulic scale modeling

The validation of the hydraulic scale model done using the field measurements has the following control parameters: water level in the upper and lower reservoirs and turbine discharge. The turbine discharge is not measured directly during the field measurements; thus, it needs to be determined afterwards. The discharge is calculated using the known turbine gross head, electric power output, and the efficiency curves of the generator and the turbine. This method is chosen over determining the discharge from the tunnel head loss, i.e., difference between the gross head of the power plant (difference between water levels in the upper and lower reservoirs, respectively) and the turbine gross head (difference between turbine inlet and turbine outlet) because the available major head loss parameters from the power plant owner in this case with an unlined tunnel is only approximate and lump values based on Manning number (rule of thumb). In addition, even if the accurate major head loss is available, the T-junction singular losses into the surge tanks and brook intake is still unknown or inaccurate. Thus, it is chosen to calculate the discharge for the various operation points using the power output and the efficiency curves. Another control parameter that needs to be determined is the inflow in the brook intake. This is a common error source in such type of field measurements. As previously mentioned, the period when the measurements take place is a dry period, with little to no rain. However, more detailed assessment or measurement of the inflow is not done on site; thus, further checks are necessary. Considering that no data are directly available about the brook intake inflow, hydrological data from monitored unregulated catchments in the region are used and scaled to the Skjerevatn catchment, the catchment of the brook intake. This is necessary so that the discharge data are reflecting the condition in the region. The calculations result in only 0.1 m^3/s inflow at the time of the field measurements, considered neglectable, comparing to the turbine discharge of 60 m^3/s, thus it is not included in the hydraulic scale model. Lastly, for ensuring a correct comparison between the field measurements and the hydraulic scale model measurements at the turbine outlet, the results for the pressure variation are adjusted for the kinetic energy. This is necessary because the diameter of the pipe in the physical model does not correspond to the draft tube diameter in the prototype. A presentation of the tunning process is detailed in *Paper 2*.

The results from the experiments are acquired using the automatic control software coded in LabView by the author. The software is implemented so that the repeatability of the experiments is ensured. For the multiple operations experiments, such as e.g., pump startup failure with emergency shut down, each operation is implemented at the worst point of the mass oscillations amplitude, to obtain the system response for the worst-case scenarios, as shown in the simplified schematics from Figure 14. The worst point is defined as the level where the surge has the highest velocity in the positive direction of the surge.

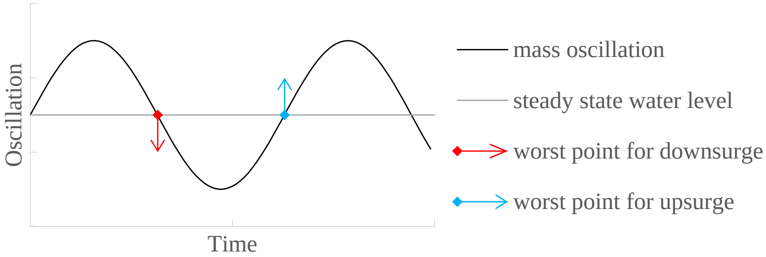


Figure 14. Worst points during mass oscillations for multiple operation procedures

The results are recorded in mA and transformed to the corresponding measure unit in the postprocessing. From mA, the results are transformed into the corresponding measure unit of the sensors using the calibration equations determined from the sensor calibration process (mbar, l/s, and mm, for the pressure sensors, flow meters, and ultrasonic sensors, respectively). The results show that during the maximum upsurge and minimum downsurge in the UST and DST, possible overflow may encounter (*Main findings→Identification of limitations for upgrading* section). The power plant owner considers that it not necessary to implement any changes to the UST, as overtopping could encounter only during a very unlikely operation and with limited consequences, thus from an investment point of view, the reconstruction would be economically unfeasible. For this consideration, only the reconstruction of the DST is further investigated, with the results presented in the *Main findings→Identification of limitations for upgrading* section.

3.1.4 Instability analysis

The final part of this thesis work consists of more general research on the design of tunnel systems with multiple brook intakes. This part comes from the desire to study mass oscillation stability for power plants with brook intakes and at the same time provide general results applicable and useful for a wider range of power plants, thus having a more generic case, not a prototype in focus. To narrow the scope, only surge shafts along the headrace tunnel are be considered, with no surge shafts along the tailrace tunnel. The already existing tunnel design from Roskrepp HPP is maintained as presented in *Chapter 2.5*, but to provide the required generalization, the BI and UST are designed as simple vertical surge shafts. Three different cross section of the surge tank are important to be studied when mass oscillations instabilities are the focus: the reference Thoma cross section, and one larger and one smaller cross section than the reference Thoma cross section. Thus, the selected cross section are 0.5 A_{th}, 1 A_{th}, and 1.5 A_{th}.

Initially, the hydraulic scale model is planned to be used for this work. Geometry modifications are designed by the author and implemented with support from the technical personnel, and a governor power feedback software is developed. It is important to mention that the discharge measurement from the flow meter could not be used in the governing software due to its averaging feature. Because of the averaging, a delay of the measurement would encounter, and without the averaging the measurement are not accurate enough. Thus, the characteristic curves for the globe valve (turbine) are measured and used in the power feedback software. However, when doing experiments with this setup, the instabilities are not triggered as intended, despite numerous trials and troubleshooting. Several variants of the governor software, and several modifications to the modelled surge tanks are done without success. For some of the variants, instabilities are observed, but these are too violent and deemed not physically accurate compared with the expected prototype behavior.

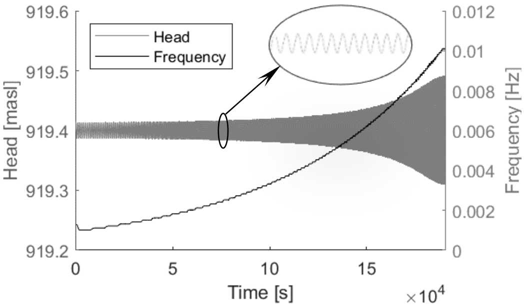


Figure 15. Head variation at turbine inlet at various guide vane oscillations frequency

A frequency-response analysis is considered to determine the cause of failure, but this is not possible due to equipment limitations, i.e., the closing and opening time of the globe valve cannot be controlled. Finally, the attempt to do physical experiments of the mass oscillations stability is abandoned. The main challenges are the accuracy of the globe valve control (signal out for operation and feedback signal for position measurement), and delay in globe valve response. For such experiments, the delay has to be very low, since the time scaling factor results in even minor delay in the model scale significant in the prototype scale. For these reasons, as well as because a numerical model would be more versatile, a numerical model with the same parameters as the presented physical model is developed (meta-model). The hydraulics of the numerical model is validated using the hydraulic scale model, as modified and new parameters are implemented on the original Roskrepp model, as presented in *Paper 3*. By using a numerical model for the investigations of mass oscillations stability, the possibility to implement a frequency-response analysis opens. From the several considered excitation-response parameters, which are presented in detail in *Paper 3*, *hq/y* is selected for two considerations: (1) the influence of the PID is disregarded; (2) the head discharge *hq* parameter is proportional to power *p*, thus equivalent to a power feedback response. Another consideration for implementing the frequency response analysis in a numerical model is that the excitation sinusoid can be implemented more accurately than it would be possible in a hydraulic scale model.

3.2 Summary of main findings

3.2.1 Paper 1

The paper presents a technical review of existing pumped storage plants in Norway. The review includes the historic development, power plant main parameters, tunnel system drawings, electromechanical installation, technical particularities, economic review such as construction costs, specific costs per kW, and stored kWh, and lastly information about operational experience with focus on the design of the tunnel system layout.

There are three characteristics of tunnels in Norwegian PSPs which are discussed in the review: unlined tunnel system, rock traps inside the tunnel located commonly near the penstock and draft tube, large number of brook intakes both along the headrace and the tailrace tunnel. From the discussion, it is shown that the topography and geology of the region are the main factors for these particularities. The good rock quality of the Scandinavian mountain-range results in low need for tunnel lining, usually reduced to only short sections along weakness zones. There are in general, with some exceptions, quite low sand sediments coming from the rivers, but rock falls can encounter inside the tunnel, leading to risk of rocks being transported to the turbine and damaging the turbine. As a result, rock traps are necessary inside the tunnels. In the case of the presented PSPs, some of them have a rock trap both along the headrace and the tailrace tunnels, while others have a rock trap only in the headrace tunnel.

Some design particularities that are regarded as specifically valuable are highlighted in this paragraph. Some of these particularities are innovative solutions for various challenges that engineers encountered in the past. One example is from Duge pumped storage plant, where the high variation of the water level in the upstream reservoir makes it difficult to provide a stable head for the RPT during pump operation. In Figure 16 can be seen the solution for this problem, where two taps are included in the design, the lower tap being used for turbine mode during lower water level, while during pumping mode, the upper tap is used as outlet in all cases, this way resulting in a stable pressure head. This solution can also be implemented in projects were upgrading of the current system to a pumped storage plant would be limited by the high variation of water level in the upstream reservoir. Jukla PSP provides another example of a particularity which can be useful for the upgrade. In Jukla PSP a closed surge tank is used for mitigating water hammer and at the same time ensuring mass oscillations stability. This can be a good alternative for HPPs where the upgrade would be limited due to spatial limitations.

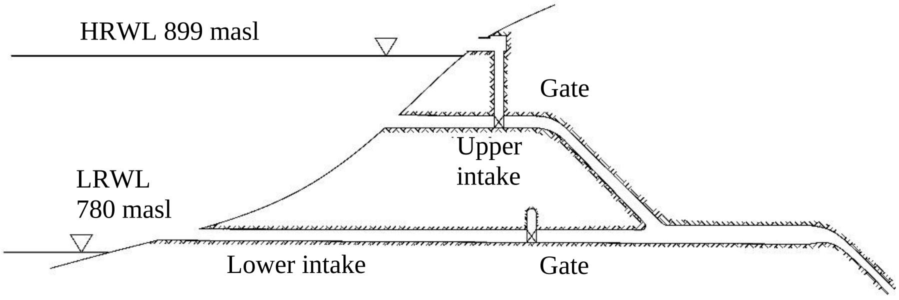


Figure 16. Intake from upstream reservoir in Duge pumped storage plant

From the operational experience of the hydropower plant operators, the tunnel systems in PSPs are more susceptible to rockfall and collapse. This is possibly because of more adverse hydraulic transients. An upgrade might encounter problems from this point of view; thus, it is important that the feasibility studies include the necessary geological investigation. This is a known topic within the HydroCen research center, and it is currently under investigation through a PhD project. The operation experience in PSPs in valuable knowledge for advancements in developing solutions for allowing the upgrade of HPP to PSP, as no previous engineering experience with such upgrades exists. More details and other particularities are presented in *Paper 1*.

From the economical point of view, the specific cost per stored kWh as the total cost divided by the storage capacity of the upper reservoir (Figure 17) is overall lower comparing to known numbers from PSPs in other countries. The cost can be reduced for construction of new PSPs by utilizing already existing reservoirs, and moreover, using existing the tunnel system would result in having costs only with the pump unit or reversible pump turbine unit, expansion of the powerhouse, and some civil works to diminish the effect of possible main challenges, as shown by Peran (2019).

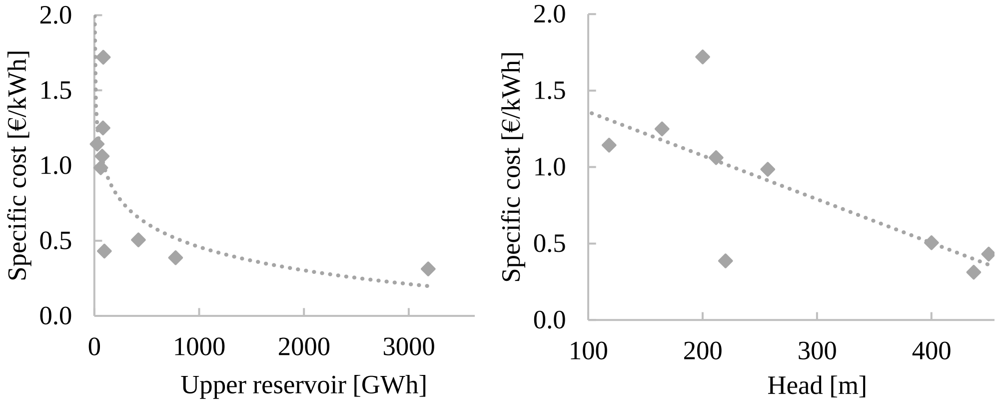


Figure 17. Specific cost per stored kWh for the pumped storage plants in Norway

The paper provides information about pumped storage plants tunnel system design, particularities, as well as information about operational experience and solutions, that are valuable for the other work presented in this thesis. The information provides a knowledge base for design challenges which are already faced, as well as engineering solutions for them.

3.2.2 Paper 2

The second paper verifies the hydraulic scale modelling technique for complex hydropower tunnel systems and introduces a novel method for design and tuning of such models. The paper answers the second objective through designing, constructing, and comparing results of a hydraulic scale model with field measurements from a complex hydropower tunnel system. The paper includes a description of the design phase, encountered challenges, troubleshooting, and validation. Figure 1 presents the prototype of the hydraulic scale model. The paper presents the step-by-step development process of the model; thus, it is regarded as valuable for researchers with the field to avoid dealing with the same challenges. The hydraulic scale model is validated with an accuracy of over 94% for both period and amplitude modeling.

Challenges of developing a hydraulic scale model for analysis of transients include the number of surge tanks, throttles, head loss, as well as limited data and information about the prototype. There are two major challenges for the design of hydraulic scale models for complex hydropower tunnel systems. The first challenge is determining the head loss distribution for different segments of the model and the prototype when limited field measurements are available. Typically, field measurements in hydropower plants include the power output, the pressure at the turbine inlet and outlet, and the water levels in the upper and lower reservoirs. The field measurements do not reveal the exact head loss occurring on different segments and at different locations in the system. The hydraulic scale model has an 82% accuracy in terms of mass oscillations damping.

Despite the low accuracy, this miss is on the conservative side, thus it is considered acceptable.

In addition, when a tunnel system has more than one surge tank along the headrace or the tailrace tunnel, the oscillations are composed of a single oscillation which occur in between any two free water surfaces. In the present case study, this translates to three oscillations, along the headrace tunnel, superposing each other (UST to reservoir, BI to reservoir, UST to BI) and forming a complex oscillation measured at the turbine inlet. The final oscillation can be decomposed, and each resulting sinusoid can be associated with the location it originated from. This way, the total head loss that influences the behavior of each sinusoid can be determined and further used for identifying the head loss associated with the tunnel stretches of interest. In *Paper 2* from the Appendix are presented the details of the method for how to determine the head loss factors h_{s1}, h_{s2}, h_{s3}, h_{s4} (Figure 18) using just the water level in the upper reservoir and the pressure variation at turbine inlet. The method can be extended for an infinite number of surge tanks.

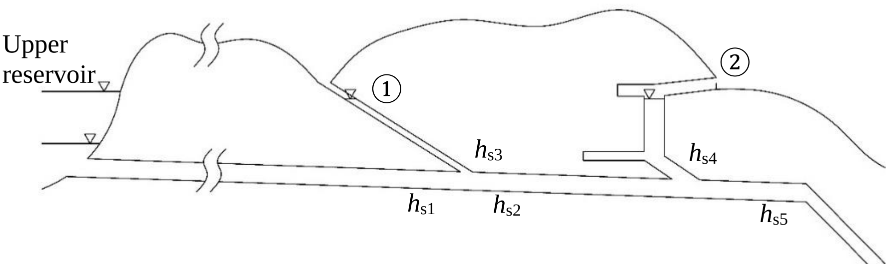


Figure 18. Minor head loss parameters distribution on relevant tunnel stretches

The second challenge is the availability of information regarding the tunnel system design from old existing hydropower plants. This challenge may not be relevant for newly developed hydropower plants with modern as-built documentation. For old HPPs, most power plant owners may only have construction drawings, and in the case of HPPs and PSPs with unlined tunnels, due to the construction methods, differences can encounter between the design and the actual construction. In the case-study, for shaft ① from Figure 1, two parameters present significant differences: the slope of the shaft (1/8.4 construction drawings, 1/8.7 as-built) and the horizontal cross section of the shaft (8 m^2 construction drawings, 12 m^2 as-built). This leads to a 50% inaccuracy from the calculated water table of the BI to the actual one. Such differences in cross section are common in unlined tunnels, due to contractual agreements between the project owner and the contractor, which are usually based on a minimum guaranteed cross section. The result of these differences is that the water table area on site is twice the one calculated based on construction drawings, which has a significant influence on the amplitude and the period of the mass oscillations in the shaft.

If the two challenges are not properly assessed or are not possible to be properly assessed because of lack of data, significant errors can encounter during model tuning. This can lead to errors in the tuning of a model, which may appear to be correct just by looking at the results. As observed in Figure 19a, the numerical model seems to be correctly tuned when it is compared to the prototype, but when the same parameters are applied in a physical model, it can be observed that the tuning is in fact incorrect.

To overcome such problems, a new method is developed. The method is presented in detail in *Paper 2* from Appendix A. The method provides a correct tuning, as observed in Figure 19b. The hydraulic scale model tunned and validated is further used to determine possible main challenges that can encounter when upgrading the study case hydropower power plant to a pumped storage plant (Objective 3).

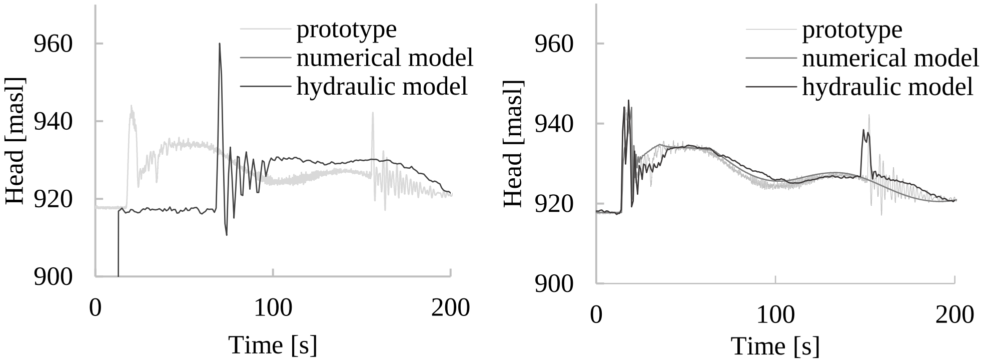


Figure 19. Comparison between head at turbine inlet showing possibility of erroneous tunning and tunning using the method defined in the work

3.2.3 Identification of limitations for upgrading

Based on the experience and results from the numerical and hydraulic scale models presented in *Paper 1* and *Paper 2*, several potential limitations in the tunnel system are identified. The conducted experiments demonstrate the water level variation in all the four shafts during limit operations at both highest and lowest water level in the reservoirs. For two secondary shafts, namely the brook intake and the adit tunnel, the water level does not rise above or decrease below the limits of the current design. For the upstream surge tank, the water level does not decrease below the limit in any case. However, as seen in Figure 20, the water level raises above the overflow weir limit in only one case, specifically, during sudden change from turbining to pumping. This is considered an unnecessary operation by the hydropower operator and very unlikely to happen accidentally. Thus, the recommendation is that it is more beneficial to impose operational limitations regarding this change, instead of reconstructing the upper chamber of the headrace surge tank.

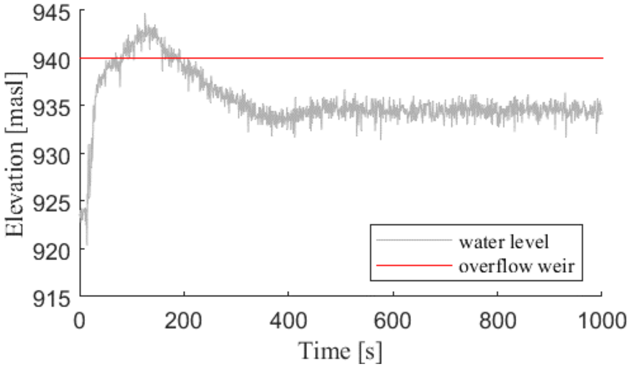


Figure 20. Water level variation in upstream surge tank during sudden change from turbining to pumping

In terms of mass oscillations amplitudes, the only main challenge identified in the system is the downstream surge tank. In this case, the lowest downsurge goes below the lower surge tank limit, resulting in air entrainment in the tailrace tunnel and draft tube for three load cases: pump startup, pump startup failure with emergency shutdown, and pump startup failure with blocked guide vanes, as seen in Figure 21. To mitigate these problems, two different reconstruction alternatives are developed for the downstream surge tank. The first alternative is building an expansion chamber at the bottom of the surge tank. This alternative is evaluated using an analytical model and the hydraulic scale model. The second alternative is building a riser inside the existing surge tank to create a differential surge tank. This alternative is not implemented in the physical model, but tested in the analytical model, showing promising results. The cross-section area of the riser (A_r) is 10 m^2, included inside the existing surge tank, thus the cross-section area of the surge tank A_{st} is reduced from 110 to 100 m^2. The overflow weir of the riser is located at 845 masl, 5 m above the overflow weir of the existing surge tank. The throttle head loss of the riser (k_0) is 2 (-), both for upsurge and downsurge, and the throttle parameters for the surge tank are 60 and 80 (-) for the upsurge and downsurge, respectively. The surge in the riser and the surge tank are calculated as follow:

$$\frac{dh_r}{dt} = \left(Q_T - Q_t \pm Q_0\sqrt{\frac{h_{st} - h_r}{k_0}} - Q_{over}\right)\frac{1}{A_r} \qquad [5]$$

$$\frac{dh_{st}}{dt} = \left(Q_{over} \pm Q_0\sqrt{\frac{h_{st} - h_r}{k_0}}\right)\frac{1}{A_{st}} \qquad [6]$$

$$\frac{dQ}{dt} = -\frac{gA}{L}(h_r + fv^2) \qquad [7]$$

Where h_r is the height of water level in the riser above the reservoir, h_{st} is the height of the water level in the outer tank above the reservoir, Q_T is the flow through the tunnel, Q_t is the turbine discharge, Q_0 is the turbine design discharge, k_0 is the head loss parameter of the throttle at Q_0, Q_{over} is the overflow rate from riser, A_r is the cross section are of the riser, A_{st} is the cross section area of the outer tank, A is the tunnel cross section, L is the tunnel length between the surge tank and the closest free water surface, and fv^2 is the aggregated friction loss and velocity head in the tunnel. The results in Figure 21 show that the implemented modifications are successful.

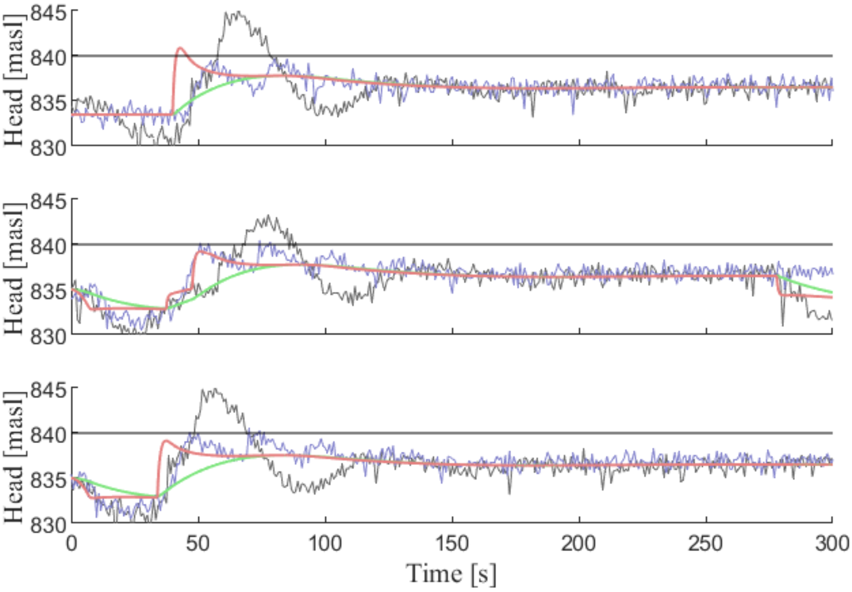


Figure 21. Water level variation in downstream surge tank during pump startup, pump startup failure with emergency shutdown, and pump startup failure with blocked guide vanes. The black horizontal line indicates the overflow weir of the surge tank. (original DST design (black), surge tank with expansion chambers (blue), differential surge tank (red-riser, green, surge tank))

The overflow weir level is also exceeded by the highest upsurge for the pump trip with blocked guide vanes, pump startup failure with emergency shutdown, and pump startup failure with blocked guide vanes operations, as shown in Figure 22. The two solutions presented to mitigate the downsurge are therefore modified to also account for the overflow as follows: in the surge tank with lower expansion chamber, an upper expansion chamber is implemented, large enough to collect the amount of water which would otherwise overflow, resulting in a two-chamber surge tank; the overflow weir of the riser in the differential surge tank is raised. The two solutions can be seen in Figure 23.

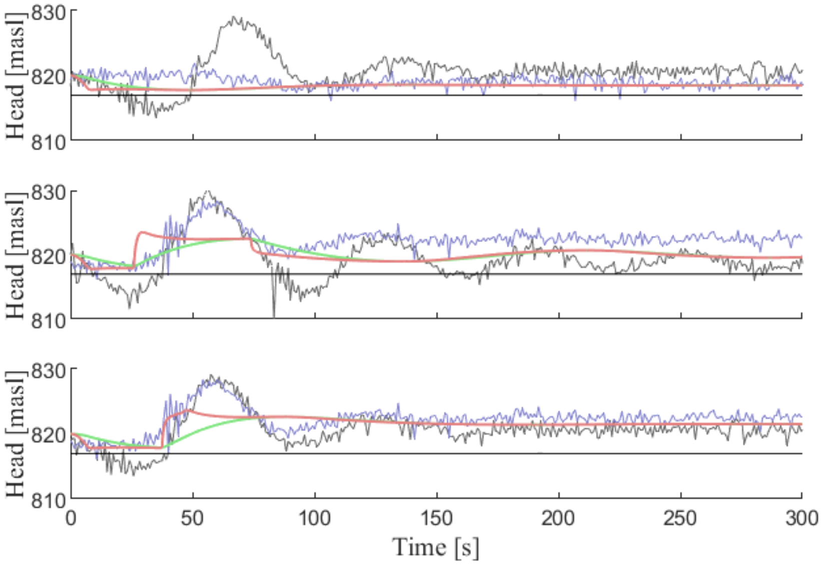


Figure 22. Water level variation in downstream surge tank during the pump trip with blocked guide vanes, pump startup failure with emergency shutdown, and pump startup failure with blocked guide vanes. The black horizontal line indicates the bottom of the surge tank. (original DST design (black), surge tank with expansion chambers (blue), differential surge tank (red-riser, green, surge tank))

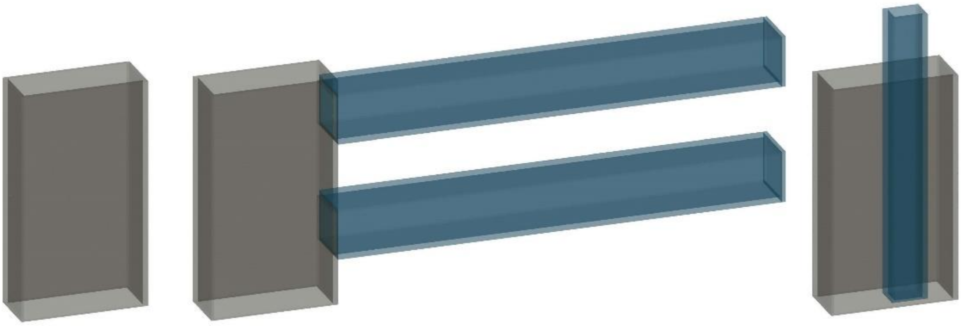


Figure 23. Downstream surge tank alternatives (from left to right: original design, design with two expansion chambers solution, design with riser solution – differential surge tank)

3.2.4 Paper 3

The paper presents the effect of the number of brook intakes in a tunnel system, the brook intake inflow, the surge tank throttles, and the brook intake throttles on mass oscillations stability. The frequency-response method is applied with a small amplitude oscillation to quantify the stability of the system when varying different design parameters for the surge tank and brook intakes. Simplifications are done in the existing hydraulic scale model, to make the results more general. The brook intake and the headrace surge tank are modelled as simple vertical surge shafts, with varying diameter: 0.5 A_{Th}, 1 A_{Th}, 1.5 A_{Th} where A_{Th} is the reference Thoma cross section area as defined in *Paper 3*. The modified hydraulic scale model is used for tuning of a 1D numerical model. In the implemented frequency response method, the guide vane position α is the excitation and the head-discharge HQ is the response (Figure 24). The choice of performing the study using numerical model, instead of the hydraulic scale model, is due to the simplicity of implementing the α excitation sinusoid, resulting in a more accurate frequency response method.

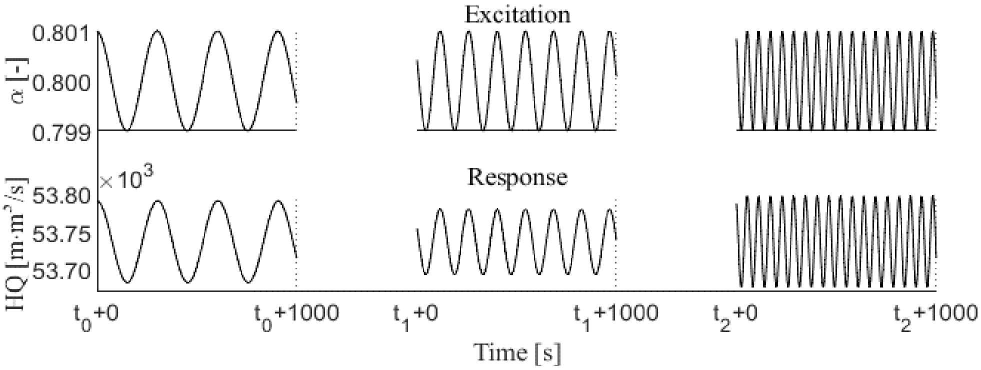


Figure 24. Excitation and response oscillations during tunnel system stability simulations

There are several methods which are possible to be implemented using frequency response analysis, two of them being *hq/y* and *h/y*. The former method shows if the surge tank is stable. The former method is challenging to be implemented in a real HPPs due to limitations of sensors for large and transient flow volumes. The latter method can be implemented in real HPPs. The downside of this method is that it does not quantify exactly if a system is stable or not, but rather it can provide a comparison between the stability of two or more systems.

When reading Figure 25 and Figure 26, the legend needs to be used combined with information in the figure title, as such: for each line from the graph, a color and a line style is associated and read from the legends, in order to get full information about the presented case. For example, for the red dot-line, the corresponding case is a tunnel system without brook intake, but only surge tank (red line), and a 0.5 ζ throttle parameter (dot line). The peaks observed in the graphs at different frequencies correspond to the surge shafts frequencies from the system.

From the various studied configurations, having A_{st}, ζ, Q_{BI} variables in both surge shafts, it is observed that the 1 A_{Th} yields a system at limit stability for a single surge shaft case, as expected and known from available literature (Figure 25). By including a second surge shaft, the system becomes stable. For small amplitudes, in the two surge shafts case, the mass oscillations stability is not significantly influenced by the size of the throttle, the response being the same for all verified throttle sizes. If in addition, there is inflow in surge tank, then the stability of the system varies again with the throttle diameter. More figures and detailed analysis of the studied cases are presented in the paper.

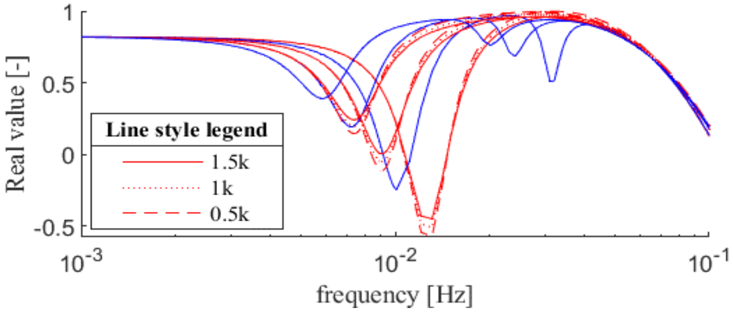


Figure 25. Influence of throttle size and number of brook intakes on the mass oscillations stability (red: single surge tank, blue: multiple surge tanks)

The system behavior when the discharge is increased is shown in Figure 26, indicating that the stability does not vary much. This is a benefit for upgrading of existing hydropower plants, as increasing the installed capacity has low influence the stability in existing hydropower plants. Systems with secondary surge shafts have an extra margin on stability that may allow for increased installed capacity. The detailed study is presented in *Paper 3*, from Appendix A.

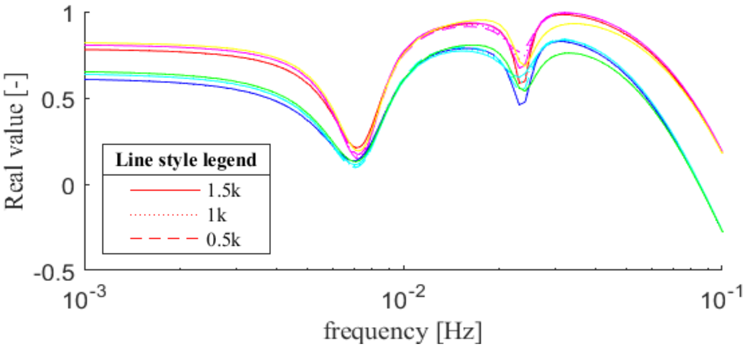


Figure 26. Influence of increased turbine discharge (red: Q_t regular, $Q_{BI1}=0$ m^3/s, $Q_{BI2}=0$ m^3/s, pink: Q_t regular, $Q_{BI1}=10$ m^3/s, $Q_{BI2}=0$ m^3/s, yellow: Q_t regular, $Q_{BI1}=0$ m^3/s, $Q_{BI2}=10$ m^3/s, blue: Q_t increased, $Q_{BI1}=0$ m^3/s, $Q_{BI2}=0$ m^3/s, cyan: $Q_{BI1}=10$ m^3/s, $Q_{BI2}=0$ m^3/s, green: $Q_{BI1}=0$ m^3/s, $Q_{BI2}=10$ m^3/s)

These results prove that when designing hydropower tunnel systems with multiple surge shafts, the surge tanks need to be designed considering the highest possible inflow in brook intakes, as the inflow can have destabilizing effects. When choosing throttle size for the main surge tank, as well as for any secondary surge tanks (brook intakes), it is shown that throttles have opposite effects on the stability if they are in the main surge tank versus the secondary surge shaft.

3.2.5 Summary of results

A summary of the most significant results presented in the papers are presented below:

- A technological review of the existing pumped storage plants in Norway including the main data, operational experience, and longitudinal section drawings. All the ten Norwegian pumped storage plants, with 5 TWh energy storage capacity, are constructed as open loops and are designed for pumping water to the upper reservoirs during flood season, thus the energy production is significantly higher than energy consumption. For this reason, the need for rapid start-stop operations is not accounted for during design, resulting in long pump startup time. This is changing as start-stop operations become more attractive, more and more pumped storage plants will have the pump startup systems upgraded, commonly including a frequency converter. The round-trip efficiency of the pumped storage plants varies between 65 and 80%. The tunnel systems represent on average half or more of the total energy loss. In pumped storage plants it is, in general, more likely to have tunnel collapses, comparing to hydropower plants. This occurs possibly due to the more adverse hydraulic transients. Considering the most common characteristics of interest for the study, Roskrepp HPP is a good candidate for further investigation, having multiple shafts, both along the headrace and the tailrace tunnels.
- For Roskrepp tunnel system, up to 50% inaccuracy is found in terms of design vs. actual dimensions from the 3D scan of the headrace tunnel and the downstream surge tank. The tuning of both numerical models and hydraulic scale models is challenging without accurate the tunnel system dimensions, especially for the older unlined tunnels, where as-built drawings are not available.
- A method for tuning of head loss parameters in models of tunnel systems with multiple shafts is designed. The method requires a minimum amount of data which can be collected from the prototype in a facile manner. The final hydraulic scale model is validated with an accuracy of 94%, 99%, and 82% for the amplitude, period, and damping of mass oscillations respectively. The low accuracy in damping is expected and common in hydraulic scale modelling, but as the damping in the hydraulic scale model is slower than in the prototype, thus considered acceptable.
- From the hydraulic scale model results, limitations in terms of downstream surge tank size are observed for six operations possible to encounter in the prototype. Two mitigating alternatives are designed and verified, reconstructing the surge tank to a two-chamber surge tank, or to a differential surge tank. The results

show that both alternatives are technically feasible, thus an economic feasibility is necessary to choose the best alternative.

- To provide valuable data for general cases, and not for a specific prototype, a generalized numerical model is used for analysis of mass oscillations stability. It can be noted that the simulations show that secondary surge shafts have a stabilizing effect, but inflow in the secondary surge shafts have the opposite effect. When the main surge tank has a throttle, the mass oscillations are more stable then when secondary surge shaft are throttled. Overall, secondary surge shafts result in a more stable system.

3.3 Contributions

Contribution 1: A technical review of currently existing Norwegian PSPs

The operational experience from already existing pumped storage plants provides valuable information for researchers and engineers to develop future upgrading projects. The review helps to point out possible technological bottlenecks that need to be addressed. In addition, the information about the design particularities shows possible solutions that can help future projects. The review can help to avoid making the same mistakes again, and to make use of good already implemented and tested solutions.

The study reveals that most of the Norwegian pumped storage plants are constructed for seasonal storage. None of the ten presented pumped storage plants are designed for system service or daily peaking purposes, but rather for pumping during flood season to serve as supply during high demand periods. The advantage of Norwegian PSPs is the large upper reservoirs which can provide large storage capacity. One reason for this is the topography, with plateaus on top of the mountains, leading to higher storage capacity in the upper reservoirs. The lower reservoirs have a sufficiently large storage capacity to provide daily and weekly pumping. The current installed capacity in PSPs is regarded as low compared to the reservoir volumes, thus there is potential for expansion.

It can be noticed a long startup time for pump operation in most presented pumped storage plants, as they are originally designed for pumping water to the upper reservoir during pumping season. There are several ongoing projects to improve the startup time in order to shift towards more frequent start-stop operations, such as replacing the startup system and including a frequency converter, as it is already implemented in Aurland III PSP. In general, there are several different electromechanical solutions, with a current trend to upgrade to more flexible solutions. In addition, the specific costs are regarded as very low when comparing to the numbers published for other PSPs in the literature. More detailed information about the contribution of this study can be read in *Paper 1*.

Contribution 2: A new method for determining the distribution of head loss factors in hydropower tunnel systems with multiple surge shafts

A common method for model tuning, both numerical and physical, is to use field measurements for obtaining a correct system behavior. This can be a challenging task, especially when limited data are available about the prototype design and from field measurements. For systems with multiple surge tanks, the mass oscillations superpose, forming final oscillations from which it can be difficult to identify the underlying sinusoids. It may even not be possible by using just a numerical model or just a physical model, as shown in *Paper 2*. However, when combining the two, it is possible to overcome this issue.

Systems with multiple surge tanks are found in this work to be especially sensitive to head loss factors. The head loss factors (singular and friction) between the different surge tanks decide which direction the water flows and will result in inaccurate modelling if they are not correctly implemented models (numerical or physical). Therefore, a significant work effort to map the head loss factors for each relevant tunnel segment is undertaken.

The new method developed in this study, presented in detail in *Paper 2* is used for tuning of numerical and physical models of complex hydraulic systems in hydropower plants. This method is developed out of need due to several co-dependent variables, such as singular loss and head loss in different regions of the tunnel system. The method is a stepwise tuning performed by dividing the complex system into simple systems with a single surge tank. In this way, the number of head loss parameters that influence the mass oscillations is decreased, and the oscillation is reduced to a single sinusoid. For each surge tank, an equation is determined for the head loss factors. In the end, all determined equations form a simple mathematical system that can be solved, and the correct head loss parameter can be associated with every tunnel stretch of interest.

Other crucial information needed for modeling of complex hydropower tunnel systems is the accurate design of the tunnel system. This has proved to be challenging, especially for older hydropower plants. The study presents a brief comparison between construction drawings and a 3D scan of the tunnel, which shows discrepancies that yield significant differences between the available drawings and the actual as-built structure. This can also lead to challenges during tuning process when a model is designed using construction drawings and tunned using field measurements in the prototype. In conclusion, accurate information about the system design is required. Finally, extended field measurements are necessary, which in most cases are not possible to be obtained, thus the method presented in the paper can be used to obtain an accurate tuning with limited field measurements.

Contribution 3: Identification of the main limitations for upgrading HPP to PSP and provided solution alternatives

The selected prototype is chosen since it has several of the component which may give limitations for upgrading of HPP to PSP: long tunnel system with surge shafts along both headrace and tailrace, tailrace surge tank together with draft tube gate, brook intake, and large reservoir water level variations. For this reason, the presented work may be useful for a large number of upgrading projects. The focus of this work is on limitations concerning hydraulic transients.

Limitations due to size are identified in both the upstream and downstream surge tanks of the case-study. However, by enforcing operational restrictions on start-stop operations, only the tailrace surge tank needs structural modifications. When the downstream surge tank is connected to the access tunnel leading to the powerhouse, such as is typical in Norway, the consequences of overtopping are severe and must be avoided. At the same time, this design makes it challenging to heighten the overflow weir due to space confinement. As a result, a more complex solution becomes necessary. Two alternatives for mitigating the limitations of the DST are developed and presented.

The brook intakes and construction adits are not found to give any limitations for an upgrade from a mass oscillations point of view. Multiple surge shafts or brook intakes are even seen to be beneficial with regard to mass oscillations. The mass oscillations become more stable when secondary surge tanks exist in a system and may provide an over-capacity that can allow for upgrades (*Paper 3*). However, the inflow in the brook intakes has destabilizing effect and must be accounted for. In most cases, brook intake inflow is not measured directly, but this should be considered in order to verify the design conditions for an upgrade.

Imposing operational restrictions after upgrading could be a last resort when the existing civil works, the size of existing surge tanks are restrictive, or when the necessary modifications are technically difficult or economically unfeasible to implement. This is the case for the upper surge tank in Roskrepp HPP, where a limitation on how fast it is allowed to change between turbining mode and pumping mode is sufficient to avoid a physical reconstruction.

Based on the work presented in this PhD thesis it is concluded that upgrading HPPs to PSPs is possible. Much of the existing infrastructure can be reused without any modifications. In the case of Roskrepp HPP only the tailrace surge tank needs physical reconstruction, while the rest of the tunnel system can be reused directly.

Contribution 4: Mass oscillations stability for tunnel systems with brook intakes

The final contribution of this work is to expand the general knowledge of mass oscillations stability in hydropower tunnel systems with brook intakes, as well as to assess the potential to utilize the stabilizing effect of brook intakes for upgrading of existing HPPs to PSPs. The effects of brook intakes design, inflow, and throttle on the stability of mass oscillations are quantified. Some of the design parameters are proven to have a positive effect, and some are found to have a negative effect, on the stability. This knowledge is useful for future upgrading of HPPs with brook intakes to PSPs.

A novel approach to the frequency-response method is used in this study. The guide vane position is used as excitation and the product of head and discharge is used as the measured response. By using *hq/y*, the stability of the surge tank is directly assessed, since *hq* is, in practice, the hydraulic power acting on the turbine. The more common approach is to use just *h/y*, but then the limit stability cannot be quantified directly, and can just be used to determine if a configuration is relatively more or less stable than another. For both approaches, the major benefit is that the results are independent of the PID governor setting. This is useful since a poorly tuned PID governor may trigger instability even if the system is stable from a hydraulic point of view. The case of poorly tunnel PID is likely to encounter in real HPPs and it is normally only noticed when investigations for an upgrade are done. The frequency-response method can analyze the hydraulic stability isolated.

For old hydropower plants, the effect of the brook intake on the mass oscillations stability may not be accounted for during the original design. This is the case for the case-study Roskrepp HPP. Since a brook intake with or without a throttle leads to a more stable system, the existing surge tank might be oversized. This is beneficial, as an oversized HPP surge tank may allow for upgrading the HPP to a PSP without reconstruction.

4 Discussion

The main objective of the work is to investigate the potential for upgrading existing hydropower plants to pumped storage plants. The investigation is presented in this PhD thesis through four research objectives, and the answer and findings related to each objective is discussed in the following.

Objective 1: Review of existing Norwegian pumped hydro

This objective is answered in *Paper 1*. The overview of existing designs for pumped storage plants tunnel systems provides a detailed insight in the Norwegian expertise on hydropower tunneling, design challenges, and operational experience of existing PSPs. The study presents the storage capacity in Norwegian PSP reservoirs, showing that there is high potential for seasonal storage in PSPs, as well as for daily and weekly storage. This is beneficial to implement in a period when the interconnected energy system between neighboring countries is under expansion. The two new subsea cables NordLink and North Sea Link linking Norway with Germany and United Kingdom, respectively, show that the Norwegian hydropower system can be a good support for countries undergoing transitions towards a more renewable system. This paper provides a valuable knowledge base for future design of PSPs in Norway and abroad.

Limitations in the answer to Objective 1 are mainly related to availability of data. Even though detailed information is provided from the power plant owners and operators, the study incorporates only ten pumped storage plants, all of which have a high-head tunnel system design from Norway. Thus, the study could be improved by including pumped storage plants with low head design or PSPs from other countries. In addition, none of the ten studied PSPs is designed for auxiliary services, thus the information about tunnel system design is limited to knowledge about pumped storage plants designed for seasonal pumping.

The research objective is considered answered, as an overview of all the Norwegian PSPs is presented and valuable information is gathered and made available for the research and engineering community. Some of the presented materials were previously confidential and unavailable to the public.

Objective 2: Verification of hydraulic modelling for upgrading of HPPs to PSPs

This objective is answered in *Paper 2*. A hydraulic scale model is designed, constructed and the results are compared with field measurements from the prototype. The results are regarded as within reasonable accuracy, and it is concluded that hydraulic scale modelling can be used for future projects. The main inaccuracy of the hydraulic scale model is that the damping of mass oscillations is faster in model than in the prototype.

However, this challenge is on the conservative side of tunnel design and is considered acceptable.

Through the present work, a specific challenge with hydraulic scale modelling of complex hydropower tunnel systems is identified. In the case of multiple shafts, it is important to have the correct proportional distribution of total head loss between the relevant tunnel stretches. A method is developed to tune the correct head loss factors. The method can have applications both in numerical and hydraulic modelling of hydraulic tunnel systems with multiple surge shafts. Moreover, the method is independent of flow direction, thus it can be used both for headrace and for tailrace tunnels, as well as both for pumped storage plants and for hydropower plants.

It is also found that the combination of a hydraulic scale model and a numerical model is far more reliable than using solely a numerical or a physical model. This especially concerns cases with limited prototype data and limited field measurements. In *Paper 2* it is show that a numerical model is tuned and demonstrates accurate results when compared with the prototype, but it is later found to have severe errors that are discovered once the combination of hydraulic scale modelling and numerical modelling is implemented. This demonstrates the usefulness and need for combined modelling for mutual verification and quality assurance.

The work on this research objective demonstrates the need for accurate information about the prototype dimensions. For newer hydropower plants, detailed as-built construction drawings may be available. For older hydropower plants though, the available documentation may be limited to construction drawings that are updated to as-built dimensions. In such cases, the necessary information can still be obtained by accurate measurements during a dewatering process, or by using an underwater mobile scanning system. Even though a 3D scan might be considered expensive or difficult to obtain due to the possible need for dewatering of the tunnel system, this can be beneficial for multiple applications. The 3D scan done in this study provides some surprising results, especially regarding the water table area in the brook intake, which is found to me double than what it could be calculated based on the design drawings available before the scan. The 3D scan can be used within all areas of hydropower research, not only for mass oscillations, but also for research regarding sediment transport, fluid dynamics, or more specific research such as research on plugs or intakes. Another application for a 3D scan is the detailed research on friction loss, a topic studied within the Tunnel Roughness project (Aberle, et al., 2020). Engineering applications can also benefit from a detailed design of the tunnel system. By having detailed information about the tunnel design, bottlenecks as well as upgrade possibilities can be analyzed in detail.

The main limitation of the work to answer this research objective is the fact that it is only tested on one prototype. Even though the hydraulic scale model provided good results, it would be beneficial to have further testing on other hydropower plants. However, the research objective is considered answered, as hydraulic scale modelling for upgrading of HPPs with complex tunnel systems is verified and proven to be reasonably accurate.

Objective 3: Identify main challenges and solutions for upgrade

The third research objective is answered by investigating limitation to upgrading in terms of the tunnel system. Several potential limitations are identified (surge tank, brook intakes, construction adits). However, for the case-study, limitations that require structural modifications are only found in the downstream surge tank. Two reconstruction solutions are proposed. These solutions can also be applied for surge tanks which present limitations also in the case of regular upgrade of the installed capacity, not only for upgrade to pumped storage. The fact that only one of the surge tanks required a structural modification to allow upgrade of a HPP to PSP proves that there is a large potential for such upgrading.

An uncertainty in the answer to the objective comes from the fact that the limitations are identified only using the hydraulic scale model. Even though the model is tuned and validated, it could be beneficial to have more investigations of the downstream surge tank, eventually using a 3D model of the surge tank. There are also uncertainties of the second proposed reconstruction solution, the differential surge tank, as it is checked only using an analytical model. Further verifications should be done either using a hydraulic scale model, or a numerical model to obtain a full validation of the solution.

The research objective is considered to be partially answered. The limitations concerning mass oscillations and surge tank are identified, and solution to allow upgrading from HPP to PSP are proposed. The major limitation of the answer to this research objects is that it is limited to mass oscillations and surge tanks. It is stressed that other potential limitations in the tunnel system also have to be controlled for, such as sand traps, concrete plugs, intakes, and gates. More research is necessary to continue the mapping and evaluation of such other limitations.

Objective 4: Investigate mass oscillations stability for systems with brook intakes

This objective is answered in *Paper 3*. A generalized hydropower system is investigated with analytical modelling, which in turn is validated with a hydraulic scale model test. A novel method is utilized to assess the mass oscillations stability for various brook intake design parameters, inflow, and throttling. The work on this research objective can have application for any hydropower plant with brook intakes, whether it is subject to capacity upgrade or upgrade to pumped storage.

One finding from the work is that most brook intakes have unregulated and unmonitored inflow. This provides a challenge when upgrading such system, since the stability is dependent on the inflow and in particular the maximum possible inflow (the design inflow). Work to identify the design inflow of brook intakes is necessary when considering an upgrade of HPPs to PSPs.

An uncertainty of the answer to the research objective is the use of a numerical model validated against a hydraulic scale model instead of field measurements from a prototype. However, this is chosen in order to be able to study a more generalized system and is regarded as a good tradeoff to provide results relevant for a larger number of applications.

The research objective is considered to be partially answered. The effect on the stability of mass oscillations from the main design parameters of brook intakes, including inflow and throttling is quantified. A limitation to the work is that only turbine mode is investigated. It is recommended that further investigations of mass oscillations stability are done to include verifications for pumping mode as well.

5 Conclusions

Based on the results presented in this work, it is concluded that it is possible to upgrade HPPs to PSPs, with regard to the tunnel system mass oscillations. For the case-study, structural reconstruction is only necessary in the tailrace surge tank. Brook intakes are found to have a positive effect on mass oscillation stability, with the implication that the main surge tank may be oversized. Based on this, upgrading of existing hydropower plants with brook intakes may be possible without reconstruction of the main surge tank.

The first research objective is achieved. A technical review of the ten existing pumped storage plants in Norway is provided. The technical design of the tunnel system and electromechanical installation is presented. The review provides description of operational experience about possible challenges that pumped storage plants may encounter.

The second research objective is achieved, as a hydraulic scale model is verified with field measurements from a prototype hydropower plant. In this case, it is concluded that hydraulic scale modelling of complex tunnel systems provides sufficient accuracy for mass oscillations modelling. The period and the first amplitude are correctly modeled, which is considered sufficient for the purpose of the work. The method is though not recommended for investigations of successive amplitudes due to the higher damping in the hydraulic scale model comparing to the prototype. In addition, a new method for head loss parameters distribution in tunnel systems with multiple surge tanks is developed and presented. It can also be concluded that reliable, detailed information about the tunnel design after construction is crucial for enabling a good tunning both for numerical and for hydraulic scale models, thus for older hydropower plants where detailed design drawings are not available, site measurements or ideally a 3D scan of the system should be done.

The third objective research is partially fulfilled. The four shafts, two along the headrace tunnel and two along the tailrace tunnel are investigated. No significant challenges are observed in three of them. In the downstream surge tank, challenges both regarding the maximum upsurge and the minimum downsurge are encountered, as expected. Two possible solutions are proposed and found hydraulically feasible, which means that upgrading of existing hydropower plants to pumped storage plants is possible with minimal reconstruction needed. Some work remains to identify potential limitations of other tunnel components, such as sand traps, intakes, and concrete plugs.

The fourth and last research objective is partially fulfilled. Investigations on mass oscillations stability on a generalized tunnel system are developed. The results are useful for any hydropower project with brook intakes. As a general conclusion, brook intakes have a positive effect on mass oscillations, and may provide the necessary capacity to allow upgrading projects. It is also important to mention that throttling of secondary brook intakes is seen as beneficial for mass oscillations stability, but throttles also result in reduced inflow, and these effects need to be accounted for in design of new power plants with brook intakes.

5.1 Suggestions for future work

Future development on the topic of upgrading hydropower plants to pumped storage plants is necessary. Several topics are regarded as potential future work:

1. Extending the state-of-the-art knowledge and information about operational experience from PSPs located in different locations around the world, especially in places with different designs and construction methods for the tunnel systems are implemented.
2. Validate hydraulic scale modelling with field measurements from additional hydropower plants.
3. Identify and evaluate other potential limitations in the tunnel system for upgrade of HPP to PSP, such as the sand trap, intake, concrete plugs, and gates.
4. Continue the abandoned attempt to model mass oscillations instability in the hydraulic scale model.
5. Investigate mass oscillations stability for systems with brook intakes for large oscillation amplitudes and in pumping operation. Verify if the mass oscillations behavior is similar both for upgrading the turbine to a RPT and for an upgrade in which a separate unit is implemented.
6. Test and verify the frequency-response method with hq/y with a hydraulic scale model and in a real power plant.
7. Study the optimum design for brook intakes functioning as surge tanks.
8. Study the possibility of reconstruction existing surge tanks to closed surge tanks to allow upgrading to PSPs.

5.2 Concluding remarks

This work investigated the possibility of upgrading hydropower plants to pumped storage plants using the existing tunnel system, with focus on mass oscillations and mass oscillations stability. Four research objectives were defined and answered, resulting in three published articles and four novel contributions. The work covered a wide topic, and further in-depth analysis of specific topics is recommended.

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Appendix A

The full versions of the selected papers presented in this thesis are included in the following. The original formatting is preserved and does not conform to the general formatting of the thesis.

Paper 1

Technical Review of Existing Norwegian Pumped Storage Plants

Livia Pitorac, Kaspar Vereide, Leif Lia

Energies 13(18):4918

energies

Review

Technical Review of Existing Norwegian Pumped Storage Plants

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Abstract: This paper presents a technical review of the existing pumped storage plants in Norway. The power system is changing towards integrating more and more renewable energy, especially from variable renewable energy sources, leading to new challenges for the security of supply, power, frequency, and voltage regulation. Thus, energy storage options are a highly researched topic in the current situation. Even though there are many energy storage technologies, most are optimal for short term grid balancing, and few are capable of providing long term (weekly or seasonal) storage. One exception is pumped storage, a mature technology capable of delivering both short term and long term energy storage. In this paper, the ten existing pumped storage plants in Norway are presented, several of which are capable of seasonal energy storage. The Norwegian knowledge and experience with pumped storage plants technology is provided as a basis for future research within the field. The review provides information about energy production and storage capabilities, construction costs, specific costs per kW and stored kWh, electromechanical installation, technical specifications, and operational experience with focus on the design of the tunnel system layout. The data presented in this review are unique and previously unpublished. A discussion and conclusions regarding the current situation, trends, and future outlook for pumped storage plants in Norway within the European power market are provided.

Keywords: hydropower; pumped storage; hydropower tunnel systems; seasonal energy storage; renewable energy

1. Introduction

Growing concerns regarding the climate change have led to a worldwide shift of focus from fossil fuels to renewable energy sources (RES) in order to reduce the environmental impacts of energy generation. In Europe, the goal of reducing greenhouse gas emissions is legislated through policy frameworks which set targets for energy consumption coming from renewable sources, starting in 1997, when the European Union (EU) set the 2010 targets. In 2018, under the "Clean energy for all Europeans" package, the EU set its 2030 targets on use of RES to at least 32% through the revised Renewable Energy Directive [1].

The main renewable energy sources constructed now are wind and solar, which are volatile and unregulated sources, where the fluctuations in energy production do not align with the fluctuations in energy demand. One way to eliminate this problem is to build many more wind and solar farms than necessary (backup power plants), in order to ensure that the energy demand is always covered. Another solution for eliminating the problem is energy storage, reducing the need for backup power plants. A very wide variety of energy storage technologies are currently available or under research, with the main ones being batteries, mechanical energy storage, hydrogen, and pumped hydro [2]. Batteries are a common solution for energy storage, having the advantage that they can be installed in any location, they have a quick energy release capability and a high round- trip efficiency varying between 70 and 95%, depending on the type of battery [3]. However, batteries can only store relatively small amounts of energy, making them a small-scale energy storage solution, suitable for power frequency and voltage regulation or hourly energy storage to help meet the peak demand. The lifetime of batteries is also limited compared with competing storage technologies. Mechanical energy storage is a technology using kinetic and gravitational energy to store energy. Compressed air energy storage (CAES) in the mechanical energy storage technology in which air is pumped in caverns or tanks during low energy demand periods. It is a mature technology, used for decades, cheap, and unlike batteries, it does not involve any use of toxic materials. The round-trip efficiency of CAES varies between 40 and 70% [4]. Disadvantages of CAES is that it requires a location with suitable geology, and moreover, the air needs to be heated during the energy generation, involving the use of fossil fuels in the diabatic method. Hydrogen energy storage is a technology in which electricity is converted into hydrogen through electrolysis, hydrogen is stored and later transformed back into electricity when the demand requires it. Despite a low round-trip efficiency of less than 50% [5], hydrogen energy storage has a high storing capacity comparing to all other energy storage technologies, being able to provide seasonal and annual energy storage, which led to an increased research interest into further developing it.

This paper focusses on the most mature and currently most applied electrical energy storage technology, pumped hydro. Pumped hydro stores energy in the form of water in a reservoir by pumping it during low demand periods and later releases it to produce energy, with the round-trip efficiency reaching above 80% depending on site-specific conditions [6]. Pumped hydro is able to provide seasonal energy storage [7,8], and is currently the world's largest energy storage technology [9]. Currently, the technology is superior in both stored energy volumes and in power capacity. Further development is being researched, and underground pumped hydro is a promising new technology that may enable construction to be independent of topography and in combination with thermal storage, drinking water storage, or desalination [10]. To compare the costs of pumped hydro with competing technologies, this paper presents a calculation of constructions costs, specific costs per power capacity, and storage capacity. Previous studies have shown that pumped hydro has the lowest costs of currently existing storage technologies [11,12]. As can be seen from calculations presented in this paper, the Norwegian pumped storage plants (PSPs) have a low specific cost per kW and a very low specific cost per stored kWh compared to what is presented for other PSPs [7,10]. This is owing to beneficial topography that reduce the costs of storage reservoirs. A comparison of specific costs and a discussion of the trends for future development are presented in the discussion.

This main contribution in this paper is a technical review of the existing PSPs in Norway. The Norwegian power network is currently interconnected with Sweden, Denmark, the Netherlands, Russia, and Finland, and there are two more connections under construction, with Germany and the UK, respectively. The power grid is operated as a state-owned monopoly, but the majority of the power generation facilities are publicly owned. Moreover, Norway is currently the world's sixth largest producer of renewable energy from hydropower, with approximately 125 TWh per year, according to the International Commission on Large Dams committee (ICOLD, Paris, France) [13]. The country has around 1600 hydropower plants (HPPs) producing about 95% of the total electricity in the national grid. Norwegian hydropower reservoirs hold approximately 50% of the total energy storage capacity in hydropower reservoirs in Europe [14]. However, only ten pumped storage plants (PSPs) exist with a total capacity of approximately 1400 MW. In this context, Norway has a large potential for expanding its pumped storage capacity and contribute with energy storage on a European scale.

Similar reviews have been published for the Austrian PSPs [15], and the US PSPs [16]. Previous reviews from Norway were published concerning the strategy for pumped storage plants [17,18] and about the cost and prospect potential by the Norwegian Water Resource and Energy Directorate (NVE) [19], but no technical review with descriptions of the existing PSPs has been published so far. Lia et al. [17] briefly presents the current state of PSPs in Norway and discusses the former and future strategies for PSPs development in Norway in the light of lack of national political solutions for power exchange on a European level, at the time. Ever since, progress has been done in the field, with two subsea cables are currently under construction, linking Norway with Germany (NordLink) and with UK (North Sea Link), with expected completion date in 2020 and 2021, respectively.

The current review covers the round-trip efficiency, construction costs, specific costs per kW and per stored kWh, tunnel system design, electromechanical installation, technical specifications, and operational experience. The review has a special focus on the design of the tunnel systems and how it influences the hydraulic transients. A discussion concerning the state-of-the-art for pumped storage plants and the future of pumped storage in Norway is provided.

Pumped Storage in Europe

Europe has the goal of becoming the first climate-neutral continent by 2050. In 2018, out of the 11,970 TWh gross energy consumption, 2270 TWh came from renewable energy sources [20]. The electricity generation from wind and solar power increased from 2% to 15% of the total electricity production from all sources between 2004 and 2018 [20]. Current research shows that the importance of energy storage increases significantly with the rise in variable renewable energy being included in the power system [21]. Currently, Europe had a total installed capacity of pumped hydro of 55 GW [22]. A total of 206 GW of long term energy storage with 30 TWh storage capacity is predicted to be installed in Europe in 2050, for the 89% renewable energy scenario [23]. For a 100% renewable energy Europe scenario, the storage need is estimated to range from 80 to 400 TWh, with installed capacity between 500 GW to 900 GW [24].

Austria, Switzerland, Norway, and Sweden have the largest available energy storage capacities in PSPs [25]. The countries with the highest pumped storage installed capacity are Italy (7685 MW), Germany (6364 MW), Spain (6117 MW), France (5837 MW), and Austria (5596 MW) [22]. Currently, Norway is 10th in Europe in terms of pumped storage installed capacity, with 1369 MW, leaving it with a high pumped hydro development capability, as Norwegian reservoirs equivalate nearly 87 TWh of energy storage [14], with 10–20 TWh of available capacity most of the time [26]. Previous studies showed the technical potential of developing additional capacity in terms of PSP without the need for constructing new reservoirs [27]. An estimation of the technical and economic potential in Austria yield that the country already exploited 75% of its hydropower potential, leaving it with 14 TWh maximum unexploited potential [28]. The Swiss Energy Strategy 2050 framework estimates an increase hydro capacity of 2 TWh, a target that can be reached only be finding hidden hydro potential [29]. In the case of Sweden, there is a 35 TWh expansion potential, currently limited due to environmental reasons, leaving it with a final potential of 6 TWh when taking into account the current technological development, which could eventually be increased with 2–4 TWh by upgrading current facilities [30]. The data about hydro potential in different counties shows that Norway has the largest unexploited storage capacity that can serve as support for further integration of the variable renewable energy sources into the European power system.

2. Historical Development of PSPs in Norway

The historical development of hydropower and PSPs in Norway is closely related with its industry development. All ten PSPs are located in the Central and West Norway (Figure 1). The first PSP in Norway is the 11 MW Brattingfoss power plant set in operation in 1955. This PSP was constructed for seasonal pumping in a hydropower scheme where the largest reservoir is on top of the scheme. Between 1962 and 1979, another five PSPs were built in Norway, with an installed capacity ranging from 35 MW to 270 MW.

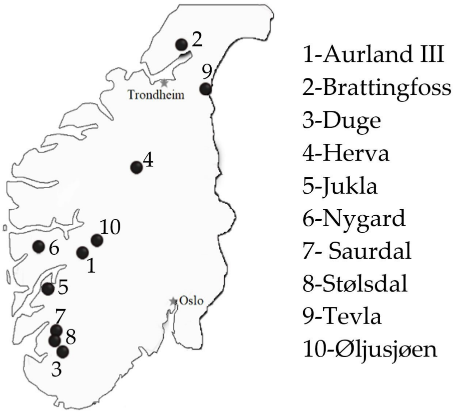


Figure 1. Map of pumped storage plants (PSPs) in Norway.

The largest PSP is the 640 MW Saurdal PSP (320 MW pumping), set in operation in 1985, as part of the Ulla-Førre hydropower scheme. Included in the same scheme is also the smaller Stølsdal PSP, with an installed capacity of 17 MW. The Ulla-Førre hydropower scheme has a total installed capacity of 2100 MW, representing 6.4% of the total output in Norway. It supplies over 4.5 TWh annual energy production, representing 3.5% of the total Norwegian annual electrical energy consumption.

With the power market deregulation in 1991, a decrease in the development of large hydropower plants occurred in Norway. This is also observed in development of pumped storage plants, with only two pumped storage plants built in the new regime. Some new projects were licensed, but the construction start was postponed for an unknown period. One project, Illvatn pumped storage plant was recently licensed, with an expected output of 48 MW and 113 GWh per year [31]. The investment decision has currently not been taken.

The reason for the reduced hydropower and PSP construction after the deregulation is mainly that the market was saturated, and supply exceeded demand [32]. Before the deregulation, the power prices were mainly set in regional long term firm power contracts based on long term marginal cost for the producers. Combined with obligations for power producer to secure power supply in their specific region and limited flexibility in the market, this incentivized investments in overcapacity [32]. These are also explanations to why there has been few new PSPs constructed after the deregulation, and why most Norwegian PSPs are constructed for seasonal storage and why there are no short term PSPs. Another reason is that the Norwegian power system, based on hydropower with large reservoirs, has significant access to power and energy reserves, resulting in relatively low prices for system services such as frequency reserves.

3. Technical Review

This section presents a technical review of the ten existing PSPs in Norway. The data in this chapter are obtained from each PSP owner through questionnaires and interviews, in addition to original unpublished design reports, documentation, and construction or as-built drawings of the tunnel alignment, powerhouse, electromechanical units, and efficiency curves.

Norwegian PSPs are most commonly designed for seasonal storage. Due to the topography in Norway, with steep slopes and high plateaus, the larger reservoirs are located in the upper part of the catchment; thus, most PSPs are used to pump water to the upper reservoir during the snow-melting season, for storage to be used during the low-flow season. The common practice is to utilize natural existing lakes and increase the water level with dams for creating the storage volume. Tunnel systems connect the reservoirs to an underground powerhouse. It is common practice to have several brook intakes along the headrace and tailrace tunnels to collect water from smaller secondary water streams.

3.1. Overview of the Pumped Storage Plants

Table 1 presents an overview of the Norwegian PSPs. The ten PSPs have a cumulative capacity of 1369 MW. All schemes are open loop schemes with natural inflow and have in sum a gross energy production of 2.6 TWh per year. Considering the 0.8 TWh consumption for pumping, the PSPs have a net energy production of about 1.8 TWh per year.

Table 1. PSPs in Norway.

Name	Turbine Capacity (MW)	Pump Capacity (MW)	Gross Annual Production (GWh)	Pump Consumption (GWh)	Net Annual Production (GWh)	Gross Head (m)	Commission Year
Aurland III	270	258	350	280	70	400	1979
Brattingfoss	11	11	33	3	30	118	1955
Duge	200	170	303	55	248	220	1979
Herva	35	31	142	24	118	257	1962
Jukla	40	41	76	22	54	230	1974
Nygard	57.5	52	138	49	89	450	2005
Saurdal	640	320	1285	333	952	465	1985
Stølsdal	17	6	61	10	51	103	1986
Tevla	50	42	125	18	107	164	1994
Øljusjøen	49	39	78	50	42 [1]	212	1974
Sum	1369	997	2591	844	1761	-	-

[1] The upper reservoir in Øljusjøen can be used for production both in Øljusjøen PSP and Borgund HPP. Thus, the gross production does not simply represent the sum between the net production and the consumption, as part of the available water is actually used for energy production in Borgund HPP.

Table 2 presents the energy storage capacities in the PSP reservoirs. The upper reservoirs are much larger compared with the downstream reservoir for all PSPs. This is due to the fact that most of the PSPs were designed for pumping of inflow during flood season and not pumping of the stored water in the downstream reservoir. The total storage capacity is over 5 TWh in the upper reservoirs and 0.85 TWh in the lower reservoirs. Two columns presenting the equivalent number of days of operation to empty or fill the reservoirs are presented. On average, it takes over 90 days with operation on full capacity to fill the upper reservoirs, and only 22 days to fill the lower reservoirs.

Table 2. Energy storage in Norwegian PSPs.

Name	Upper Reservoir			Lower Reservoir		
	Mill. m^3	GWh	10^3 GWh/MW	Mill. m^3	GWh	10^3 GWh/MW
Aurland III	448	440	1556	10	10	36
Brattingfoss	107	31	2480	8	2	218
Duge	1398	755	3879	926	500	2570
Herva	109	69	1747	22	14	389
Jukla	236	116	2124	31	15	272
Nygard	103	114	1715	43	47	761
Saurdal	3105	3331	4978	230	247	737
Stølsdal	2.4	1	31	1	0.5	37
Tevla	204	82	1650	5	2	43
Øljusjøen	161	84	1518	27	14	328
Sum	5873	5023	21,678	1303	851	5391

3.2. Construction Costs and Specific Costs

The construction costs for each of the ten PSPs are estimated based on today's prices to compare with other technologies and the individual PSPs. The Norwegian national cost base for hydropower has been applied to calculate the costs [33]. This cost base is regularly updated and is based on statistical construction costs for hydropower projects in Norway. Table 3 presents the estimated costs for the Norwegian PSPs. When compared with other published PSP costs, the Norwegian PSPs have a low specific cost per kW and a very low specific cost per stored kWh [7,10]. The specific cost per stored kWh is based on the energy storage capacity of the upper reservoir. This does not consider the limitation of the lower reservoir, but this is regarded as acceptable owing to the natural inflow to both upper and lower reservoir. Note that for comparison with other storage technologies and PSPs, these number do not reflect the fact that the Norwegian PSPs are open loop type with a significant net power production in addition. They also do not reflect the fact that most of these PSPs are located on top of a larger hydropower system and provide a significant value for the cascade of hydropower plants downstream.

Table 3. Construction costs and specific costs.

Name	Construction Costs (mill. €)	Specific Cost per kW (€/kW)	Specific Cost per kWh (€/kWh)
Aurland III	212	787	0.51
Brattingfoss	30	2834	1.14
Duge	300	1501	0.39
Herva	60	1721	0.99
Jukla	146	3654	1.72
Nygard	41	739	0.43
Saurdal	995	1555	0.31
Stølsdal	64	3760	121.6
Tevla	103	2079	1.25
Øljusjøen	79	1612	1.06

The main reason for the large variation in specific cost is the role of each power plant, as most of these projects are included in larger hydropower schemes where the dams and tunnel systems benefit additional hydropower plants. As an example, the water pumped in Stølsdal PSP is to a large extent used for production in other HPPs located downstream in the scheme; thus, the energy production in Stølsdal specifically is very low. Its contribution to the total energy production of the hydropower scheme is not quantified in this paper owing to a large number of variables and uncertainties.

In Figure 2 it can be observed a correlation between the specific cost per kWh and the upper reservoir capacity, and head, respectively. The data included in the graphs are from nine of the PSPs. The data point from Stølsdal PSP is excluded due to the unnaturally high specific cost owing to the strategic placement in the larger scheme of hydropower plants, as explained above.

The data show trends with decreasing specific cost with increasing upper reservoir capacity and head. This shows that optimal pumped storage plants are with high head and large upper reservoir, as could be expected. The decrease in specific costs seems to be logarithmic and converging with increasing reservoir capacity, and almost linearly decreasing with the increase of head. It can be noticed that the specific cost is almost halved when the head increases from 200 m to 400 m. At some point this trend must break of as it cannot continue to zero, but the breaking point cannot be found from our range of data.

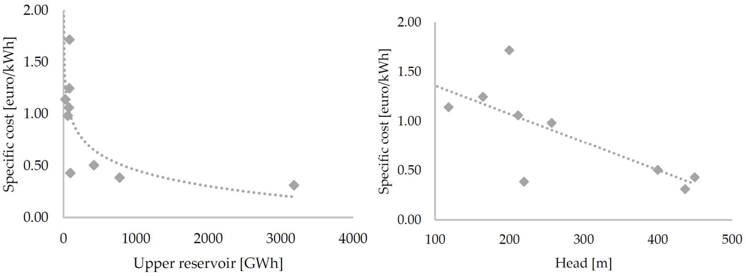


Figure 2. Cost correlation analysis for the Norwegian PSPs.

3.3. *Tunnel System and Hydrulic Transients*

A schematic layout of a typical Norwegian PSP is presented in Figure 3. During turbining, water is transported from the upper reservoir to the turbine through the headrace tunnel and the penstock and continues to the lower reservoir though the tailrace tunnel. During pumping, it flows in reverse from lower reservoir to the upper reservoir. Along the tunnel various shafts can be observed, such as surge tanks and brook intakes. Surge tanks are constructed in order to reduce the pressure strain on the penstock from water hammer. Brook intakes (knows also as secondary intakes) are used to transport water from smaller catchments along the tunnel system, for an extra inflow. Commonly, these types of intakes are unregulated. The rock trap in Norwegian tunnels is normally located before the penstock, in order to protect the mechanical components from fallen rocks in unlined tunnels. Normally, a Norwegian PSP is located entirely underground, featuring D-shape tunnels constructed using the drill and blast method. Due to the good rock quality, lining is needed just along short sections where the tunnel crosses weakness zones, the rest of the tunnel being left unlined with local rock bolting and shotcrete where necessary (Figure 4).

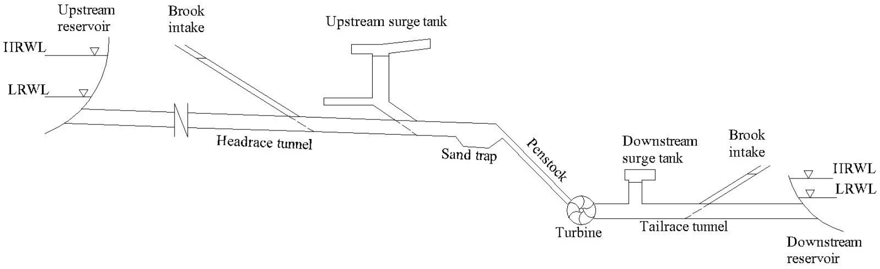


Figure 3. Example of typical Norwegian PSP layout.

Figure 4. Typical drill and blast tunnel in Norwegian PSPs: without lining (**left**) and with lined section (**right**).

A unique characteristic of Norwegian PSPs is the use and placement of rock traps in the tunnel systems. As previously mentioned, the hydropower tunnels are mainly unlined (Figure 4); thus, the risk of fallen rocks being transported to the turbine needs to be mitigated. In addition, in most cases, the road established in the tunnel during construction is not removed, therefore during power plant operation, parts of it erode and are flushed towards the turbines. In order to avoid damage to the penstock and the mechanical equipment, a rock trap and a fine trash rack are placed upstream the penstock, two examples being shown in Figure 5.

Figure 5. Rock trap and trash rack: view from upstream (**left**) and view from downstream (**right**).

In most of the PSPs (Figure 6), there are also several brook intakes located along both the headrace and the tailrace tunnel. If the location of the brook intake is favorable, this is designed to function as a surge tank as well, otherwise, a separate surge tank is built, if necessary. The PSP tunnel systems in Norway are long, varying between 2 km and 17 km; thus, surge tanks are normally constructed in order to reduce the effect of the water hammer. As a consequence, mass oscillations occur in the system which result into the need for a well-analyzed design of the surge tank. In many projects, the preliminary design of the surge tank size is done using the Thoma stability criteria [34]. The design of the surge tank is a quite straightforward process if the surge tank is the only shaft in the system [35]. In Norway, the tunnel systems are often more complex with multiple brook intakes and unplugged adits along the main tunnels; thus, the design may require a more refined analysis. Commonly, the surge tank is a two-chamber surge tank type (Brattingfoss, Duge, Øljusjøen) or a shaft with upper expansion chamber (Herva, Nygard, Tevla). In one case, Jukla PSP, an underground closed surge tank filled with pressurized air is applied. Goodall et al. [36] and Vereide [37] present a more detailed description of closed surge tank design in Norway.

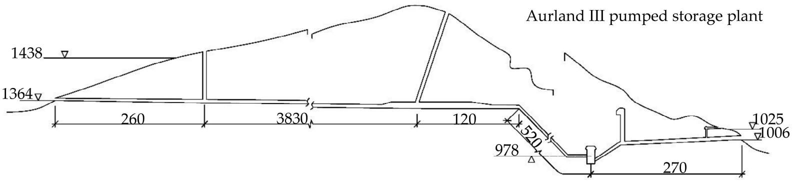
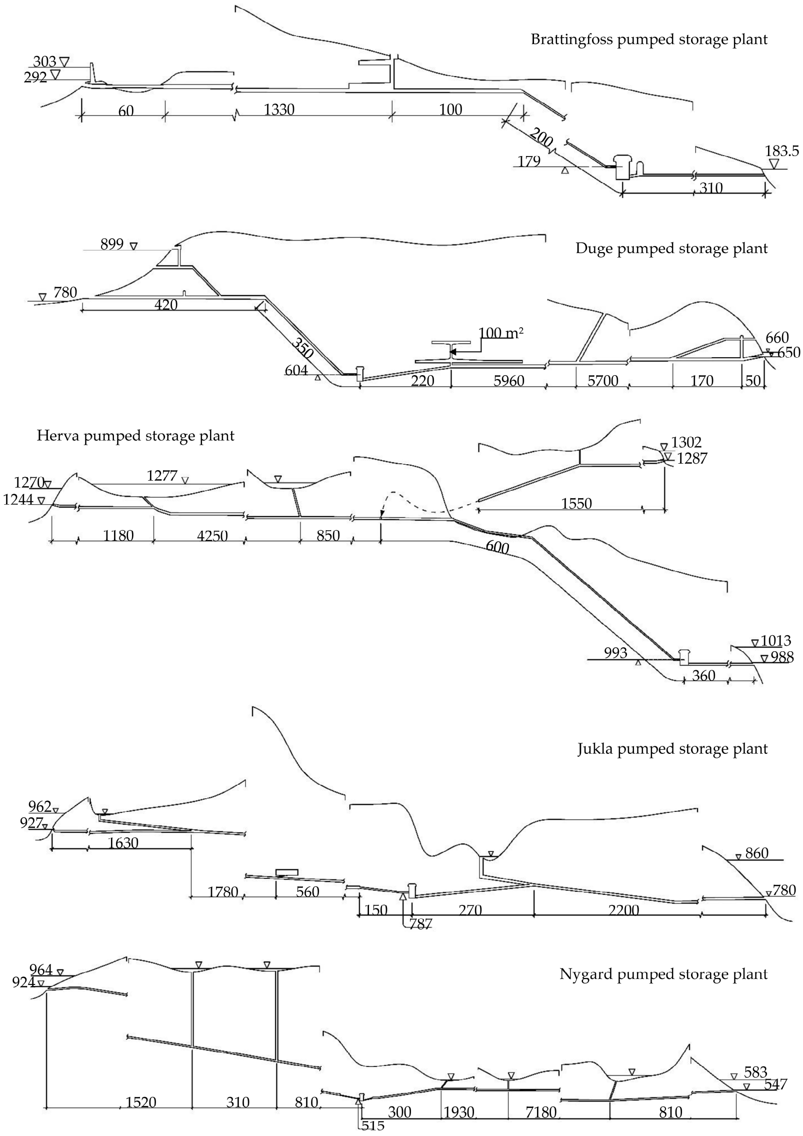


Figure 6. *Cont.*


Brattingfoss pumped storage plant

Duge pumped storage plant

Herva pumped storage plant

Jukla pumped storage plant

Nygard pumped storage plant

Figure 6. *Cont.*

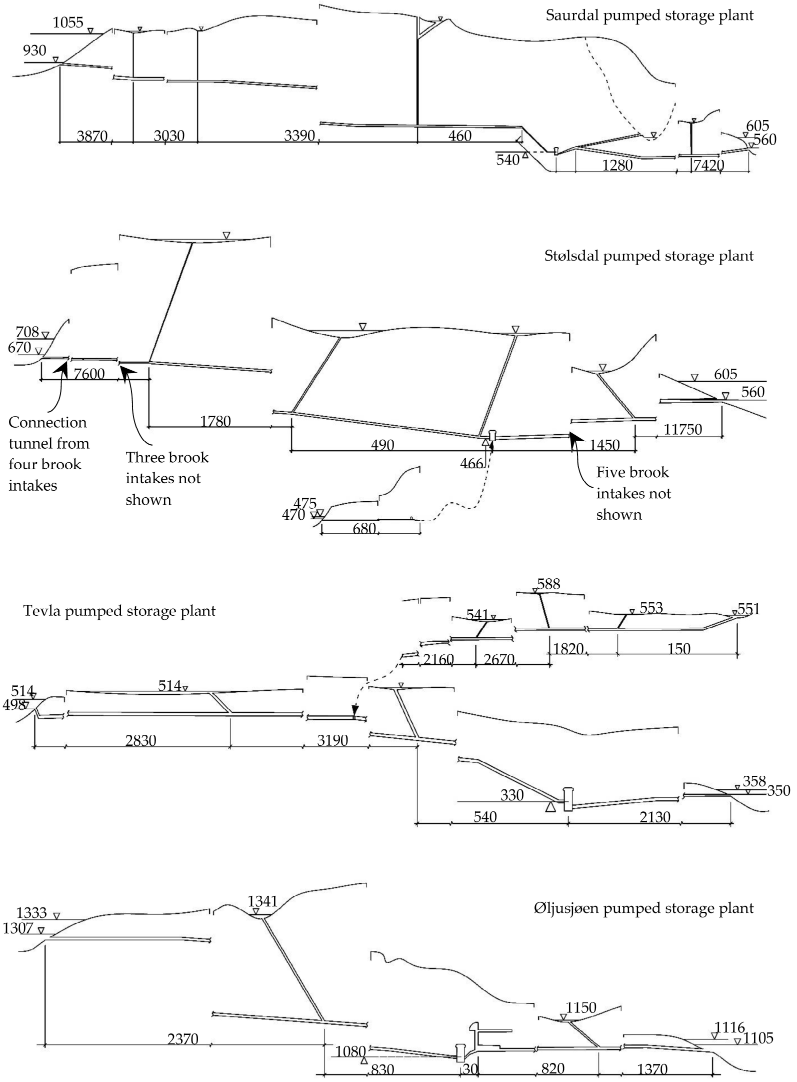


Figure 6. The tunnel system layouts of the pumped storage plants in Norway.

3.4. Electromechnical Installation

An overview of the mechanical installation and electrical equipment in the Norwegian PSPs are shown in Tables 4 and 5, respectively. Out of the ten PSPs in Norway, seven have reversible pump turbines (RPTs) and three have separate pump and turbine units. Generalized, there are five different start-up procedures for pumping mode:

1. In air with pony motor, soft-starter, or frequency converter.
2. In water with electrical back-to-back start with a generator.
3. In water with mechanical back-to-back start with a turbine.
4. In water with frequency converter.
5. Direct start.

Table 4. Overview of mechanical equipment in Norwegian PSPs.

Name	Turbine Type and Number of Units	Start-Up Procedure in Pumping Mode	Pump Start-Up Time (Minutes)
Aurland III	2 vertical RPT	In air with an 11.4 MVA1 frequency converter	9 min
Brattingfoss	1 horizontal Francis turbine and 1 pump	In air, mechanical back-to-back	N.A.
Duge	2 vertical RPT	In air with 5 MW pony motor	15 min
Herva	1 horizontal unit with 2 runners (pump and turbine) and 1 machine (motor-generator)	Mechanical back-to-back	10 min (first hours)
Jukla	1 vertical RPT	Pony motor of 4.3 MVA	11 min
Nygard	1 vertical RPT	In air with frequency converter	6.5 min
Saurdal	2 vertical Francis turbines and 2 vertical RPT	Electrical back-to-back	7 min
Stølsdal	1 Francis turbine and 2 pumps	Direct start	N.A.
Tevla	2 vertical RPT	In air with frequency converter	N.A.
Øljusjøen	1 vertical RPT	Direct start	3 min

1 MVA = megavolt-ampere.

Table 5. Overview of electrical equipment in Norwegian PSPs.

Name	Generator Output		Motor Consumption		Speed of Rotation	Transformer
	(MVA)	(MW)	(MVA)	(MW)	(RPM)	(kV/kV)
Aurland III	2 × 150	2 × 135	2 × 150	2 × 126	500	420/15.5
Brattingfoss	14	11	14	10.6	428	66/6.3
Duge	2 × 120	2 × 100	2 × 106	2 × 85	375	320/13
Herva	45	35	32	31	500	132/8
Jukla	44	40	48	41	500/375	67/12
Nygard	65	57.5	65	52.3	750	300/11.4
Saurdal	4 × 185	4 × 160	2 × 185	2 × 160	428	324/18.5
Stølsdal	20	17	N.A.	2 × 3	375	300/6.6
Tevla	2 × 30	2 × 24.8	2 × 30	2 × 21.1	500	132/8.8/4.4
Øljusjøen	55	49	50	38.6	428	300/7

For the first pump startup procedure, air is introduced in the pump with compressors, forcing the water out of the spiral casing. The units are then started in pumping mode with the pump rotating in air. The rotor is accelerated using a pony motor, soft starter, or frequency converter until the full speed of rotation is reached. When the speed of rotation is set to synchronous speed, air is released, water is admitted back inside the spiral casing, and the pump operation starts.

In the second procedure, the electrical back-to-back start, a pump unit is started using a nearby generator unit. With the two machines (generator and pump motor) being connected through the electrical system, both are excited with a current. The turbine runner starts to rotate; thus, the frequency increases, which triggers the motor to accelerate as well, until it synchronizes with the generator speed of rotation. When the motor reaches the synchronous speed of rotation, it is disconnected from the generator, the turbine unit is shut down, and the pumping commences.

The third start-up procedure, mechanical back-to-back start is implemented with a mechanical connection between the turbine and pump. This can be achieved in PSPs where the pump and the turbine runners are on the same shaft. In this procedure, first the turbine is started, accelerating the entire unit to the nominal speed of rotation. After the synchronization, the inlet valve of the turbine closes while the pump valve opens in parallel, and the pump operation starts.

The fourth start-up procedure is the most modern one, using frequency converters to start in water. With this technique, the units can be connected to the grid even if the unit is not at the synchronous RPM, resulting in a gentler starting with less momentum. Several variants exist such as full-size converters, part-size converters, transistor, and thyristor-based technology.

The fifth procedure, direct start is a brute connection of the pump motor to the grid from standstill. This method is the simplest and most traditional one, in which both the grid and the unit have to sustain a high start-up load, making it suitable just for small units, where both the grid and the machinery can withstand it. This procedure is characterized by high starting torque and full voltage and frequency from the beginning. In some cases, the pump starts with the main valves closed, and first opening when the normal operating pressure is reached.

Figure 7 shows the efficiency curves in turbine mode for ten of the installed turbines. The best efficiency point (BEP) of each turbine varies between 90.4% and 93.5%, and the power specific speed varies between 0.33 and 0.88 radians. The best efficiency point during pumping is known for 7 of the RPTs/pumps and it varies between 87.4% and 90.8%, with only two pumps having BEP under 88.2% and the other five having the BEP above 90.6%.

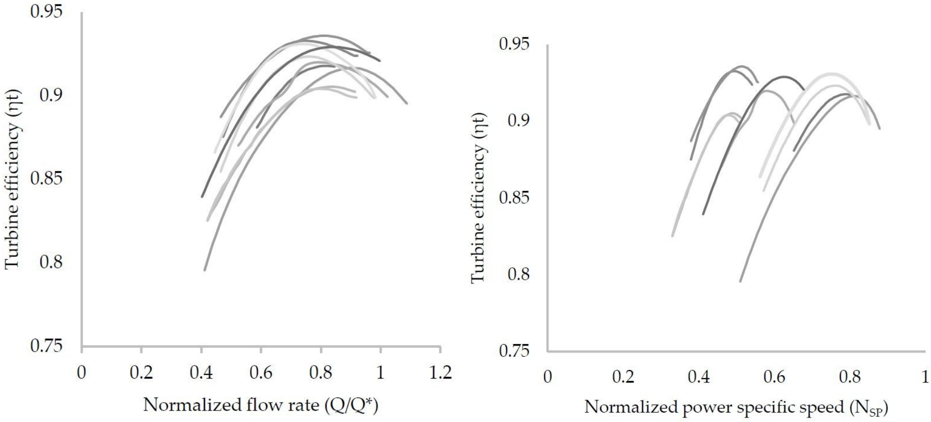


Figure 7. Anonymized efficiency for a selection of the turbines in the described PSPs, function of unit flow (left) and function of power specific speed (right).

The round-trip efficiency for the ten PSPs varies between 65% and 80%. The waterway head loss in each PSP is calculated using an assumed Manning–Strickler number of M = 33 for the unlined tunnels, and M = 85 for the steel lined penstocks. The waterway is usually one of the main causes of energy losses ranging from less than 1% (Nygard) and up to 15% (Duge) depending on tunnel lengths. The round-trip electromechanical losses including the transformation in the range from 20% to 25%. The generator-motor and transformer efficiencies are assumed standard values of 98% and

99%. The real turbine and pump efficiencies as presented in the anonymized graphs above are used in the calculations. These calculations assume operation of full capacity, which is conservative as this generates the highest waterway head losses.

It is noted that all of the Norwegian PSPs are designed primarily for seasonal storage and pumping of water during the spring and autumn high flow seasons. Most of the power plants were not designed for frequent start–stop pump operations, which are reflected in the relatively time-consuming start-up procedures, varying between 6.5 min and few hours, in the case of old ones, and only going down to 2.3 min for the recently upgraded ones. The pump startup time is known for seven PSPs, out of which five have a startup below 10 min, meaning that they are be able to provide tertiary frequency reserves [38].

3.5. Particularities

Each of the ten PSPs have certain particular design features worth to mention. This section presents some of the most interesting from a hydraulic point of view. In the Brattingfoss PSP, the headrace tunnel crosses a steep valley, similar to a narrow canyon. In this area, an overground suspended pipe connects the upstream reservoir with the headrace tunnel as seen in Figure 8. Another feature of the Brattingfoss PSP is the design of the unit, which has both the pump and turbine runners connected to the same motor-generator on the same shaft. A horizontal sketch of the unit can be seen in Figure 9.

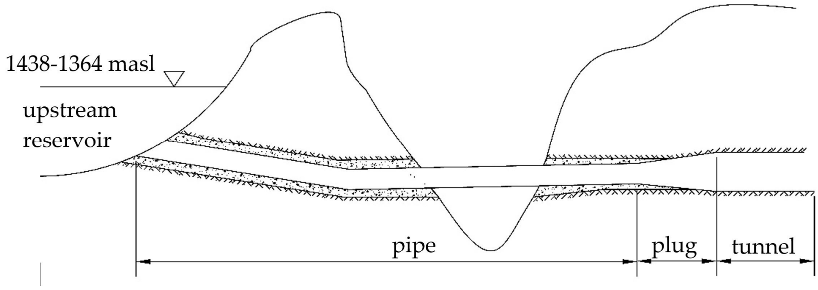


Figure 8. Pipe section in Brattingfoss PSP.

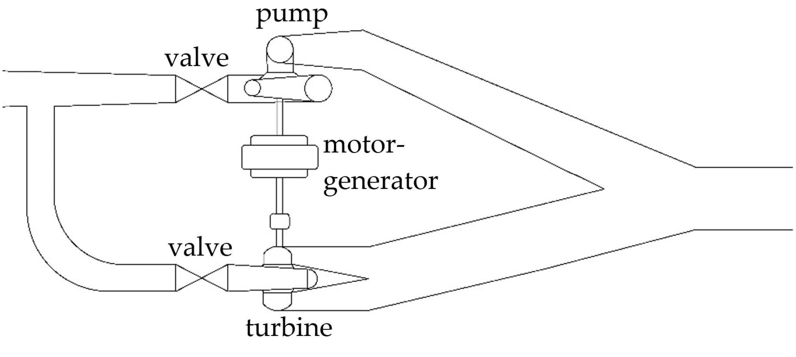


Figure 9. Electromechanical layout plan view in Brattingfoss PSP, planar view.

The Duge PSP features a special intake design at the upstream reservoir. As shown in Figure 10, there is a higher and a lower intake. Both intakes can be used in turbine mode, while during pumping mode, only the upper intake is used. The reason for this is that the pump needs a minimum head in order to operate, which cannot be fulfilled when the water level in the upstream reservoir is low. In situations with low water levels, the gate of the lower intake is closed, and water is pumped only through the upper one, creating a waterfall down into the reservoir. Owing to the resulting energy loss, such situations occur very seldom. It can also be noted that the LRWL is below the lower intake, the reason being that the last volume of water can be released to power plants located downstream through bottom outlets, in case of severe draughts.

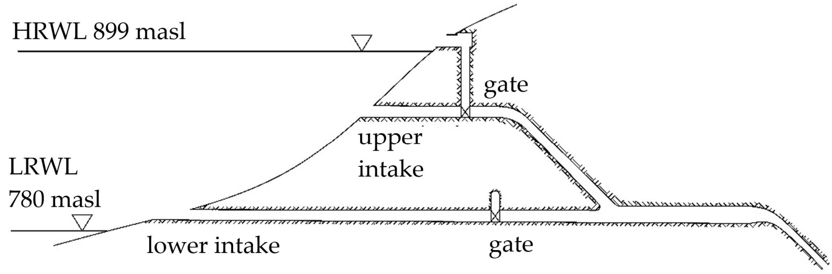


Figure 10. Upstream intakes in Duge PSP.

The Herva PSP has two upstream reservoirs with different water levels; Hervavatn is regulated between 1302 and 1287 masl, and Storevatn is regulated between 1270 and 1244 masl. The reservoirs are used alternatively depending on the available reservoir volume. This gives a better flexibility in operation, and a larger total storage capacity.

The Jukla PSP has several interesting features. It has four upstream reservoirs: Juklavatn (1060 to 950 masl), Dravladalsvatn (957 to 880 masl), Jukladalsvatn (1083 to 990 masl) and Langavatn (962 to 927 masl). In addition, water from several brook intakes and transfer reservoirs is diverted to Dravladalsvatn using a series of diversion tunnels and channels. Downstream of the PSP, the water is diverted to two downstream reservoirs, Svartedalsvatn (860 to 834 masl) and Mysevatn (855 to 775 masl), which serve both as intake reservoirs for pumping mode and for a downstream power plant. Another particularity of Jukla PSP is the use of closed surge tank (Figure 11) for controlling the pressure transients. The closed surge tank has a total volume of 5500 m^3, with an absolute pressure varying between 675 and 228 mWC, depending on which reservoirs are active [39]. Finally, owing to the large variation in water level between the different reservoirs, the generator has the possibility to short-circuit some of the poles to allow operation at either 500 RPM or 375 RPM.

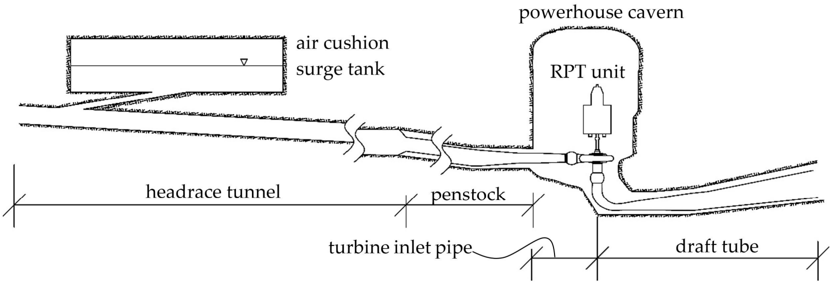


Figure 11. Jukla air cushion surge tank and powerhouse detail.

The Nygard PSP is used to pump water from Stølsvatnet (584 to 547 masl) up to Skjerjavatnet (964 to 944 masl) during summer seasons and is used for power production during winter. While the PSP is part of the Modalen river, Skjerjavatnet is part of Eksingedalen river. Thus, in order to use Skjerjavatnet as an upstream reservoir, the original lake outlet was dammed, water being diverted through a tunnel to the PSP and further to Stølsvatnet in Modal river. In addition to the two reservoirs, water from eight brook intakes is used.

The Saurdal PSP is part of Ulla-Førre, the largest hydropower system in Norway, including Blåsjø, the largest reservoir in Norway, with about 8 TWh of energy storage, serving as upstream reservoir. Blåsjø was created by rising the levels in three natural lakes; Førrevatn, Oddatjern and Storvatn, which are located in two different river schemes. Saurdal has four units of 160 MW, whereof two of them are reversible pump turbines. Another characteristic to Saurdal is a U-tunnel section along the headrace tunnel (see Figure 12). As in the case of Brattingfoss, the headrace tunnel crosses a steep valley, but the solution in this case was the construction of a U-tunnel as seen in the figure. In addition, the upstream surge tank in Saurdal PSP is also used as a brook intake, with a maximum inflow of 2.1 m^3/s. This makes Saurdal PSP a good example of using a brook intake as a surge tank in Norwegian PSPs.

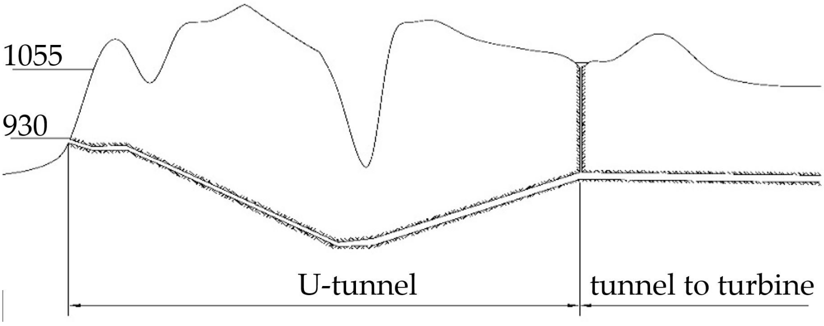


Figure 12. U-tunnel in Saurdal PSP.

The Stølsdal PSP is smaller in terms of reservoir capacities, but it features 19 shafts along the headrace tunnel, mostly including brook intakes, and just one surge tank. The other 18 shafts are diverting water from 22 brook intakes to the headrace tunnel, out of which, four collect water from lakes with minor regulation. This makes the Stølsdal PSP the most complex PSP in Norway from the hydraulic point of view. The maximum total inflow in the 22 brook intakes with a mean cumulated discharge of 15 m^3/s; considering that the maximum turbine capacity is 22 m^3/s, during snow melting or rainfall, the water from the brook intakes cover over 70% of the turbine capacity. The General water level and necessary minimum head are controlled using two upstream reservoirs, Bjørndalsvatn (708 and 697 masl) and Sandsavatn (605 and 560 masl).

The Tevla PSP is used to prevent flood loss by pumping water to the upstream Fjergen reservoir during high inflow periods. The upstream reservoir has a larger storage capacity (204 mil. m^3), as opposed to the downstream reservoir of just 4.5 mil. m^3. Water from Fjergen is used for production in both the Tevla PSP and the downstream the Meråker HPP. The headrace tunnel in Tevla is a Y-tunnel, with one branch connecting the powerhouse to the upstream reservoir, having a cross section of 28 m^2, and the second branch, with a cross section of 10 m^2, transferring water from four brook intakes. In addition, on the first Y-branch, there is one more brook intake. The surge tank is located along the main headrace tunnel (28 m^2).

The Øljusjøen PSP has initially been built for pumping the water in the upstream reservoir during flood periods, for further use in other downstream HPPs. Thus, water is pumped from a lower reservoir (Eldrevatn) and 16 brook intakes located along the tailrace tunnel system, to the upstream reservoir (Øljusjøane). Along the headrace tunnel system, there is just one brook intake, whose shaft is also used as a surge tank.

4. Operational Experience

The operators of the PSPs have been interviewed on operational experience as a follow-up for the technical questionnaires. During the interviews, each operator was asked about possible operational restrictions, rock falls, tunnel collapses, sand problems, problems or restrictions during tunnel dewatering, and measures taken to solve or prevent any encountered problem. Some specific topics of lessons learned are presented in this section.

Aurland III PSP has in 2016–2017 been upgraded with new starting mechanism for pumping mode [40]. Previously, this PSP had a direct start with half of the nominal voltage provided by two coupling windings in the transformer that resulted in a high strain of the electromechanical equipment. Now, a frequency converter is installed, reducing the strain on the machinery during start-up. The drawback that Aurland III encounters is that in pumping mode, the units are not started both at the same time, a company decision in order to avoid the risk of failure. A frequency converter or soft starter investment is considered for the Duge PSP as well [40].

Three of the ten PSPs have reported tunnel collapses. The Duge PSP experienced a tunnel collapse in the 12 km long tailrace tunnel shortly after the first water filling. The tailrace tunnel is mainly unlined, and the collapse occurred in a weakness zone of which the strength was overestimated. The Saurdal PSP experienced a tunnel collapse in the tailrace tunnel after several years of operation. Recently, a major tunnel collapse was discovered also along the headrace tunnel of the Saurdal PSP, which could not be cleaned due to safety reasons; thus, construction of a by-pass tunnel is currently under investigation. Finally, the Stølsdal PSP reported a tunnel collapse in one of the brook intakes. At Duge PSP, the main reason for the tunnel collapse was not the fact that it was a PSP, as the collapse occurred shortly after commissioning. For the two other PSPs one may speculate that the operation as a PSPs might have increased the stresses of the rock mass surrounding the tunnels and might have influenced the collapse.

The Duge PSP has reported a problem of rotor lifting, where the rotor of the unit is lifted of its bearings when operated at too high load. This situation started after a refurbishment of the units in 2017. The reason is the very high submergence of the units (more than 40 m) combined with a long tailrace tunnel (12 km) that results in a high pressure from downstream on the turbine. The power plant is currently operating with a restriction of maximum 80% of installed capacity. Measures to repair the units and return to normal operation are currently undertaken.

The Duge PSP has a very long tailrace tunnel. To dewater and inspect the tunnel, over 600,000 m^3 of water has to be pumped more than 50 m in vertical elevation out of the tunnel. This is very costly and has only been done once in the power plants lifetime (after the tunnel collapse). Recently, a tunnel inspection of the 12 km long tailrace tunnel in Duge was successfully conducted with a remotely operate vehicle (ROV). The tunnel inspection took less than 24 h and could be conducted without dewatering the tunnel. The ROV was used to scan and film the inside of the unlined tunnel to document the current condition after 50 years of operation. The condition was found to be good with only minor and insignificant rock fall.

The Duge PSP currently experiences problems with sand and debris clogging filters and seals in the turbine during pumping mode. This problem started after a change of downstream water level restriction for pumping mode. Previously, pumping was not allowed below 655 masl in the lower reservoir. In the last years, this restriction has been changed to 650 masl. It is likely that during the 40-year lifetime of this power plant, sand and debris has deposited in the lower reservoir close to the intake and is now being sucked back into the tunnel during pumping on lower reservoir levels.

The Herva PSP reported limitations due to the design of the electro-mechanical equipment. The unit consists of separate pump and turbine runners, connected to the same motor-generator machine; the pump runner only being connected to the unit when running in pumping mode. Due to a time-consuming coupling procedure of the pump runner, the pump is only operated once a year, for a few weeks during flood season. During pump operation, the turbine runner is still coupled to the motor-generator; thus, in order to reduce the friction losses, the water is evacuated from the turbine spiral case. Such limitations would make it impossible for the Herva PSP to be used for primary frequency control or secondary frequency control unless the pump runner is kept connected all the time.

5. Discussion

The Norwegian power system is almost entirely based on hydropower plants with storage reservoirs, with very small percent of variable energy sources, resulting in a robust power system with sufficient energy storage and frequency reserves. As a result, all ten pumped storage plants in Norway were not designed for system services or daily peak demand, but for pumping water during flood season, in order to store it for the high demand periods. Another reason for the PSPs to be designed for capturing the flood water is that in Norway, due to the topography, the larger reservoirs are mainly located on plateaus on the top of the catchments. The Stølsdal, Nygard, and Duge PSPs have the upper reservoir twice the size of the lower reservoir. For Aurland III and Tevla PSPs, the proportion between the two reservoirs is around 1 to 45. This demonstrates that the main purpose of the pumping in most of the schemes is to pump inflow and not water stored in the downstream reservoir. However, most of the schemes have sufficient size of the lower reservoir to also allow daily and weekly pumping of stored water to profit from variations in the power prices.

The specific costs per kW is low and the specific cost per stored kWh is very low when compared with published number for PSPs in other countries [7,10]. This can be explained by the Norwegian topography, which enables efficient construction of reservoirs with large volumes at high elevations. For construction of new PSPs in Norway, the costs can be expected to be even lower, as these can be constructed between already existing hydropower reservoirs. The costs can be further reduced by upgrading existing hydropower plants and utilizing the existing tunnel systems. The costs will then be reduced to only the pumping units and powerhouse expansion. The total existing available hydropower storage in Norway is currently about 85 TWh. Previous studies have identified potential to construct over 60,000 MW of pumped storage in Norway [18].

The technical review shows that there is currently only 1369 MW installed capacity in PSPs in Norway. All PSPs have a head between 103 m and 465 m, placing them in high head hydropower plant category. Five out of these are large PSP, having an installed capacity above 50 MW, and the others are medium PSPs. There is no small PSP (below 10 MW), this being because they were designed to work as support for various industrial factories around the country, which needed a large, rather constant power supply. When looking into the power production versus the power consumption of each PSP, it is observed that the net power production is positive in all cases. This is consistent with the fact that all PSPs are open loop schemes, meaning that the water used for generation comes both from pumping and from the catchment in which the PSP is located.

The typical Norwegian PSPs has three special design characteristics, comparing with PSP in other parts of the world. First, the tunnels are commonly constructed using the drill and blast method and are left unlined after commissioning, this being possible due to the good rock quality in the Scandinavian mountain range. Even if unlined tunnels have a higher tunnel roughness than lined tunnels, which leads to an increase in the major head loss, by not lining the tunnels, the cross section is larger, compensating for the influence of the roughness. This design is applied for all ten PSPs presented in this paper. Second, a rock trap solution is normally located inside the tunnel, upstream the penstock or downstream the draft tube. Since erosion in the Norwegian rivers is usually relatively small, a sand trap at the intake upstream the tunnel is not necessary. On the other hand, leaving the tunnels unlined could lead to rock falls which, if not trapped, can be transported to the turbine and damage it. Another possible source of debris that needs to be trapped is pieces of eroded road. Typically, for facilitating transport within the tunnel during construction, inspection, or maintenance, a road is built in the tunnel, parts of which can be eroded and transported to the turbine. In order to prevent any damage by rock falls or eroded road parts, a rock trap is placed within the tunnel. For this reason, a rock trap is located upstream the penstock or downstream the draft tube, respectively. The third design characteristic of Norwegian PSPs is the typical high number of brook intakes. Due to the topography, Norwegian hydropower tunnels are long, crossing under many small secondary streams. For this reason, along the tunnels there are several brook intakes capturing the water from the secondary streams and bringing to the system. Along the headrace tunnel of the PSPs in Norway, there are on average between zero and three brook intakes, except for Tevla PSP and Stølsdal PSP, which have 6 and 10 brook intakes, respectively. Both Tevla and Stølsdal PSP have side tunnels with the only scope of connecting brook intakes to the main headrace tunnel. Interesting is the fact that water is brought to the system through brook intakes along the tailrace tunnel as well, in the case of PSPs, as opposed to HPPs. It can be noticed that there is no correlation between the size of the PSP and the number of brook intakes. No correlation between the size of the reservoirs and number of brook intakes could be observed either.

The most common unit used in Norwegian PSPs is the reversible pump turbine, found in seven of the plants (Aurland III, Duge, Jukla, Nygard, Saurdal, Tevla, and Øljusjøen). The start-up procedure for pumping is varied, but a common feature of most PSPs is that the pump is started in air. All of the PSPs were designed for seasonal pumping during high flow periods during spring and autumn. The majority of the PSPs therefore have time-consuming starting mechanisms to reduce costs and electromechanical strain on the units. The operation of the pumps is still primarily for seasonal storage during periods with high inflow. However, more frequent start–stops and operation also during low flow periods can be observed. It is therefore becoming more attractive for the PSP owners to upgrade the starting mechanism for enabling more frequent and rapid start–stop operations.

6. Conclusions

There currently exist 1369 MW installed capacity with an energy storage capacity of about 5 TWh in the ten existing PSPs in Norway. The construction costs have been calculated with current prices based on a national cost base with price statistics for hydropower in Norway. The results show that the specific costs per kW is low and the specific cost per storage kWh is very low compared with published numbers from PSPs in other countries. There is a large potential for construction of new PSPs in Norway. The costs of new PSPs can be even lower as they can be constructed between existing reservoirs and by upgrading already existing hydropower plants into PSPs.

The round-trip efficiencies range from 65% to 80% for the ten PSPs. Most of the PSPs in Norway have long tunnel systems, which is one of the main causes of energy loss. The round-trip energy loss from the tunnel system ranges from less than 1% (Nygard) to 15% (Duge). The round-trip electromechanical losses including the transformer range from 20% to 25%. It is noted that the electromechanical efficiencies may be improved by upgrading the units, while the tunnel system head loss is usually not feasible to reduce.

All the Norwegian PSPs are open loop, with significant natural inflow to the reservoirs. This results in operation primarily as a normal hydropower plant with shorter periods of pumping. The PSPs have a significantly higher energy production compared with energy consumption. The operation of the Norwegian PSPs is still mainly for seasonal pumping, but a shift towards more frequent start–stop operation can be observed. Pumping during nighttime and no operation during daytime is becoming more frequent.

In general, the Norwegian PSPs have time-consuming pump starting mechanisms, being designed for seasonal storage. However, it is possible to upgrade the starting mechanism as it was done in Aurland III PSP in 2016–2017. Such upgrading is becoming more attractive when the spread between high and low power prices is increasing, and system services are priced higher.

Tunnel collapses have occurred in three out of ten PSPs. Two of them occurred after several years of operation and may be related to the additional strain of pumping operation compared to normal hydropower plants. The variation of the pressure on the rock mass around the tunnel is significantly higher in PSPs as opposed to HPPs; thus, this needs to be accounted for during design of tunnel systems.

The hydraulic system of each PSP in Norway is unique and with many interesting features. Several technical solutions can still be regarded as innovative and the operational experience is worthwhile to share with the research community.

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Paper 2

Hydraulic Scale Modelling of Mass Oscillations in Pumped Storage Plants with Multiple Surge Tanks

Livia Pitorac, Kaspar Vereide, Leif Lia, Michel Cervantes

In Review: Journal of Hydraulic Engineering

Paper 3

Stability of Mass Oscillations in Hydropower Plants with Brook Intakes

Livia Pitorac, Kaspar Vereide, Bjørnar Svingen, Leif Lia

In Review: IEEE Transactions on Energy Conversions

Appendix B

The appendix holds statements from the co-authors confirming co-authorship and the contribution made by the PhD candidate.

*) Statement from co-author Leif Lia.

I hereby declare that I am aware that the works entitles as follows, of which I am co-author, will form a part of PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase, and writing phase.

- Technical Review of Existing Norwegian Pumped Storage Plants
- Hydraulic Scale Modelling of Mass Oscillations in Pumped Storage Plants with Multiple Surge Tanks
- Stability of Mass Oscillations in Hydropower Plants with Brook Intakes

NTNU, 6/7-2021 …………………… Leif Lia ………………………………

Place, date Signature co-author

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*) Statement from co-author Kaspar Vereide.

I hereby declare that I am aware that the works entitles as follows, of which I am co-author, will form a part of PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase, and writing phase.

- Technical Review of Existing Norwegian Pumped Storage Plants
- Hydraulic Scale Modelling of Mass Oscillations in Pumped Storage Plants with Multiple Surge Tanks
- Stability of Mass Oscillations in Hydropower Plants with Brook Intakes

Trondheim, 2021-06-29 …………………… Kaspar Vereide ………………………………

Place, date Signature co-author

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*) Statement from co-author Michel Cervantes:

I hereby declare that I am aware that the works entitles as follows, of which I am co-author, will form a part of PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase, and writing phase.

- Hydraulic Scale Modelling of Mass Oscillations in Pumped Storage Plants with Multiple Surge Tanks

Luleå, 28/06-2021 …………………… Michel Cervantes ………………………………

Place, date Signature co-author

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*) Statement from co-author Bjørnar Svingen:

I hereby declare that I am aware that the works entitles as follows, of which I am co-author, will form a part of PhD Thesis by the PhD candidate who made a significant contribution to the work in the planning phase, research phase, and writing phase.

- Stability of Mass Oscillations in Hydropower Plants with Brook Intakes

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