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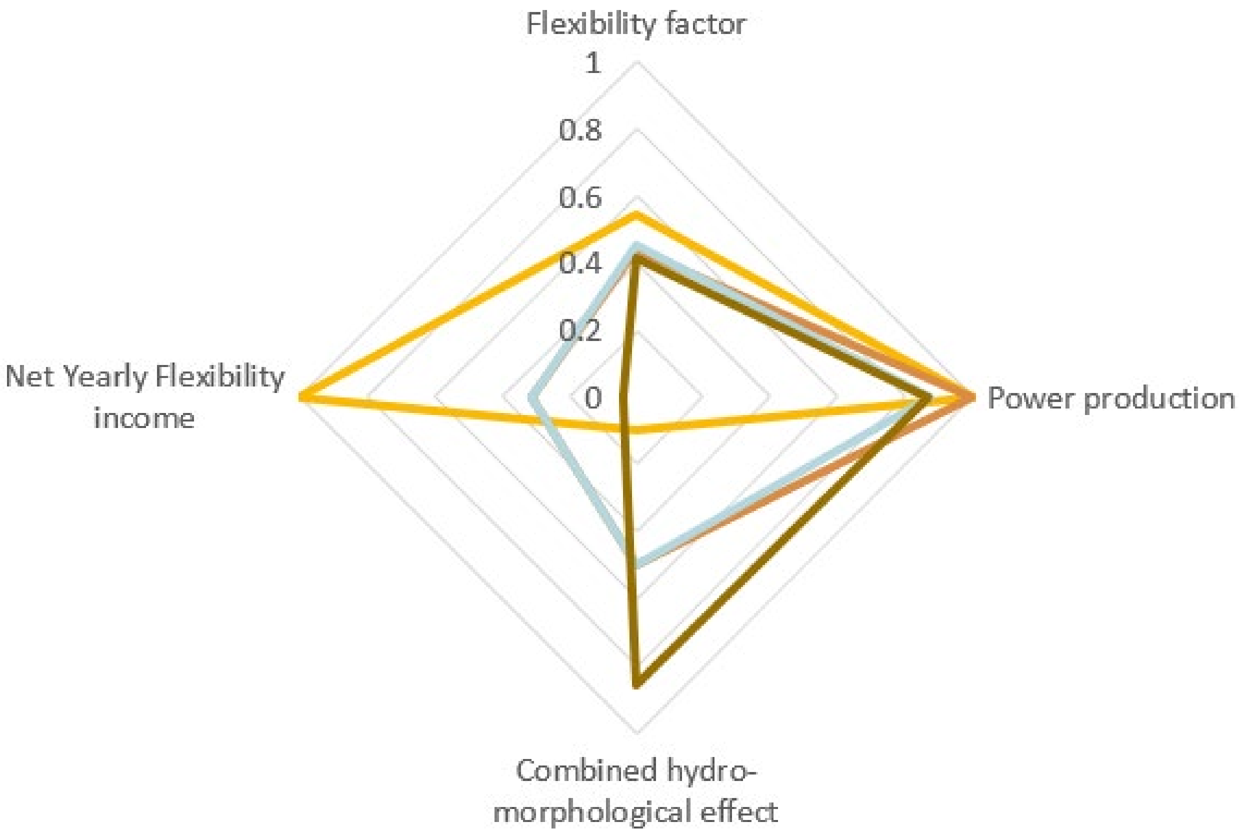
Sustainable Flexibility Metrics

Measuring economic flexibility relative to environmental and structural sustainability

Siri Mathisen, Kristine Lund Bjørnås, Krishna Kanta Panthi, Tonje Aronsen, Markus Majaneva, Kyriaki Tselika



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FORSIDEBILDE
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NØKKELORD
Fleksibilitet, bærekraft, smoltproduksjon, nedkjøringshastighet, miljørestriksjoner

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Abstract

Mathisen, S., Bjørnås, K. L., Panthi, K. K., Aronsen, T., Majaneva, M., Tselika, K., 2023. Sustainable Flexibility Metrics. HydroCen Report 40. Norwegian Research Centre for Hydropower Technology

This report is written as part of the multidisciplinary Work Package 5 in HydroCen. Increased production from variable renewable energy sources leads to a higher demand for flexible power sources to fill the gap with low-variable production. At the same time, a review of the environmental requirements for Nordic hydropower systems, due to new regulations for sustainable activities and long-planned hydropower concession revisions, may lead to several new constraints for hydropower production with the aim of ensuring sustainable use of water and improved balance between multiple uses of water. Consequently, we see an increased need for methods and tools that can quantify the effect of environmental requirements on energy and flexibility and distinguish between the two. This can help us improve the balance between energy production and the environmental consequences, and also better inform us about the costs of flexibility for nature, and vice versa.

This report describes the first steps towards establishing a framework for systematic quantification of the regulation capabilities of hydropower in terms of a set of metrics and the trade-offs between them. The framework considers trade-offs between different operational patterns, balancing profitable operation and environmental impacts. Together, the system of trade-offs between indicators or metrics for different aspects of flexible operation will be a tool for assessing how regulation and flexibility can be obtained from hydropower systems with minimal impact on other factors, such as the environment and costs. The assessment system will also give information about the sensitivity of different regulatory constraints to the ability to provide flexibility from hydropower systems. The assessment system and the individual metrics can be a valuable knowledge base for revision of terms and refurbishment of hydropower systems in future, because it will provide information on the drivers behind capabilities, economical profit and environmental impacts of flexible operation of hydropower.

For two separate watercourses, Aura and Surna, there are four case studies with a variety of environmental constraints: Constant and time-varying constraints on water bypassing a hydropower plant, on the run-down of the flow in part of a river and on the minimum flow in part of a river. These case studies are assessed using combinations of five independent metrics: the flexibility factor, the produced power, the net yearly flexibility loss, the salmon smolt production and the combined hydromorphological effect (EnviPEAK). The cases include proposed and implemented concession revisions as well as cases aimed at preserving the environment in the water course.

The report concludes that the flexibility quantification framework proposed is indeed a foundation for systematic quantification of the regulation capabilities of hydropower in terms of a set of metrics and the trade-offs between them. The report recommends further testing of the developed framework using different combinations of environmental constraints on the hydropower production planning, different environmental considerations, environmental metrics in the reservoirs, and that the industry should be given an increased opportunity to test and evaluate the value of the metrics in production planning, and the useability of, the framework. The assessment framework contributes to a quantification of the cost in terms of the flexibility to preserve the environment around a watercourse, but the report also recommends that more research should be done to search for complimentary good and easily understandable flexibility metrics. We recommend further research to quantify the cost in terms of environmental impact on the flexibility of hydropower planning, especially with future value and use of nature in mind. We also recommend more research projects that increase the experience in multidisciplinary work, as this is important to understand a broader picture and the impacts of choices made in one discipline on other research fields.

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Sammendrag

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Denne rapporten er sluttproduktet fra det tverrfaglige prosjektet Sustainable Flexibility Metrics (SusFlexMet) som er en del av arbeidspakke 5 (WP5) i HydroCen. Økt variabel kraftproduksjon fra fornybare energikilder som vind og sol skaper et behov for balanserende fleksibel kraftproduksjon fra vannkraft. Samtidig må regulanter forholde seg til strengere miljøkrav gjennom vilkårsrevisjoner og nasjonale og internasjonale regelverk slik som Vannforskriften (Norges implementering av EUs vanndirektiv) og EUs taksonomi for bærekraftig økonomisk aktivitet. Strengere miljøkrav kan føre til begrensninger for fleksibiliteten i systemet, for å sikre bærekraftig bruk av vannressursene og en forbedret balanse mellom flerbruksinteresser. Som en konsekvens av konflikten mellom behov for mer fleksibel energi og hensynet til miljøet, trenger vi nye metoder og verktøy for å kvantifisere effekten av ulike miljøbegrensinger på energiproduksjon og fleksibilitet, samt å kunne skille mellom disse. Formålet er å bedre balansen mellom hensynet til miljøet og behovet for kraftproduksjon, samt å øke kunnskapen om hva slags kostnader økt fleksibilitet har for miljøet og omvendt. Denne rapporten beskriver et første steg mot et rammeverk for å systematisk kvantifisere vannkraftens reguleringsevne med et sett måltall og avveiningene mellom dem. Rammeverket tar for seg avveiningene mellom ulike driftsmønstre og balansen mellom økonomisk drift og miljøhensyn. Sammen vil et system for avveininger mellom indikatorer eller måltall for ulike aspekter ved fleksibel drift bli et verktøy for å vurdere hvordan vannkraften kan være regulerbar og fleksibel, med minimal påvirkning på andre faktorer som miljøet og kostnader. Rammeverket beskrevet i denne rapporten vil også gi informasjon om hvor stor effekt ulike regulatoriske begrensninger (miljøbegrensninger) har på fleksibiliteten til vannkraftsystemet.

Rapporten har tatt utgangspunkt i to ulike vassdrag, og i hvert vassdrag er det skissert fire scenarioer (caser) basert på ulik grad av hensyn til miljø (ulike miljøbegrensninger). I denne rapporten er det først og fremst hensynet til laksebestandene som er tatt med som måltall for miljø, hovedsakelig på grunn av tilgjengelighet på data. Det er heller ikke tatt inn miljøhensyn i magasiner. Måltallene som er inkludert er: fleksibilitetsfaktoren, kraftproduksjon, netto årlig fleksibilitetstap, produksjon av laksesmolt og kombinert hydromorfologisk effekt (EnviPEAK). Både miljøhensyn som er foreslått i litteratur og implementerte miljøbegrensninger er inkludert i scenarioene/casene.

Prosjektet konkluderer i denne rapporten med at det foreslåtte rammeverket for å kvantifisere fleksibilitet utgjør et grunnlag for en systematisk kvantifisering av reguleringsevnen til vannkraft i form av et sett måltall og avveiningene mellom dem. Rapporten anbefaler videre testing av det foreslåtte rammeverket ved å bruke ulike kombinasjoner av miljøbegrensninger i produksjonsplanlegging, ulike miljøhensyn med tilhørende måltall/indikatorer (flere artsgrupper og også miljøhensyn i magasiner) samt at industrien burde få anledning til å teste og evaluere måltallene og brukbarheten til rammeverket. Rammeverket bidrar til en kvantifisering av tap av fleksibilitet ved ulike miljøhensyn/miljøbegrensninger, men rapporten påpeker også at det gjenstår mer arbeid for å utvikle eller finne gode og brukervennlige måltall som balanserer kostnader med hensyn til miljø og fleksibilitet ved produksjonsplanlegging. Vi anbefaler også økt tverrfaglig forskning på dette feltet siden problemstillingene vil ha nytte av en bredere innfallsvinkel enn det man kan oppnå uten å inkludere flere fagfelt.

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Content

Foreword

The main purpose of this report is to document the work done in the HydroCen Open Calls project SusFlexMet. The aim of the study is to develop a framework for systematic quantification of the flexibility of hydropower production in terms of a set of metrics and the trade-off between them, while also considering a sustainable environment around individual hydropower watercourses. The results should be an assessment system that is suitable for validating the capabilities of supplying flexibility in a sustainable way, using metrics that are well-founded within their field and also understandable for non-experts.

Trondheim, December 2023

Siri Mathisen
Project manager

1 Introduction

The power market is changing. An increase in power production from variable renewable energy sources leads to a higher demand for flexible power sources that can cover the load demand when the production from the variable sources is low. With the implementation of the EU Water Framework Directive [1] and the EU taxonomy for sustainable activities, combined with long-planned hydropower concession revisions, the environmental requirements for the Nordic hydropower systems will undergo a review. Consequently, several new policies for hydropower production may be introduced with the aim to ensure sustainable use of water and an improved balance between multiple uses of water. This will have an impact not only on the energy production, but also on the flexibility of the different hydropower systems. Flexibility is the electricity system's ability to balance production and consumption. As the variable power production increases, the need for flexibility in the total power system also increases, especially for both short and longer time scales such as a few hours, few days and up to a couple of weeks. It is therefore important to assess methods and tools that can quantify the environmental effects and requirements on energy and flexibility and distinguish between the two. Here, flexibility is measured for a price taker responding to a price in an energy market. This means that reserve capacity, other services in the power system and bottlenecks are not considered. The assessed methods and tools can help us move towards an improved balance between energy production and the water course environment and also better inform us on the impact of flexibility for nature, and vice versa.

The project will take the first steps towards developing a framework for systematic quantification of the regulation capabilities of hydropower in terms of a set of metrics and the trade-offs between them. The framework will consider trade-offs between operational patterns and profits from flexible operation, environmental effects and increased costs due to potential weakening (damages) on the physical structures such as tunnels and shafts and wear on the equipment. Together, the system of trade-offs between indicators/metrics for different aspects of flexible operation will be a tool to assess how regulation and flexibility can be obtained from hydropower systems with the least impact on other factors such as ecosystems and costs. The assessment system will also give information about the sensitivity of different regulatory constraints (reservoir levels, e-flows, ramping etc) on the ability to provide flexibility from hydropower systems. The assessment system and the individual metrics can be a valuable knowledge base for revision of terms and refurbishment of hydropower systems because it will give insights into the drivers behind capabilities and costs for delivering flexibility and regulation from hydropower.

The project builds partly on work on flexibility metrics done in the HydroCen Open Calls project FlexMetrics. The research in this project was done by SINTEF Energy Research, and the outcome can be found in [2], [3].

1.1 Flexibility in the production planning

In the Nordic power market, the flexibility of a hydropower system can be understood as **the ability to deliberately move production in time according to a price signal**. A simplified explanation is that there is a higher production when the price is high and a lower production when the price is low. In a production planning algorithm, with large reservoirs and the ability to plan ahead, the production should consider future prices and the value of water. If the expected prices are higher than today's price, then the flexibility also allows the system to save water for a higher price in the future. As the power price is a result of supply and demand, then a higher price represents a higher need for power, for example because of an increased demand (due to e.g. cold temperatures) or because of a reduced supply (due to e.g. low wind power production or outages or less precipitation).

In this report, an environmental constraint is defined as a constraint to the concession decided regulation of the production plan for a hydropower system, with the aim to maintain environmental conditions around the watercourse. Binding environmental constraints tend to influence the production plan and restrict the hydropower production. When a hydropower production strategy is made, it is optimised with respect to the system revenue, not the flexibility. Therefore, although a binding environmental constraint reduces the system revenue, it must not necessarily reduce the flexibility of the system.

1.2 Flow characteristics links economy with ecology

Streamflow, or discharge, is a master variable in river and stream ecosystems. Maintaining the magnitude, frequency, duration, timing and rate of change of the so-called "natural flow regime" has since long been considered pivotal to maintaining their ecological integrity [4]. Lotic (running water) ecosystems such as rivers and streams are inherently dynamic, and the community of organisms inhabiting a river have adapted to that river's dynamics.

The natural flow regime
- Magnitude
- Frequency
- Duration
- Timing
- Rate of change

There is ample evidence that manipulation of the natural flow regime through for instance hydropower production has effects on the distribution and abundance of organisms in lotic ecosystems. Flow characteristics are therefore a natural link between hydropower production and flexibility metrics and environmental constraint metrics.

There is a certain historical bias in terms species groups investigated, with many studies focusing on fish [5] especially salmon. The adverse effects of flow manipulations from hydropower on fish is well documented [6] [7], even if fish responses to changes in flow magnitude may be variable and context dependent [8]. This underscores the need to consider each system separately. Even though there is a biased focus on environmental impacts of hydropower on fish, there is ample evidence that all aspects of the river ecosystem potentially can be influenced by flow manipulations including birds, mammals, insects, and plant communities [7]. Expanding hydropower in a river system is identified as one of the major threats to freshwater biodiversity [9].

The field of environmental flow science has emerged and grown rapidly as a response to the need to balance society's need for stable renewable energy without losing aquatic ecosystem functioning. Environmental flows are defined by the Brisbane Declaration as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" [10].

One of the most prominent results of Norwegian environmental flow research is the CEDREN-developed framework of Environmental Design (ED) of regulated salmon rivers [11]. As the name implies, this framework has focused on the needs of Atlantic salmon, but the method has recently been expanded upon to consider also other species groups as well as cultural ecosystem services [12]. The ED principles map the river system, based on information on the salmon populations and the hydropower system and evaluates whether the population is limited by hydrological and/or habitat bottlenecks. Central to the design solutions part of ED is the building block method for designing a flow regime throughout the year. Each building block should resolve a hydrological bottleneck specific to the salmon population in that system, for instance increase minimum flow in the summer months when the young fish grow the most (block 4 in Figure 1).

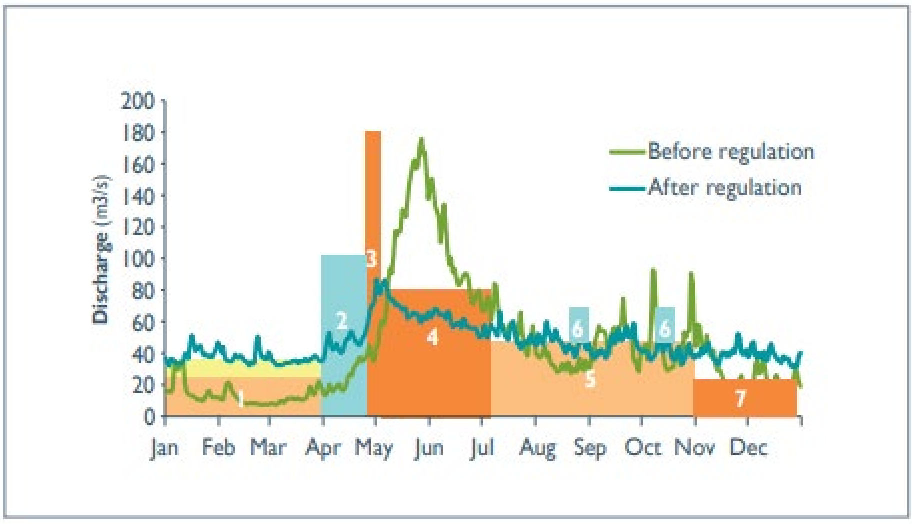


Figure 1. The building block method of Environmental Design, copied from the handbook [11].

There is however a gap in implementing scientific knowledge into management decisions. Even with conceptual tools such as the building block method as aid, several new environmental constraints in revision verdicts have sanctioned only a simple flow regime of, for instance, minimum flow in winter and summer. In practice, setting the minimum flow requirement in regulated rivers is often based on pragmatic decisions rather than detailed ecological analyses. An often-used metric is the hydrological statistic Q_{95}, i.e., the discharge that is surpassed in 95% of the days in a year. This metric was for instance used in the Norwegian prioritization list for hydropower license revisions [13].

Minimum flow requirements concern the timing and magnitude of flows. The increasing need for flexibility in hydropower production has led to an increase in hydropeaking operations, i.e., prominent flow fluctuations and high rates of change to meet time-varying energy demand. While minimum flow requirements are much more commonplace, flow ramping constraints have only been set for approx. 350 Norwegian hydropower licenses [14].

Research on the environmental effects of hydropeaking in Norway has been somewhat biased towards salmon, and a bias towards fish responses is also seen in the international literature [15]. Even though the research is mainly based on salmon; the general principles may also be valid for other riverine fish. A synthesis of Norwegian studies have shown that in general, the risk of stranding of juvenile salmon is higher in the winter, and in particular in the daylight hours [16]. The same synthesis is the origin of the often quoted down-ramping limit of 13 cm:

"A down-ramping rate of 13 cm/h reduces the risk of juvenile salmon stranding, but trials have shown that stranding of young-of-the-year happens regardless in exposed locations with high water velocities, coarse sediment dominated by rocks with lots of cavities and side slope lower than 5%. To avoid stranding on exposed locations, down-ramping should be slower than 6 cm/h, but even then, it is not always possible to eliminate the risk of stranding." [Our translation.]

Hydropeaking will influence other organisms in addition to fish, such as mammals (beavers and otters), the benthic communities, birds and the plant communities in the vicinity of the hydropower outlet [17]. The environmental effects of hydropeaking have been a topic of interest in several Norwegian research programs throughout the years, the most comprehensive being "Konsekvenser av effektkjøring på økosystemer i rennende vann" [Consequences of hydropeaking on ecosystems in running water], a RCN funded program led by SINTEF Energy Research, running 1997-2002 [16], and EnviPEAK, a project within the RCN funded Centre for Environment-friendly Energy Research (FME) CEDREN (Centre for Environmental Design of Renewable Energy) [17]. In this report we have mainly considered downstream effects, but water level fluctuations in reservoirs will also influence the environment in the upstream reservoirs)[5], [18]. In addition to mitigation measures related to hydrological bottlenecks for salmon production, the ED principles also involves mitigation measures to remove habitat bottlenecks [11]. This has not been considered in the SusFlexMet project.

1.3 Project objectives

Primary objective: Develop system of metrics - The project will take the first steps towards developing a framework for systematic quantification of the regulation capabilities of hydropower in terms of a set of metrics and the trade-offs between them. The result will be an assessment system suitable for validating the capabilities of supplying flexibility in a sustainable way from individual hydropower watercourses. The metrics should be well-founded within their field while at the same time being understandable for non-experts.

Secondary objectives:

1. Interdisciplinary collaboration - Besides developing the system, the project also aims at consolidating knowledge from different fields into a coherent framework. Interdisciplinary collaboration and common understanding of the metrics is key.
2. Show-case results from HydroCen - The framework has the potential to be an easy-to-understand way of showing a lot of the research that is going on in HydroCen, also for non-expert users.
3. Future-proof - Even if we are not able to cover all fields/metrics now, the system should be able to incorporate more metrics in the future.

2 Methods

2.1 Hydropower production flexibility metrics

In this study, we have a price-taking perspective, which assumes that variations in the power production of one hydropower system will not affect the power prices for the area. This study uses two metrics to assess the flexibility of hydropower production in the case studies: The equivalent electrical storage and the flexibility factor. Both measures are described and tested in [2], and the selection criteria for the considered flexibility metrics were that they should be simple to use, precise, and that they should be universal and work for all cases.

The objective of this project is to work towards a framework that can give a systematic quantification of the regulation capabilities of hydropower. We want to be able to calculate the flexibility of a hydropower system, but we also want to describe the usefulness of these flexibility metrics. Therefore, in addition to these measures that explicitly describe the flexibility or change in flexibility of a system, the change in produced power for the system will also be included.

The input to all measures is time series with power prices and production data, derived from either simulations or historical production.

2.1.1 Flexibility factor

The flexibility factor, also known as the value factor, measures the relationship between the average achieved price for the system's production and the average price for the time period [19], [20]. It is a scalar number that is easy to understand and compare across systems. It does not always lead to intuitive interpretations and should therefore be supported by other measures. The flexibility factor is defined in (1), where π^* is the average achieved price, which is the revenue divided by the production for a period, and $\overline{\pi}$ is the average price over the same period.

$$FF = \frac{\pi^*}{\overline{\pi}} = \frac{\hat{I} / \hat{P}}{\overline{\pi}} \tag{1}$$

To enable comparison of the flexibility factor between different cases, the average income and production $\overline{I}$ and $\overline{P}$ are adjusted for the change in the reservoir between the start and end reservoirs V^0 and V^T, and the adjusted values are used to calculate the flexibility factor:

$$\hat{P} = \overline{P} - (V^0 - V^T) \tag{2}$$

$$\hat{I} = \overline{I} - (V^0 - V^T)\overline{\pi} \tag{3}$$

2.1.2 Equivalent electrical storage

In [21], a measure for flexibility is presented, using an imaginary electricity storage unit to represent the flexibility of the system that is lost due to a change in the operating conditions. In other words, the loss of flexibility that is caused by the introduction of an environmental constraint can be compensated for with an equivalent electrical storage unit possessing equivalent properties. The equivalent electrical storage is parametrized with the capacity P_{cap} [MW] and the equivalent storage size *E* [GWh].

The capacity is defined as the 95-percentile of the absolute value of the difference in power production in MW when the constraint is introduced, Δp_t, over each time step in the time series:

$$P_{cap} = 95\%(|\Delta p_t|, \forall t \in [0, T]) \tag{4}$$

The equivalent storage size is defined as the difference between the maximum and the minimum value of the balancing energy *B*, which is the accumulated difference in power production when the constraint is introduced, then subtracting the average accumulated production difference:

$$E = B^{\max} - B^{\min} \tag{5}$$

$$B_t = \sum_{\tau=1}^{t} \Delta p_\tau - \sum_{\tau=1}^{t} \overline{\Delta p} \tag{6}$$

Where $\overline{\Delta p}$ is the average production difference in GWh per time step. Both *E* and P_{cap} are scalars. Together, the equivalent storage size and the capacity describe the energy storage unit representing the flexibility of the system, illustrated as a battery in Figure 2. In addition to the two parameters, this project has looked at the net income from the flexibility storage, I_{flex}, or the net yearly flexibility loss of the case relative to the unconstrained case. We define this as the revenue that is lost (or possibly gained) in the system due to the introduction of the environmental constraint, and can be calculated by summing the products of the change in balancing energy per time step with the price of that time step:

$$I_{flex} = \sum_{t=0}^{T-1} (B_{t+1} - B_t)\pi_{t+1} \tag{7}$$

This can be seen as the income from production by the flexibility storage generated from the change, minus the cost of the input to the flexibility storage, as illustrated in Figure 3.

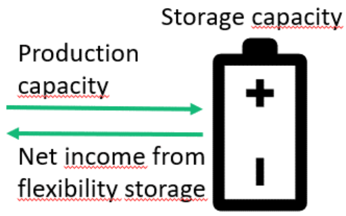


Figure 2: Energy storage unit representing the flexibility of the system.

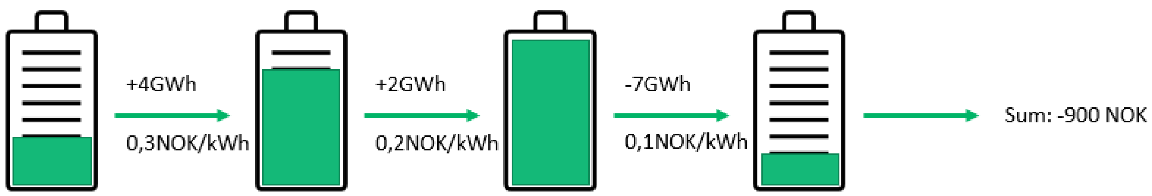


Figure 3: Net income from flexibility storage

The net income from the flexibility storage can also be calculated by finding the difference in income for all time steps and subtracting the average income difference for the whole time period:

$$I_{flex} = \sum_{t=1}^{T} \Delta p_t \pi_t - \sum_{t=1}^{T} \overline{\Delta p} \pi_t = \sum_{t=1}^{T} (\Delta p_t - \overline{\Delta p}) \pi_t \tag{8}$$

Although the net yearly flexibility loss is calculated using the equations above, we use the metric net yearly flexibility income in the illustration to increase the understanding of the metric and more easily compare different metrics, as a high number will correspond to a higher flexibility than a low number. The net yearly flexibility income is the negated value of the net yearly flexibility loss.

2.1.3 Change in produced power

We recall from the introduction that flexibility is defined as the ability to move production in time according to a price signal. However, although the flexibility factor gives a measure for the relationship between the achieved price and the average price and thus the usefulness of the production in each case, it does not truly measure if the production is moved from more favourable hours to less favourable hours. Indeed, if we chose to only produce in the one hour when the price is higher, then the flexibility factor would be maximised. However, this does not reflect the loss of produced power. The production has been moved in time according to a price signal, it has been removed.

To better reflect this aspect of the change in flexibility in the flexibility factor, the produced power has been included as a metric for the flexibility of the hydropower system. To be able to compare cases, the metric uses the power production in each case relative to the unconstrained case, and thus gets a percentwise value for each case.

2.2 Environmental metrics

We have considered several environmental metrics that could be used in the framework for systematic quantification of the regulation capabilities of hydropower. They are outlined in this chapter. For the Atlantic salmon both the environmental design concept and the EnviPEAK classification system can be used to investigate the effect of hydropower on salmon populations and calculate environmental metrics. For other species no such framework exists, and it might be more relevant to use indicators on population viability derived from field data. Furthermore, metrics based on species communities such as benthic invertebrates could potentially fit well into the methodology developed in the Sustainable Flexibility Metrics project. For this report we have focused on environmental metrics/indicators relevant to flow characteristics. Other hydropower related environmental effects such as temperature changes, migration barriers and supersaturation are not considered as they are less connected to hydropower production planning.

2.2.1 Salmon (*Salmo salar*)

The Atlantic salmon is of unique importance culturally and economically. It has an anadromous life cycle and will stay approximately 1-5 years in the river after hatching in the spring/early summer. The juveniles will then smoltify and migrate to the feeding grounds at sea, before returning to their natal river to spawn in the autumn after typically 1-4 years [22]. The homing behaviour causes genetically distinct populations, and salmon are therefore managed at the population level. Hydropower regulations are one of the major threats to wild salmon populations, although this is classified as a stabilized threat [23].

The framework of Environmental Design has been developed for regulated salmon rivers. The "Handbook for environmental design in regulated salmon rivers describes how to evaluate, develop and implement measures to improve conditions for salmon populations in regulated rivers, while taking hydropower production into account" [11] . The handbook describes how to identify the bottlenecks for salmon production (habitat related as well as hydrological), and how to develop design solutions that will benefit the salmon population, but also take the power production into account. The hydrological bottlenecks are related to changes in flow in summer, changes in flow in winter, spawning water level ratio, changes in temperature and changes in flood frequencies. Smolt production and smolt survival are highlighted as the main metrics to measure the long term population viability [11]. Smolt production can be estimated based on habitat and hydrological variables (see section 2.2.2) Other potential metrices that can be obtained from field work include:

- Density of young/adults
- Fish growth
- Fish condition
- Spawning population
- Catches (number/biomass)

The handbook for environmental design [11] provides further descriptions of these indicators/metrics.

2.2.2 Salmon smolt production

In regulated rivers with Atlantic salmon (*Salmo salar*) populations, the salmon population status is often used as a metric for the environmental health of the system. This contrasts Norwegian Authorities' goal of ecosystem-based management but is at the same time understandable considering the wild Atlantic salmon's high status and cultural importance in Norway. Sanctioned environmental monitoring often include annual electric fishing to estimate densities of juveniles, and thus recruitment bottlenecks. Salmon smolt (out-migrant) production is used as an indicator for the productivity of the salmon population and can be used as a proxy for a population's long-term viability. There are numerous ways of linking salmon smolt production to the flow regime of hydropower-regulated rivers. Depending on the available information, one of two broad approaches can be taken:

1. Modelling expected smolt production bottom-up as a function of habitat characteristics.
2. Modelling the flow regime's impact on smolt production top-down using census data.

Approaches in the first category can span from simple approaches to advanced combined hydraulic and ecological modelling. A simple approach is to identify flow-wetted area relationships, calculate wetted area during critical low-flow periods, assess the area's habitat quality for salmon and use expected smolt density for that habitat class multiplied by the critical wetted area [24]. The flow-wetted area relationship can be found by digitizing wetted area polygons from orthophotos in a GIS. Photos from at least three different flows should be analysed, and the flow-wetted area relationship can be fitted to a logistic curve.

A more advanced approach is to use coupled hydraulic modelling (wetted area, depth, and velocity in an area for a given flow) and fish-habitat models. Fish habitat models can range from those based on "habitat suitability criteria" and "weighted usable area" [25], to those incorporating net energy intake from drift-feeding [26], to fully-fledged individual-based models that incorporate feeding, predation, competition and adaptive behaviour of individuals [27]. To our knowledge, fish habitat modelling has been sparsely used in Norwegian hydropower-regulated rivers, with some exceptions [28] [29].

2.2.3 Hydropeaking impacts on salmon – the EnviPEAK classification system

The CEDREN project EnviPEAK developed a classification system for ecological impacts of hydropeaking on salmon [17], [30]. The system contains one axis with six hydromorphological parameters and one axis with seven population vulnerability factors (Table 1). Each hydromorphological parameter is given a value of 1-4 based on set quantitative and qualitative criteria, and the combined effect is calculated as:

$$\text{Combined effect} = (E1 \times E2) + E3 + E4 + E5 + E6. \tag{9}$$

Each vulnerability factor is given a value of 1-3 based on set quantitative and qualitative criteria, and the combined score is calculated as:

$$\text{Combined score: } V1 + V2 + V3 + V4 + V5 + V6 + V7. \tag{10}$$

Table 1. Factors and value range in the EnviPEAK classification system.

Hydromorphological effect factors	Value range
E1: Rate of change	1-4
E2: Dewatered area	1-4
E3: Magnitude of flow changes	1-4
E4: Frequency	1-4
E5: Distribution	1-4
E6: Timing	1-4
Vulnerability factors	**Value range**
V1: Effective population size	1-3
V2: Degree of limitations in recruitment	1-3
V3: Low flow periods as bottleneck for fish stock size	1-3
V4: Habitat degradation	1-3
V5: Reduced water temperatures that lead to population effects	1-3
V6: Other factors	1-3
V7: Percentage of impacted river length compared to total length	1-3

2.2.4 Examples of other keystone species and associated potential metrics

Depending on the case involved, different environmental metrics will be relevant. An identification of the keystone species in the part of the watershed that is considered will be necessary. Most aquatic organisms will be impacted by hydropower regulations due to changes in flow characteristics [4], such as:

- Changes (reductions) in wetted area, floods and water velocity due to reduced flow
- Reduced substrate/habitat quality due to sedimentation
- Changes in natural temperature conditions
- Changes in ice formation in the winter
- Fragmented habitat due to migration barriers
- Fluctuations in discharge and water levels

Indicators and tools to describe the effect of hydropower on different species, services and activities are being developed in the HydroCen project "extended environmental design" (Harby et al. in prep). The indicators and threshold values developed in this work could be used in the further development of the work started in this report. Parameters used in "Vannforskriften" the Norwegian water regulation that corresponds to the EU Water Framework Directive (WFD) could potentially also be used in the proposed framework.

2.2.4.1 Trout (Salmo trutta)

Unlike salmon, the trout has two different life history strategies. The same species can either become anadromous (sea trout that migrate to feeding grounds in the sea before they return to their home river to spawn) or remain in their freshwater habitat for their entire life cycle (stationary trout) [31]. Unlike salmon, trout populations can thus be affected by hydropower regulation in all life stages.
Important flow characteristics (in addition to the regulatory effects mentioned at the start of Section 2.2.4) that influences trout populations are similar to the salmon [11], and includes low winter flow, low flow during spawning and egg deposition, high flow during spawning followed by low flow may cause egg mortality due to stranding if the eggs are deposited above the water level. Relevant metrics related to trout will include:

- Density of young
- Fish growth
- Fish condition
- Smolt production (for sea trout)
- Spawning population
- Catches (number/biomass)
- Cath per unit effort (CPUE) for reservoirs

2.2.4.2 Freshwater pearl mussel

The freshwater pearl mussel (*Margaritifera margaritifera*) has a complex life cycle, and the different life stages have different environmental needs. The life cycle includes a larval stage attached to the gills of trout (*Salmo trutta*) and salmon (*Salmo salar)* [32]. The freshwater pearl mussels are therefore also dependent on the presence of its host organism to fulfil its life cycle. Furthermore, the freshwater pearl mussel is embedded in the substrate as adults and have little opportunity to respond to changes in the environment such as water level or temperature and water chemistry fluctuations/changes. Given the complex environmental requirements, the freshwater pearl mussel is impacted by hydropower regulations due to the changes in hydrology and habitat described in section 2.2.4. The density and presence of freshwater pearl mussels will be limited by the minimum flow throughout the year and also the presence of hosts (fish). Long periods with low flow will lead to stranding. The mussels can survive shorter time periods of low flow, but it may cause stress and lowered resilience to other impacts. Increased sedimentation, siltation and turbidity are among the factors that will have strong negative effects on recruitment and presence of freshwater pearl mussels [32].
Relevant metrics related to freshwater pearl mussels are:

- Density of visible adults
- Presence of younger mussels buried in the substrate
- Presence of larvae on host gills
- Density of host fish
- And proportion of host fish with larvae and density of larvae on the fish.

Freshwater pearl mussels are present in parts of Surna, which is used as a case in this report. The population in Lomunda is classified as healthy [33], and is not relevant to specific part of the Surna case we included. However, the freshwater pearl mussel is on the IUCN red list for endangered species[33], it is declared a national responsibility species and has its own management plan [34]. Including metrics of relevance to the freshwater pearl mussel when the species is present in the watershed will be of special importance.

2.2.5 Species diversity/abundance of benthic invertebrates

Benthic macroinvertebrates, which include diverse groups of animals such as insects, crustaceans, and segmented worms, are important for the river ecosystem functioning. They are responsible for breaking down organic material that is supplied to the river and they are important sources of food for fish. Since these animals are highly diverse, roughly 95 % of the at least 2800 Norwegian freshwater species are invertebrates [35], they also have very different habitat and environmental requirements. Further, some species have several generations each year while others have multi-year life cycles. This means that different species have different tolerance for hydromorphological changes.

There is a strong link between flow conditions and community composition of benthic macroinvertebrates, and frequent unnatural changes in water flow can lead to high mortality of benthic animals through drifting, stranding, and freezing [36]. Especially shallow areas with large and frequent changes in water-cover will have a reduced benthic fauna, both in density and species diversity. For example, insects from the orders Ephemeroptera, Plecoptera and Trichoptera (so called EPT taxa), which are considered as a group of key organisms in river ecosystems and ecological assessments, are sensitive to alterations of habitat or abiotic factors [37]. In fact, some species of EPT are probably more vulnerable than fish to rapid water level declines and disappear completely from areas that dry out or that have reduced water cover periodically [16], [38], [39]. Besides mortality due to drifting, stranding, and freezing, changes in water flow can affect the occurrence of fine sediments, which changes biochemical processes, and which in turn affect benthic community negatively [40].

In Norway, studies on benthic macroinvertebrates have a long history and there exist ample knowledge on their distribution [35]. In recent years, larger efforts have been laid to connect this information with knowledge on hydropower, i. e., research centres CEDREN and HydroCen. Within HydroCen, the most important water-level regulation related variables affecting benthic macroinvertebrates have been summarized [12], and ways of including them in an environmental design analysis have been drafted [41]. Here, we present the most relevant points from those reports in relation to flexibility metrics.

- Perhaps the most important factor for benthic macroinvertebrates is how fast the rate of water flow changes. This is because a rapid drop in the flow rate is a situation that aquatic species are not evolved to cope with. Naturally occurring water level reductions usually last for several days, buffered by the effect of topography. Slow rate of lowering gives the organisms enough time to follow the retreat of the water. It has been suggested that a drop in water level of between 6 and 13 cm/hour, depending on the bottom profile is sufficient [16]. The slower the better for the benthic macroinvertebrates.
- Another important factor is related to the amplitude of change – how much the water level sinks. Many EPT species lay their eggs in shallow water and early stages use the innermost centimetres close to land. Newly hatched stages of particularly non-biting midges (Chironomidae) and mayflies (Ephemeroptera) along the bank are important for the smallest fish larvae. However, the more water level sinks the more species are affected. This effect is dependent on the substrate topography – a trough-shaped riverbed will lead to less affected area than a flat, long-bottomed riverbed. Further, on a steep riverbank, the distance to the water-covered area is shorter, and more organisms will be able to survive by escaping.
- Third important factor is time between the changes in water level. This will have an impact on the degree of extinction, and how many of the organisms are present after the previous water level drop. However, what is optimal is not obvious. Most EPT species are very fragile and die in minutes on land [42], but some species can move down into cavities in the substrate, and thus be able to follow the water level down into the interstitial space between gravel. However, regulated rivers usually have a more compacted, sedimented substrate with smaller voids, because power regulation results in fewer flushing natural floods [43]. Recolonization of reflooded areas begins immediately, but for some species it takes several days to complete [44]. For species with rapid recolonization, it is possible that frequent changes in water level could cause repeated mortality, while for species that take longer to recolonize this mortality effect might be smaller. Temperature also plays a role - most riverine organisms are adapted to cold water. Exposure to the sun and high temperature increases mortality of species that can tolerate a bit of drying out as well, such as snails (Gastropoda), segmented worms (Clitellata) and house-building caddisflies (Trichoptera) [45] .

These points raise questions about how to transform this knowledge into a metric that is understandable for non-experts and valid for measuring flexibility capabilities of hydropower. Due to our limited timeframe in the project, we did not try to include a macroinvertebrate metric in our system of metrics but decided to pave the way for inclusion of such a metric in a future, more comprehensive, system of flexibility metrics.

Since benthic macroinvertebrates are good indicators of water quality, a considerable amount of research has been invested to develop, test, and intercalibrate different metrics that measure impact of various anthropogenic stressors [46], [47]. In line with the European Water Framework

Directive [1], Norway has implemented standardized methods and tools to assess ecological status of rivers, but only acidification and eutrophication are monitored if following the national guidance [48]. Therefore, internationally intercalibrated metrics measuring the impact of flow rate on benthic macroinvertebrates do not exist in Norway.

However, there are some metrics that are developed to measure impact of changes in flow within the WFD Northern Geographical Intercalibration Group [49], of which Norway is a part. These metrics should be rigorously evaluated and tested in a Norwegian setting. Here, we give a short description of them and make suggestions how to possibly incorporate them in the flexibility metrics.

- LIFE index (Lotic-invertebrate Index for Flow Evaluation [50]) is based on scoring each benthic invertebrate taxon according to water velocity categories. A higher value is given to organisms that are dependent on rapid and turbulent flows. Thus, the index is used to measure macroinvertebrates' sensitivity to changes in the flow.
- PSI index (Proportion of Sediment-sensitive Invertebrates [51]) is based on scoring each benthic invertebrate taxon according to its sensitivity to fine sediment deposition. The index describes the percentage of fine sediment-sensitive taxa, and a higher value indicates less sedimented river.
- TT (occurrence of Type-specific Taxa [52]) is based on macroinvertebrate occurrence data at reference sites grouped a priori into different types of rivers following WFD typology. The index describes deviance from a reference status.
- IBIBI (Intercalibrated Benthic Invertebrate Biodiversity Index [53]) is based on occurrence of EPT taxa at reference sites. Like TT, IBIBI describes deviance from a reference status, but the reference status is set based on geography and not river type.

Since these metrics are intended to measure the ecological status of waterbodies so that status can be compared among different waterbodies, they are presented as EQRs (Ecological Quality Ratio). EQR represents the relative difference between the observed value of an index and the expected value in the absence of human disturbance (ratio of observed to expected taxa). The scale of EQRs is based on WFD normative definitions [1] where the ecological status is evaluated on five levels: high ("the taxonomic composition and abundance correspond totally or nearly totally to undisturbed conditions"), good ("there are slight changes in the composition and abundance of invertebrate taxa from the type-specific communities"), moderate ("the composition and abundance of invertebrate taxa differ moderately from the type-specific communities"), poor ("waters achieving a status below moderate shall be classified as poor or bad") and bad ("waters in which large portions of the relevant biological communities normally associated with the surface water body type under undisturbed conditions are absent, shall be classified as bad") status. To compare the status of different waterbodies, EQRs are further normalized to common scale (nEQRs). The expected value is modelled based on a set of empirically selected environmental parameters in the case of LIFE and PSI indices [54], while in the case of TT and IBIBI, the expected value is based on historical data and expert judgment [52], [53]. The reference values of the LIFE and PSI indices are site specific while the reference values of TT and IBIBI are type and region specific, respectively. This means that TT and IBIBI are grounded on a simpler approach and follow more explicitly the suggestion made in the WFD [1] than LIFE and PSI indices.

The nEQRs fit our flexibility metrics scale. However, predicting the species present in a river based on the discharge only is a bit more difficult. To our knowledge, it has not been attempted on Norwegian rivers, but standardized methodology exists for Great Britain where the LIFE index is implemented in the RIVPACS system [54]. Therefore, the LIFE index shows the highest potential for incorporation in our flexibility metrics. Predicted reference values of the LIFE index for selected sites of a given river could be calculated and compared to modelled 'observed' LIFE index values of the sites under various discharge scenarios. Flow velocity estimates for modelling the observed LIFE index values could be obtained through hydraulic modelling. The O/E LIFE ratios could then be transformed to nEQRs and included in the flexibility metrics. However, this principle needs further development and verification before implementing it.

2.3 Pressurized waterway systems

Hydropower has for many decades provided Norway with low-cost and low-emission energy production, which has benefited to the Norwegian industries and the society at large. Today, Norway has an average annual hydropower production of 137 TWh with an installed capacity of exceeding 34 000 MW [55]. The country is among the top sixth countries in terms of hydroelectric power production in the world. The major hydropower development in Norway took place between 1950 and 1990. In most of the occasion, water needed for power generation in Norwegian hydropower plants is being conveyed from reservoirs or rivers to the power stations using unlined pressure tunnels and shafts. The total length of hydropower tunnels/shafts in Norway is more than 4300 km and over 100 unlined pressure tunnels/shafts with a maximum static head of up to 1047 m [56]. Unlined tunnels are designed in such a way that water pressure in the tunnel is withstood by the rock mass itself and rock support is provided only in areas where weakness or fracture zones prevail.

Most of the waterway systems (pressure tunnels and shafts) of Norwegian hydropower plants are over 30 years old. Hydropower plants constructed before 1990s were mostly designed to be operated as base load plants, where the hydropower producers have had well planned and in advanced agreed supply of electricity amount throughout the year with the industries and the society. Hence, most of the high-pressure tunnels and shafts were found to be safe regarding long term function excluding few reported failures of some unlined pressure tunnels under static loading conditions, which occurred in earlier years of operation is a well-studied issue [57].

However, the operational regime has significantly changed since the de-regulation of power market in 1991. As a result of the changing operational regime, there are now more frequent start/stop sequences (Figure 4Figure 4) compared to the time they were designed and built [58], meaning these plants are not optimized for today's market and operating pattern with frequent start stop sequences (hydropeaking).

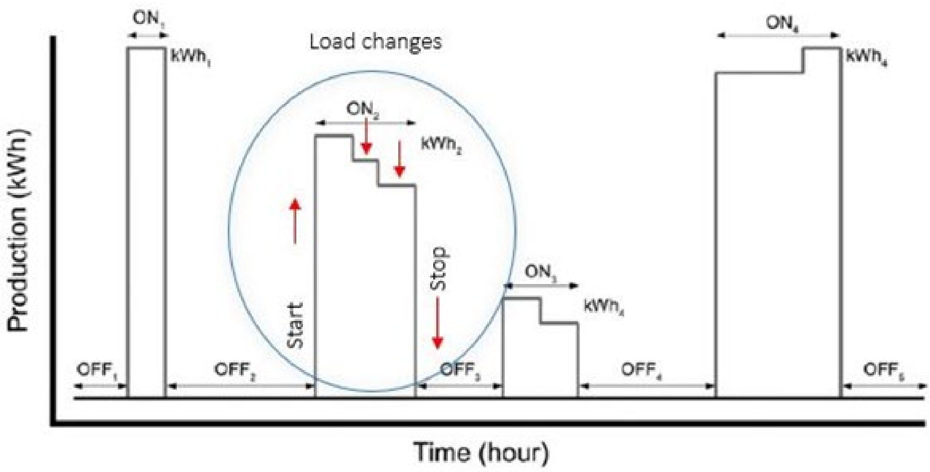


Figure 4: Typical operation regime of hydropower plant under start/stop sequences.

This trend is expected to increase further since the share of electricity from variable renewable energy sources such as solar and wind power in the energy market is continuously increasing [59]. This is significantly affecting or will affect the operational regime of hydropower plants. This is because Norwegian hydropower plants have potential to function as a battery and balance the surplus/deficit of intermittent energy being fed into the grid by variable renewable energy sources. For over last decade the high-pressure headrace tunnel and shaft systems and turbines are being operate with high fatigue loads originating from off-design operating condition to start-stop and speed to no-load conditions. The research carried out by Neupane et al [58] has demonstrated that the fatigue load (hydraulic impact) from such operating conditions (as indicated in Figure 5) on the high-pressure headrace systems will lead to the long-term creep.

The problem of fatigue damage (block falls/tunnel collapses) are becoming and will become more frequent, which the Norwegian hydropower industry should be aware off. The industry needs tools and methods to operate the high-pressure headrace system in a sustainable and environmentally friendly way in order to find the costs for flexible operation with minimum physical and environmental damages.

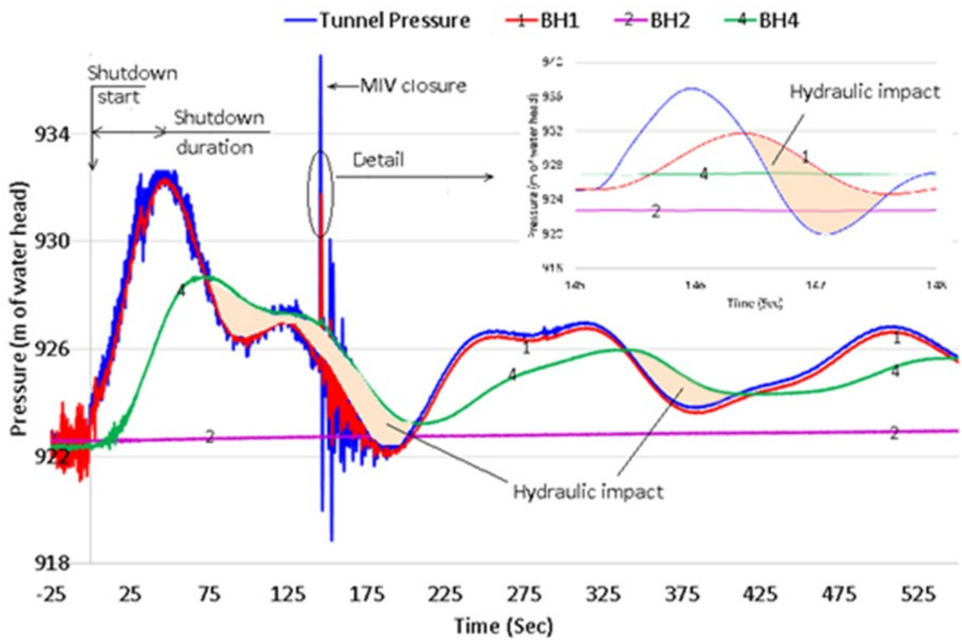


Figure 5: Typical pressure transient and pore pressure responses under start/stop sequences [58].

It is evident that the changed scenario of hydropower operation caused by de-regulation of power market and more and more addition of intermittent renewable energy sources will cause even more frequent start-stop cycles in the high pressure headrace tunnels and shafts, which will not only cause long-term creep leading to block falls but also will make fluctuation on the downstream flow from the side rivers from where water is discharged to the pressure tunnels system.

It is noted here that by redesigns and optimization there is a possibility to enhance capacity of existing hydropower systems. However, substantial part of the optimization should be related to the pressure tunnels and shafts. Moreover, the state-of-the-art hydropower technology should encompass new generation equipment, efficient waterway systems, side intakes, dams and reservoirs that take care of environmental friendliness. This means, enhancing flexibility and mitigating environmental impacts are and will be the key issues for the enhancement of long-term sustainability of Norwegian hydropower plants. Hence, innovative, and research-based design, modern construction and operation methods with full digitalization and automation will be the key to enhance environmental friendliness. The beauty of hydropower plants is that these plants have long lifespan and can be further developed through refurbishment, retrofitting, and upgrading existing infrastructure to enhance both long-term sustainability and environmental protection.

More importantly, Norway has many hydropower plants that operate in between large reservoirs, which are being ideal to upgrade to pumped storage power plants. Hydropower represents an important asset for the system operators due to its fast response and ramping capabilities. The industry well understands that the improvement on the hydropower installation capacity to provide system services will increase economic values and permit increased integration of variable renewable energy in the power market system. A natural realization of this is retrofitting pumping capabilities in existing power plants, which may lead to further changes in the operation of hydropower plants. Therefore, environmentally sustainable exploitation of hydropower in tandem with ecosystem sustainability will become a key-factor in future hydropower plants.

2.4 Resulting metrics

The project aims to start developing a framework for systematic quantification of the flexibility of hydropower and provide an assessment system that is suitable for validating the capabilities of supplying flexibility in a sustainable way from individual hydropower watercourses. In Sections 2.1.1, 2.1.2, 2.1.3, 2.2.2, 2.2.3, the metrics that will be used in this assessment system are described. The next task will be to illustrate these parameters to correctly represent the challenge of balancing flexibility against sustainability.

The choice of illustration has landed on a radar chart or a spider chart, which shows data on several axes simultaneously. The axes have the same range, which means that the results must be scaled to fit into the chart. Using one universal data range for all flexibility assessments would make comparisons between watercourses easier, but it might not be directly comparable and could be a false sense of security. The flexibility factor, relative power production and the EnviPEAK classification results can be scaled in the same way for all cases, but net yearly flexibility income and salmon smolt production are case specific.

The resulting axes are:

- Flexibility factor (Section 2.1.1)
- Net yearly flexibility income (Section 2.1.2)
- Power production (Section 2.1.3)
- Salmon smolt production (Section 2.2.2)
- The EnviPEAK classification system (Section 2.2.3) (for the Surna cases)

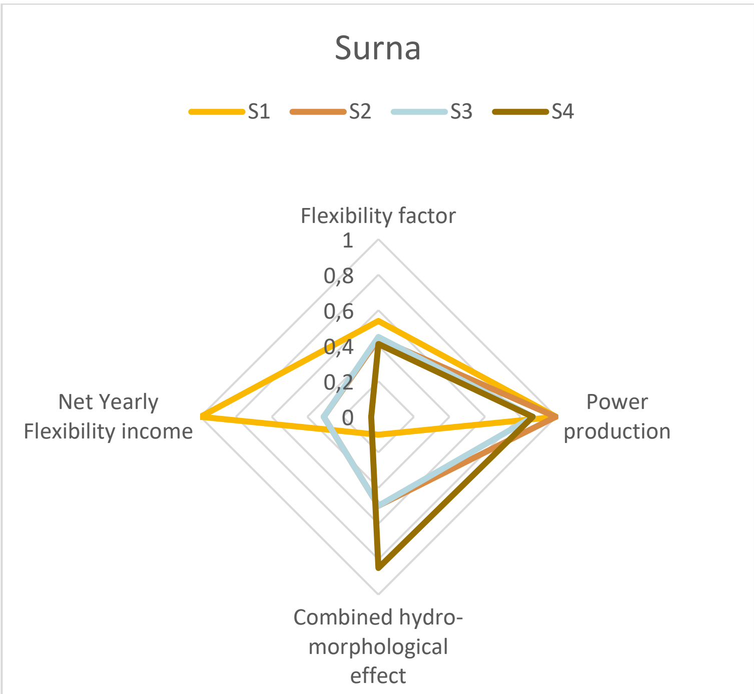


Figure 6: Spider chart showing example results for one four cases in one watercourse.

3 Case studies

3.1 Case descriptions

The sustainable flexibility metrics have been tested in several case studies, listed in Table 2. The cases use two hydropower systems, Aura and Surna, and for both systems, 4 case studies have been performed. The first cases (A1 and S1) are based on the hydropower production systems descriptions without any environmental constraints. The second cases (A2 and S2) are the systems with the environmental constraints that have been in use since the original concessions from 1962 [60], 1965 [61] and 1966 [62], for Surna, and 1953 [63] and 1959 [64] for Aura, and until the revisions in 2021 [65], [66]. For Aura, there are no environmental constraints in Case A2, so Case A1 and Case A2 use the same data. The third case for Aura (A3) is the system with the environmental constraints that were suggested, but not approved, in the concession revision in 2021 [66], and for Surna (S3) is the system with the environment constraints that are described in the conclusion of the concession revision in 2021 [65], which are a softer version of the constraints suggested by the Norwegian Water Resources and Energy Directorate (NVE) [67].

Table 2: Case descriptions

Case	System	Conditions
A1	Aura	No environmental constraints
A2	Aura	No environmental constraints
A3	Aura	Minimum bypass constraint from Aursjøen
A4	Aura	Time varying bypass constraint from Aursjøen
S1	Surna	No environmental constraints
S2	Surna	Minimum discharge constraint on Surna (VM Skjermo in Figure 7) Time varying ramping constraint on Trollheim
S3	Surna	Minimum discharge constraint on Surna (VM Skjermo in Figure 7) Time varying ramping constraint on Trollheim Minimum bypass constraint on Rinna and Store Bulu (OVF Rinna)
S4	Surna	Minimum discharge constraint on Surna (VM Skjermo in Figure 7) Constant ramping constraint on Trollheim Minimum bypass constraint on Rinna and Store Bulu (OVF Rinna)

The Aura and Surna hydropower systems are shown in Figure 7. Aura consists of 4 reservoirs, Aursjøen, Osbuvatn, Reinsvatn and Aura, and two stations in red, numbers 44805 and 44801. The bypass constraint in Aura is illustrated with the stippled line from Aursjøen. The bypass constraint in Aura is a bypass from Aursjøen to the Aura River, which bypasses all production units. In Case A3, the bypass constraint is set to 1 m^3/s, constant throughout the year. This constraint was suggested in the revision in 2021 [66], but not approved as it was not expected to improve much the environmental conditions in the Aura river, but it would lead to a considerable energy loss. In Case A4, the bypass constraint is a time varying constraint shown in Table 3, derived from the work described in Section 3.2.2s.

Table 3: Bypass constraint used in Case A4.

Start week	End week	Bypass constraint on Aursjøen
1	21	0.91 m^3/s
22	39	6.37 m^3/s
40	52	0.91 m^3/s

Surna consists of 5 reservoirs, OVF Vindoela, Graasjoe, OVF Rinna, Trollheim and VM Skjermo and 2 stations, numbers 45701 and 45703. The correspondence between the topology of Surna and the geography is shown in Figure 8. In Case S2, which builds on the environmental constraints that have been in use since the original concessions, there is a minimum discharge constraint of 15 m^3/s on Surna river, measured at the point Skjermo. This corresponds to the virtual module Skjermo in Figure 7. Case S2 also uses a self-inflicted time-varying ramping constraint on the discharge from Trollheim station, measured at Skjermo. This time-varying ramping constraint consists of a hard constraint, demanding that the reduction in flowrate in Surna from 50 m^3/s to 15 m^3/s should last no shorter than 8 hours, a swimup constraint, demanding that the reduction in flowrate in Surna from 50 m^3/s to 15 m^3/s should last no shorter than 6 hours, and a soft constraint, demanding that the reduction in flowrate in Surna from 50 m^3/s to 15 m^3/s should last no shorter than 4 hours. This corresponds to a rate of change at 5 cm/h, 10 cm/h and 13 cm/h, respectively. The hard constraint should be used in daylight during the winter, and the soft constraint should be used when it is dark during the winter. The winter is defined to be from the 1st of January to the 14th of March, and from the 15th of October to the 31st of December. The soft constraint should be used during the summer, except for the period from May 15th to June 14th, when the swimup constraint should be used. The hard constraint corresponds to a downwards ramping limit of 5 cm/h of the water level in the river [65]. In this project, the ramping constraint has been simplified to comply with the model used (described in Section 3.1.1), and the simplified constraint is shown in Table 4.

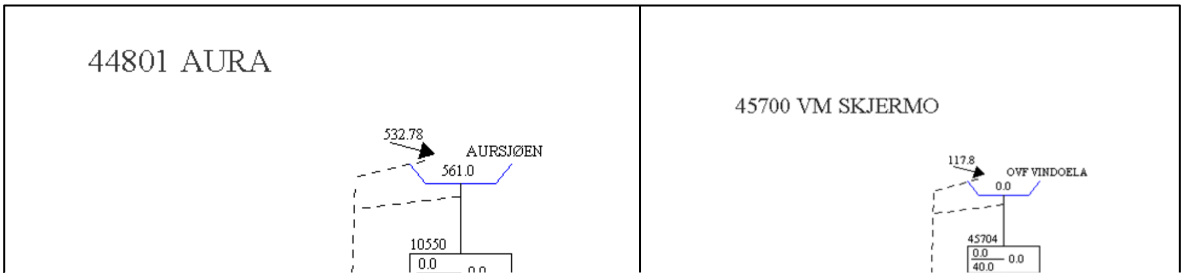


Figure 7: Topology of the Aura (left) and Surna (right) hydropower systems as they are modelled in the hydropower production planning model ProdRisk.

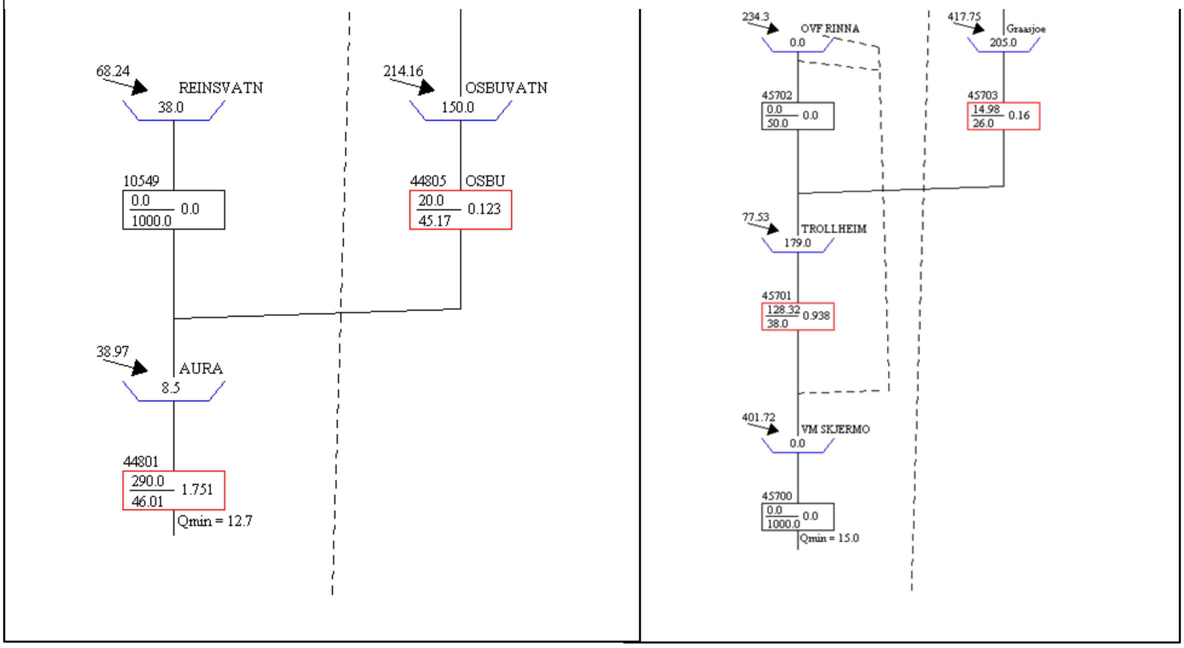


Table 4: Ramping constraint used in Case S2 and S3.

Start week	End week	Ramping constraint on Trollheim
1	10	4.375 $m^3/s/h$ 5cm/h
11	19	8.75 $m^3/s/h$ 13 cm/h
20	21	5.83 $m^3/s/h$ 10 cm/h
22	40	8.75 $m^3/s/h$ 13 cm/h
41	52	4.375 $m^3/s/h$ 5cm/h

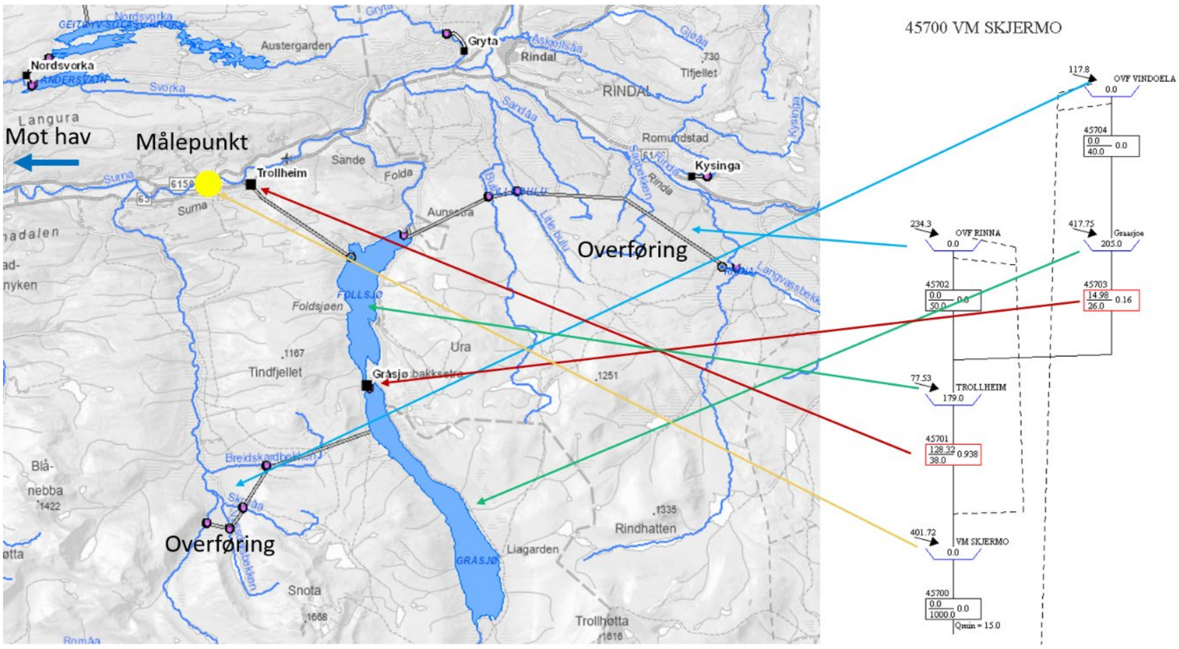


Figure 8: Correspondence between topology of Surna watercourse and the geography.

For Case S3, the conclusion from the concession revision in 2021 is used. The control regulations from the concession demand that like before, a minimum discharge constraint of 15 m^3/s on Surna river, measured at Skjermo, shall be maintained. The concession revision also concludes with two new minimum bypass constraints: In Rinna, measured at Rinna dam, there shall be a minimum bypass constraint of 1.4 m^3/s from May 1st to October 31st, and a minimum bypass constraint of 0.26 m^3/s from November 1st to April 30th. In Store Bulu there shall be a minimum bypass constraint of 0.9 m^3/s from May 1st to October 31st, and a minimum bypass constraint of 0.2 m^3/s from November 1st to April 30th. In the model runs of Case S3, these two bypass constraints will be found in the same place, OVF Rinna, and will therefore be combined. The bypass constraint used in Case S3 can be found in Table 5. Additionally, the ramping constraint on the power plant Trollheim measured at Skjermo, that is used in Case S2, is continued in the revised concessions, and therefore the constraints shown in Table 4 will also be used in Case S3.

Table 5: Bypass constraint used in Case S4.

Start week	End week	Bypass constraint on OVF Rinna
1	17	2.3 m^3/s
18	44	0.46 m^3/s
45	52	2.3 m^3/s

For Case S4, the original recommendations from the Norwegian Water Resources and Energy Directorate are used. They demand that the hard downwards ramping constraint of 5 cm/h should be valid for the whole year, except for extraordinary operation situations. This ramping constraint corresponds to the hard constraint used during wintertime. It is shown in Table 6. The concession revision concludes that this constraint would be too radical, and that it would deprive Trollheim powerplant of the opportunity to contribute to the regulation and special regulation of power grid. Case S4 will investigate the consequences that this constraint has on the flexibility of the hydropower production. The constraint on Trollheim measured at Skjermo is shown in Table 6. In addition to the downwards ramping constraint, Case S4 uses the same minimum discharge constraint on Surna river of 15 m^3/s measured at Skjermo as Case S2 and Case S3, and the same bypass constraint as in Case S3, shown in Table 5.

Table 6: Ramping constraint used in Case S4.

Start week	End week	Ramping constraint on Trollheim
1	52	4.375 $m^3/s/h$

3.2 Hydropower production flexibility metrics

3.2.1 Model

The influence on the flexibility of the hydropower planning by the introduction of hydropower constraints were tested using the medium-term hydropower scheduling model ProdRisk [68]. ProdRisk is a stochastic model that can give a sample space of the production planning for a hydropower watercourse, operating as a price taker in the day-ahead market. In the simulation results from ProdRisk we find the operating patterns of the watercourse in question for a broad range of scenarios based on historical inflow and price data. The dataset used for the Aura cases is a result of HydroCen-work described in [69], [70], and the dataset used for the Surna cases origins from the NVE. Both datasets use NVE inflow data.

The price series used together with the datasets for Aura and Surna are derived from the price series used in the same HydroCen-work [69], [70], altered to provide a higher variation and a higher mean price. This is done to emphasize the need to move production in time and thus get cases that can better illustrate the change in flexibility between the cases. The price series has a resolution on 3 hours, which means that there are 56 price periods for each week. The quantiles of the prices can be found in Figure 9, showing extreme cases with prices up towards 200 øre/kWh. The duration plot in Figure 10 shows that the high prices occur in about 5% of the time, and that the price is zero in about 5% of the time as well. The average price is 40.446 øre/kWh.

ProdRisk has been used with the *serial simulations* setting, running 58 historical inflow and price scenarios sequentially. The simulation horizon is 52 weeks, representing a whole year and repeated 58 times with the end values of the previous scenario as the start values for the next scenario. The strategy has been calculated for 156 weeks for every scenario. The 58 historical scenarios were also used to produce the strategy for the datasets.

The Aura cases have used the operating version of ProdRisk[1], whereas the Surna cases have used a prototype of ProdRisk that is able to include the constrain discharge ramping from a power plant. The description of the additional constraint is described in [71], [72]. The ramping constraint is defined for the Trollheim station, not the virtual module Skjermo.

[1] R10.5.0

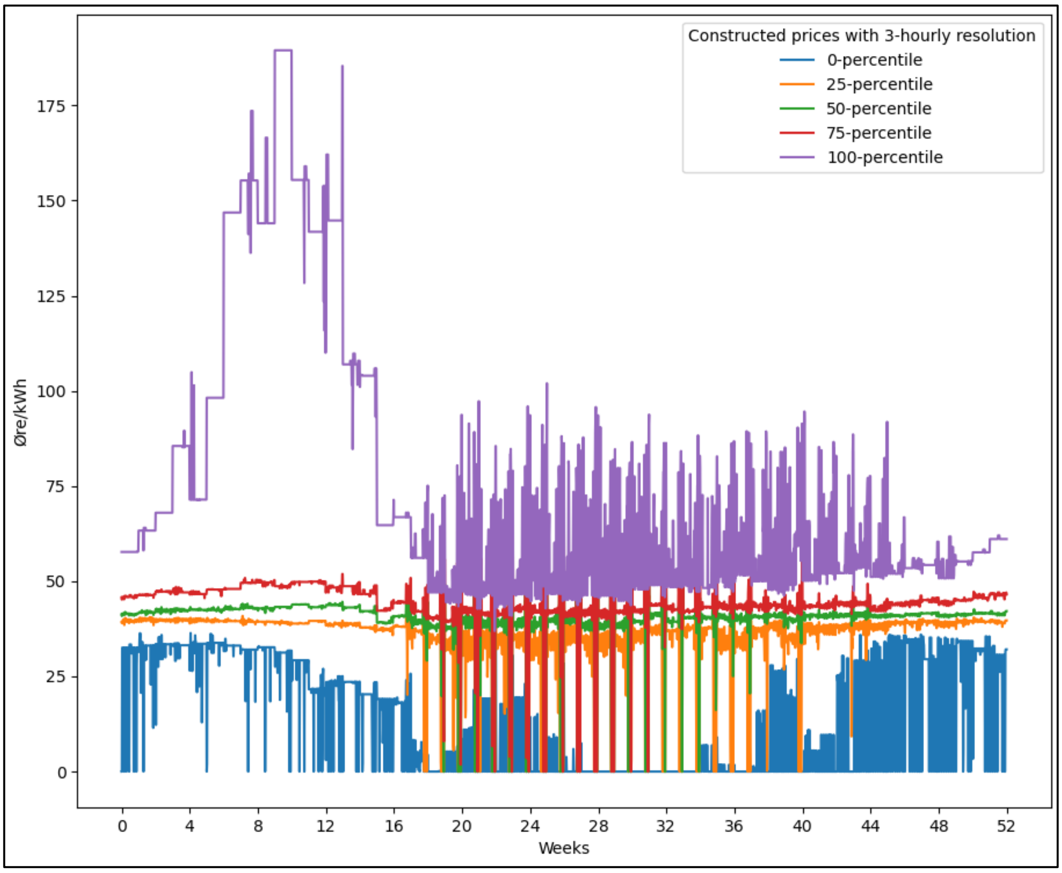


Figure 9: Quantiles of the prices used for the Aura and Surna case studies.

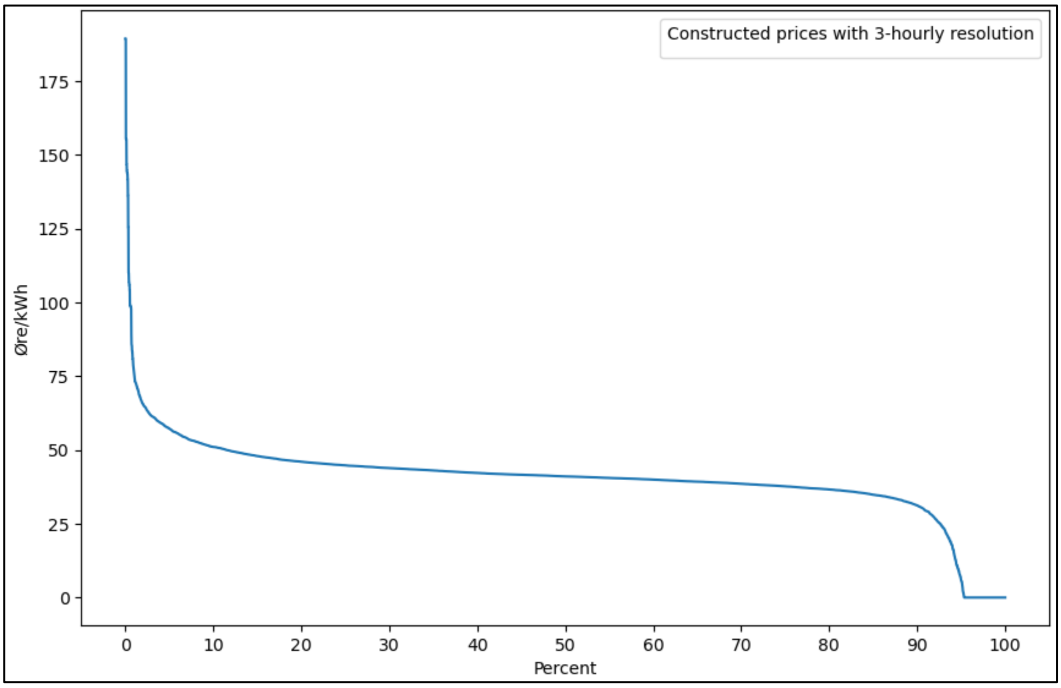


Figure 10: Duration plot of the prices used for the Aura and Surna case studies.

3.3 Environmental metrics

3.3.1 Environmental considerations in the Aura system

The Aura River hydropower regulations (Aurareguleringene) were recently subject to environmental re-licensing. The hydropower system consists of a series of brook intakes and pressure tunnels leading to Aursjøen reservoir, and a subsequent pressure tunnel from Aursjøen via two lower reservoirs before Aura hydropower plant near Sunndalsfjorden, approx. 30 km north of Aursjøen (Figure 11, see also Section 3.1). The relicensing documents highlight salmon and sea trout as important environmental values in the Aura River. Prior to hydropower development in the Aura catchment, salmon and sea trout could migrate approx. 9 km upstream from lake Litlevatnet. Today, low flow due to water abstractions for hydropower creates physical migration barriers approx. 2 km upstream from lake Litlevatnet, i.e., approx. 7 km of river is now unavailable to salmon and sea trout in since the hydropower was built.

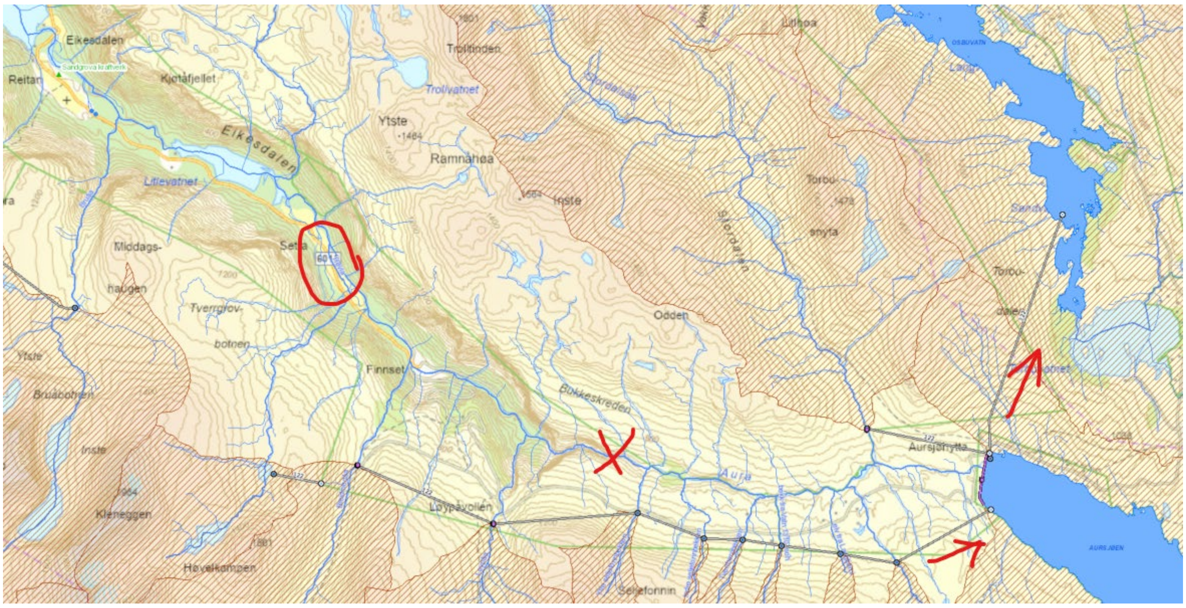


Figure 11. Arrows: Stored water is transferred from brook intakes, via lake Aursjøen and further north towards Aura hydropower plant. X: natural salmon and sea trout migration stop before HP development. Circle: low flow creates physical migration barriers in this area today.

3.3.2 Relationship between flow and salmon production in river Aura

In the recent environmental relicensing process for the Aura regulation, the Norwegian Water Resources and Energy Directorate (NVE) recommended that River Aura should not get a licenced minimum flow requirement. Their reasoning was that there was "high uncertainty regarding the minimum flow required to attain significant improvement of the conditions for anadromous fish in Aura", and that "the production loss would be high" for the considered minimum flow alternatives (directly translated). The Ministry of Petroleum and Energy followed NVE advice and did not sanction a minimum flow.

When deliberating the feasibility of different environmental parameters in river Aura, we found that most of the available information from the system were on the Atlantic salmon and trout populations. We chose to follow up on the method used by NINA in a report on the effects of different minimum flow constraints on salmon in river Aura [73], hereafter referred to as "NINA report 1324". In this report, the smolt production potential in the anadromous part of Aura was estimated for five different scenarios of water release originally described by Statkraft, the HPP owner. Figure 12 shows the main steps in the method. We replicated the method for our case study flow releases.

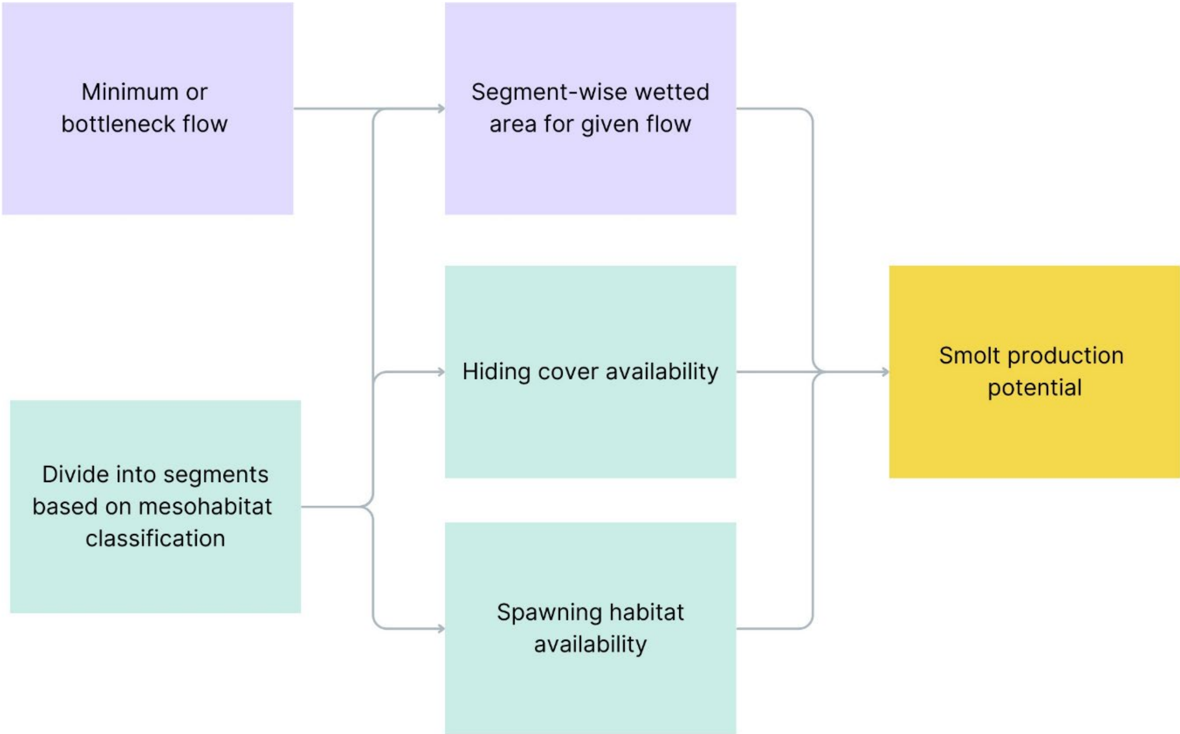


Figure 12. Steps in the smolt production potential calculation method.

<u>**Minimum or bottleneck flow**</u>
In NINA report 1324 the 25-percentile for summer flow at Litlevatn was uses as a reference point for calculations of smolt production potential. These hydrological data was based on calculations made by Statkraft. Release of a minimum flow at Aursjø dam is included in cases A3 and A4, while there is no minimum flow in cases A1 and A2 (Table 7).

Table 7. Flow releases in the different cases. Flow at Litlevatn gauging station consists of minimum flow released from lake Aursjøen (if applicable) and flow from remaining unregulated parts of the catchment area (residual flow). Hydrological bottlenecks are the 25-percentile summer flow as well as the minimum week-averaged winter flow, from NINA report 1324 (p. 21).

SUMMER	Case A1 & A2	Case A3	Case A4 (A220)
Minimum flow from Aursjøen	0 m^3/s	1 m^3/s	6.37 m^3/s
25-percentile flow at Litlevatn	3.35 m^3/s	4.35 m^3/s	9.72 m^3/s
WINTER			
Minimum flow from Aursjøen	0 m^3/s	1 m^3/s	0.91 m^3/s
Min. week-averaged flow at Litlevatn	0.3 m^3/s	1.3 m^3/s	1.2 m^3/s

<u>**River segments**</u>
In NINA report 1324, the stretch between Eikesdalsvatnet and the salmon migration barrier at Per Nilsspranget was classified into 13 segments using the mesohabitat classification system of Environmental Design [11].

<u>**Segment-wise flow-wetted area relationship**</u>
Formulas for the relationship between wetted area and streamflow for each of the 13 segments in the NINA report 1324 was provided by Torbjørn Forseth (pers.comm.).

Hiding cover and spawning habitat

In NINA report 1324, the habitat suitability for salmon spawning and rearing in each segment was assessed by sampling dominant and sub-dominant substrate as well as weighted hiding cover availability, both classified according to the method of Environmental design [11]. From the habitat mapping, productivity classes *low*, *intermediate*, or *high* were assigned (Table 8). These correspond to standard intervals of expected smolt production per 100 m^2. These are assumed to be valid still.

Smolt production potential

The Environmental Design method has found standard smolt density values for the three habitat classes (Table 8). However, as hydropower regulation imposes additional bottlenecks on recruitment, two corrections were made in NINA report 1324:

1. Reduction of smolt density proportional to the reduction of flow during critical hydrological bottlenecks **in summer** before vs. after hydropower-regulation for each case.
2. Reduction of smolt density proportional to the reduction of flow during critical hydrological bottlenecks **in winter** before vs. after hydropower-regulation for each case.

The underlying assumption of these correction factors is that salmon smolt production is reduced proportionally with reduction in wetted area.

It is important to note that NINA report 1324 also concluded that habitat measures in addition to a minimum flow regime would be necessary to reestablish the salmon population "*To obtain natural salmon recruitment for the whole of River Aura, physical mitigation measures are necessary to ensure successful upstream migration under all discharge regimes. Moreover, extensive habitat measures are recommended on a c. 700 m long river stretch where the water submerge in the riverbed at low discharge*.»

Table 8. Standard density per productivity class assigned to the 13 river segments (baseline before correction).

Segment	Productivity	Standard density [11] [smolt/100 m²]	
		min	max
1	intermediate	5	9
2	high	7	13
3	high	7	13
4	low	2	4
5	high	7	13
6	intermediate	5	9
7	high	7	13
8	intermediate	5	9
9	intermediate	5	9
10	high	7	13
11	high	7	13
12	high	7	13
13	intermediate	5	9

Table 9. Correction factors for smolt density (bottlenecks).

SUMMER	Case 1 & 2	Case 3	Case 4 (A220)
Wetted area at 25-percentile flow before regulation		391 294 m^2	
Wetted area at 25-percentile flow in the case	263 958 m^2	281 185 m^2	334 207 m^2
Reduction in wetted area	33%	28%	15%
WINTER			
Wetted area at min. week-averaged flow before regulation		184 886 m^2	
Wetted area at min. week-averaged flow in the case	104 831 m^2	201 532 m^2	196 801 m^2
Reduction in wetted area	43%	No reduction	No reduction

3.3.3 Environmental considerations in the Surna river system

Hydropower regulations concerning Surna river (Folla-Vinddølareguleringen) was also recently subject to environmental license revision (final decision in 2021). The system contains of a series of brook and lake intakes leading water to the reservoirs of lake Gråsjø and lake Follsjø before it is used at Trollheim hydropower plant (Figure 13, see also Section 3.1). The new environmental license requires minimum flow release in the side rivers Bulu and Rinna, but not in the side rivers Vinddøla and Folda. The Norwegian Water Resources and Energy Directorate (NVE) recommended a minimum flow release in the side rivers Rinna and Bulu, as well as a strict ramping constraint at the hydropower plant. Loosely translated, the NVE recommended to discourage "*peaking operations at Trollheim HPP during daytime in the winter when discharge at Skjermo is below 50 m^3/s. The down-ramping rate should not exceed 5 cm/h when the discharge is below 50 m^3/s.*" Instead, the ramping constraints in the relicensing followed the self-inflicted restraints Statkraft had set earlier (Section 3.1).

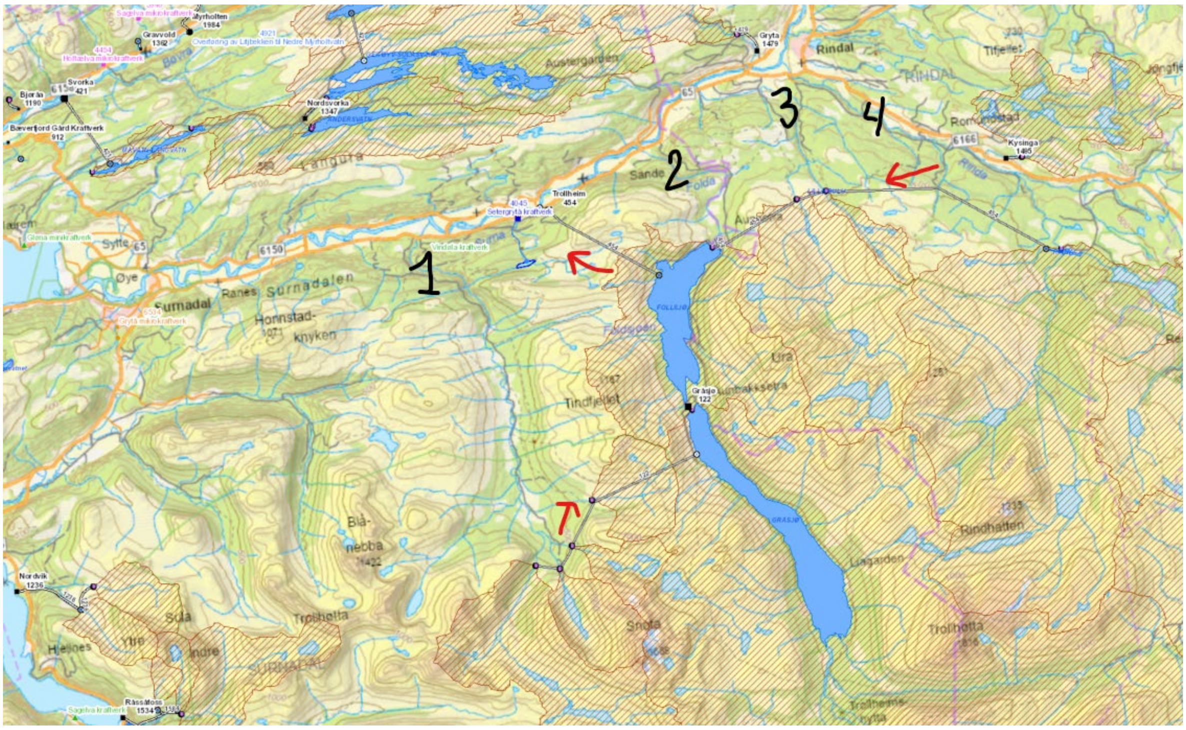


Figure 13. Side rivers Vinddøla (1), Folda (2), Bulu (3) and Rinna (4) experience reduced flow due to HP development. Water from high up in these side catchments is diverted to the Gråsjø and Follsjø reservoirs and then to Trollheim hydropower plant (arrows show direction).

Surna is one of Norway's designated national salmon rivers. In favourable years, salmon can migrate the main river all the way up to Lake Lomundsjø (Figure 14), corresponding to approx. 56 km river length. Several of the side rivers also have or have had viable salmon and sea trout populations. There are remnant populations of freshwater pearl mussel in Surna.

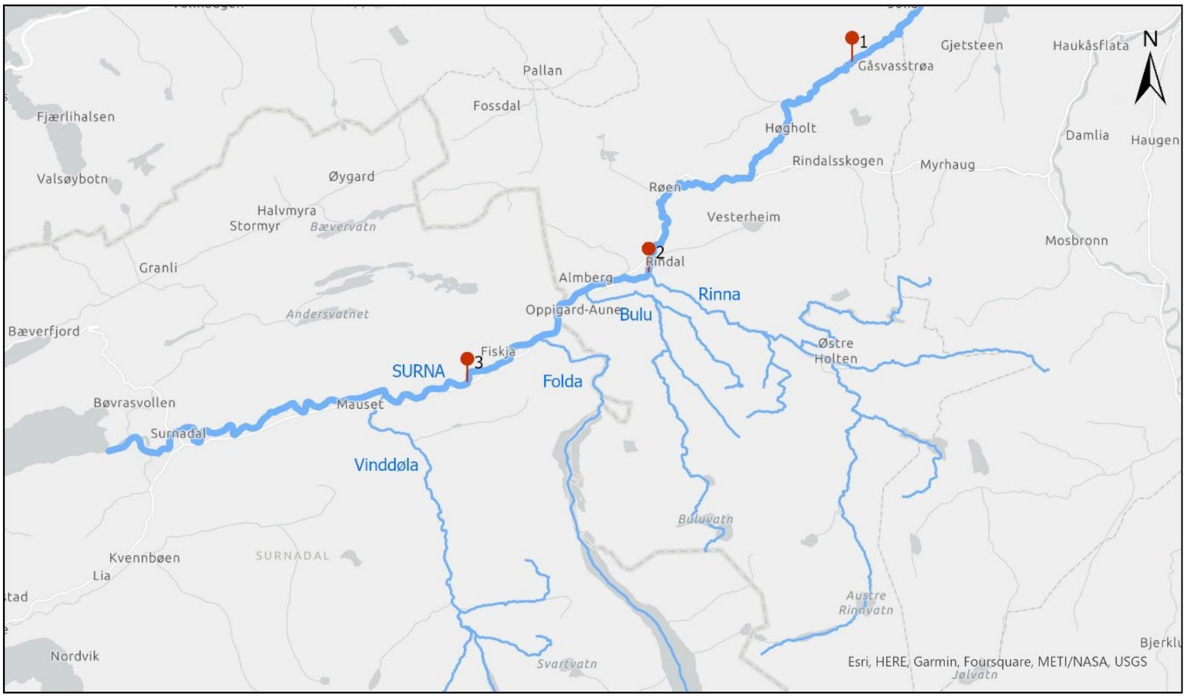


Figure 14. Surna river (thick blue, direction northeast to west) and the most important hydropower-affected side rivers Vinddøla, Folda, Bulu and Rinna. Salmon can migrate all the way up to Lake Lomundsjø (1) in favourable years. Surna is not affected by hydropower regulations above

the confluence of river Rinna (2). Diverted water from the highlighted side rivers meet Surna at the outlet of Trollheim power plant (3).

3.3.4 Relationship between flow and salmon production in river Surna

Due to most data in this system being on the salmon population we will also use the Surna case study for salmon as an environmental metric. For practical reasons, we limit the scope of the analysis to the lowermost parts of the main river, i.e., the part that is affected by hydropower regulations. This part can be divided in two: 1) the residual flow segment between the confluence with Rinna and the HP outlet, and 2) the segment from the HP outlet to the fjord.

As hydropeaking is an important part of the Surna simulation cases, we decided to use the EnviPEAK classification system of hydropeaking impact on salmon as the environmental metric (Table 10). Surna has actually been one of the case study rivers in the development of the EnviPEAK classification system [30], meaning we could to some degree use to compare our results with previous analyses. We chose to ignore the biological vulnerability factors due to uncertainty surrounding their responses in simulated case studies.

Table 10. The EnviPEAK classification system.

Hydromorphological parameters	Value range
E1: Rate of change	1-4
E2: Dewatered area	1-4
E3: Magnitude of flow changes	1-4
E4: Frequency	1-4
E5: Distribution	1-4
E6: Timing	1-4
Vulnerability factors	**Value range**
V1: Effective population size	1-3
V2: Degree of limitations in recruitment	1-3
V3: Low flow periods as bottleneck for fish stock size	1-3
V4: Habitat degradation	1-3
V5: Reduced water temperatures that lead to population effects	1-3
V6: Other factors	1-3
V7: Percentage of impacted river length compared to total length	1-3

How much of river Surna is affected by hydropeaking?

Several of the hydro-morphological effect factors require pinpointing which part of the river that is exposed to hydropeaking. There are no lakes or other physical structures that could lead to significant dampening of the hydropeaking wave in the stretch from the HP outlet to river Surna's outlet into the fjord. This was also found in hydraulic modelling trials (Figure 16). We therefore consider the whole river downstream from the HP outlet as affected by hydropeaking. According to Surna centerlines in NVE's ELVIS database and GIS measurements this stretch is 23,9 km long (Figure 15).

Figure 15. The almost 24 km long hydropeaking-affected stretch of river Surna.

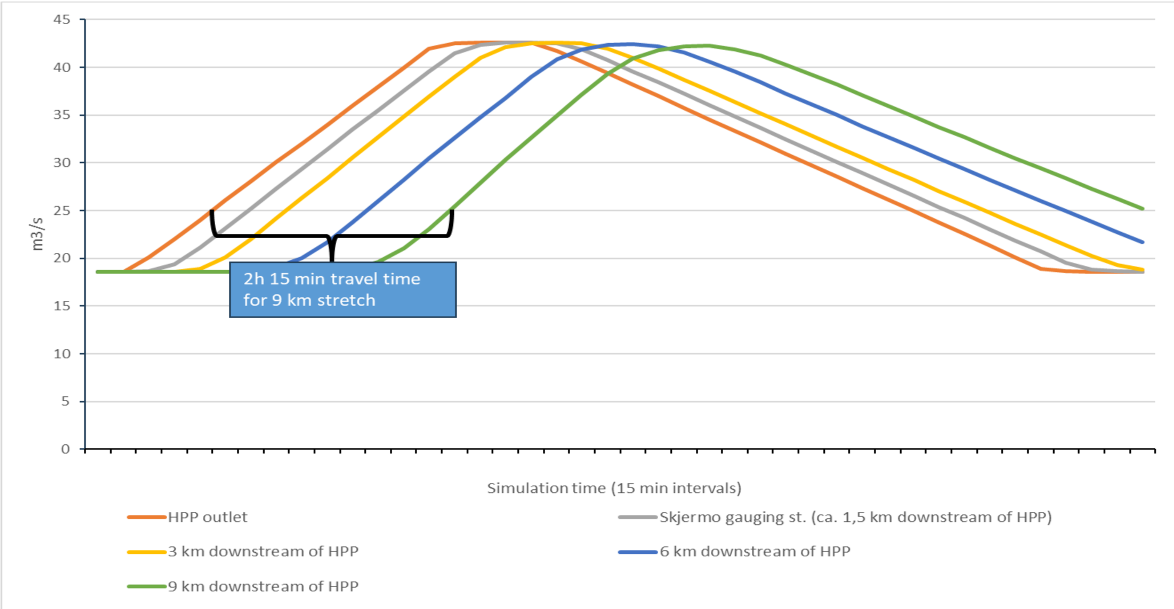


Figure 16. Hec Ras hydraulic modelling of a hypothetical hydropeaking wave. Transects sampled from 0-9 km from the HPP outlet shows that the wave form is conserved.

E1 Rate of change

Rate of change should be calculated from representative locations in the affected part of the river [30]. In practice, there is only one gauging station, i.e., only one point in which relevant data is gathered, which is at Skjermo. Rate of change for Case S1 was calculated for the simulated time series of flow at Skjermo 1958-2015. The simulated time series has a 3-hour resolution, while the authors of the classification system recommend a resolution of 1h or finer. Discharge was back-calculated to stages using the Q-H formula of the stage-flow hydrograph from Skjermo gauging station[2], and the change values between two consecutive steps were sorted from lowest (most extreme down-ramping) to highest (most extreme up-ramping). In between the extremes, there will also be natural flow changes, for instance when the hydropower-plant is not running. The system developers recommend not to use the most extreme rate of change in a time-series, but rather the 90-percentile for assessment of E1. To separate hydropeaking rate of change from natural rate of change, we set the definition baseline for hydropeaking operations at changes > 5 cm/h. The 90-percentile value of 20.7 cm/h was therefore taken from the subset of down-ramping rates that exceeded 5 cm/h (Figure 17). This corresponds to a “very large” rate of change in the classification system (Table 11).

[2] https://sildre.nve.no/station/112.27.0

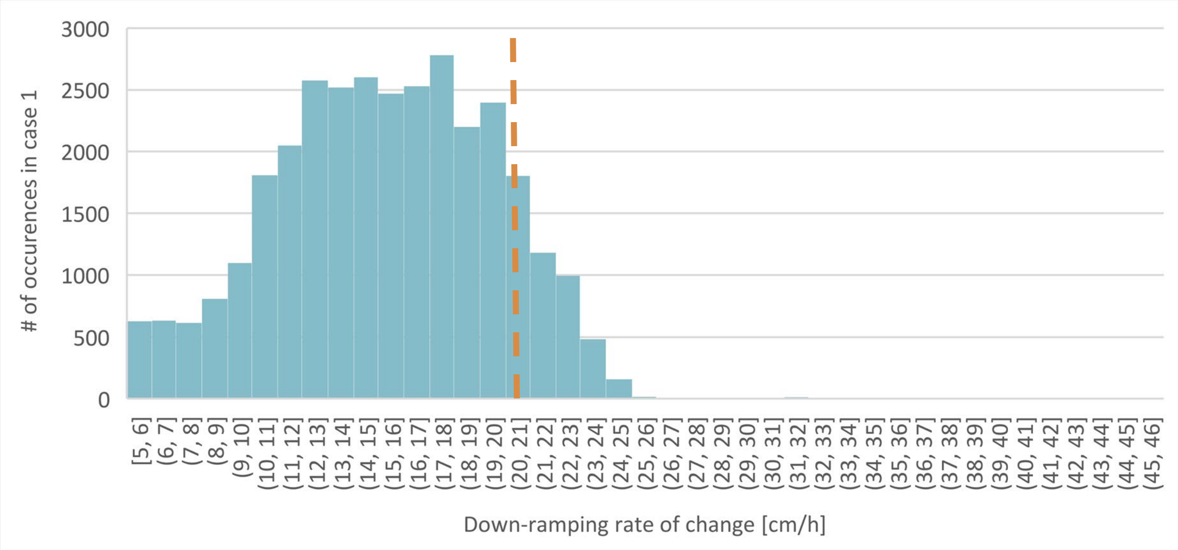


Figure 17. The down-ramping rate that is considered hydropeaking in case 1. The dashed line indicates the 90-percentile value used for rate of change.

For the other cases, the maximum rate of change is explicitly stated in the case descriptions. In Case S2 and Case S3, the rate of change is allowed to vary between 5-13 cm/h, depending on the time of year. This corresponds to the effect category "moderate" rate of change. In Case S4, the rate of change is stated in the case definition as no more than 5 cm/h. This will per definition be in the "small" rate of change category in the EnviPEAK system [30].

Table 11. E1 rate of change for the different cases and corresponding category.

	Rate of change	E1 category	E1 score
Case 1	20.7 cm/h	Very large	4
Case 2	5-13 cm/h	Moderate	2
Case 3	5-13 cm/h	Moderate	2
Case 4	<5 cm/h	Small	1

E2 Dewatered area

The flow-wetted area relationship for approx. 24 km stretch from the HPP outlet to the road 65 bridge in Surnadal city centre was calculated using Hec Ras 2D hydraulic modelling (Table 12). We did not use true bathymetry, but rather a red laser Lidar DTM from the national elevation model of Norway (hoydedata.no). Red laser does not penetrate the water surface; hence the "bathymetry" is rather a representation of the water surface. This source of error is, however, consistent among all the simulated constant flows.

Table 12. Hydraulic modelling simulation parameters.

Parameter	Value	Unit
Terrain	NDH Surnadal-Rindal 2pkt 2016	NN2000 terrain elevations
Computational mesh cell size	4	m
Manning's n (constant	0.04	
Upstream boundary condition	Constant flow: 3 7 15 30 70	m^3/s
Downstream boundary condition	Stage height (ocean level): 0	m.asl.
Computational mode	Diffusion wave	

For calculation of wetted area per flow scenario, we used the "inundation boundary" optional output with a depth tolerance of 0.05 m (i.e., areas shallower than 5 cm are not considered inundated). This gave a logarithmic flow-area relationship that is assumed to hold also for flows < $3 m^3/s$ and > $70 m^3/s$ (Figure 18).

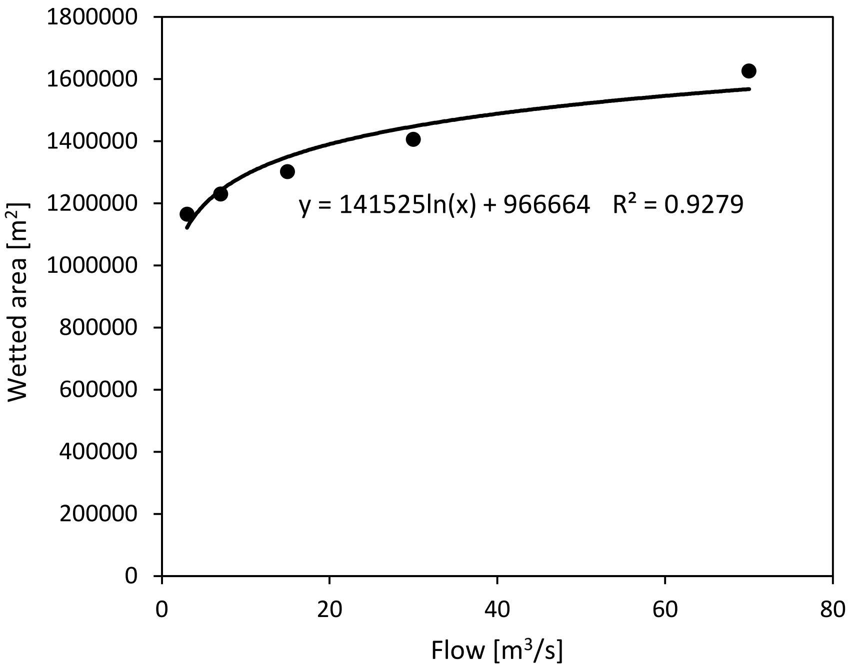


Figure 18. Modelled relationship between flow and wetted area for the hydropeaking-affected stretch downstream of Trollheim HPP.

What are Q_{max} and Q_{min} for the different cases?

The E2 effect factor "dewatered area" corresponds to the wetted area change between the situation with hydropower production (Q_{max}) and the situation with minimum flow or natural base flow (Q_{min})[30]. For cases S2-S4, the minimum flow, i.e., Q_{min} is 15 m^3/s at Skjermo. For Case S1, the 95-percentile flow at Skjermo over all ProdRisk simulation results was used. The HPP maximum capacity is 38 m^3/s for all cases, and with an assumed base flow of at least 1-2 m^3/s from upstream of Trollheim HPP, 40 m^3/s may be an appropriate Q_{max} for all simulated cases.

Table 13. Minimum and maximum flow and corresponding wetted area (WA). E2 and E3 are calculated based on these numbers.

	Q_{min}	Q_{max}	WA_{min}	WA_{max}	E2. Dewatered area	E3. Flow ratio
Case 1	1.5 m^3/s	40 m^3/s	1 024 047 m^2	1 488 733 m^2	31 %	27
Case 2	15 m^3/s	40 m^3/s	1 349 921 m^2	1 488 733 m^2	9 %	2.7
Case 3	15 m^3/s	40 m^3/s	1 349 921 m^2	1 488 733 m^2	9 %	2.7
Case 4	15 m^3/s	40 m^3/s	1 349 921 m^2	1 488 733 m^2	9 %	2.7

E4. Hydropeaking frequency

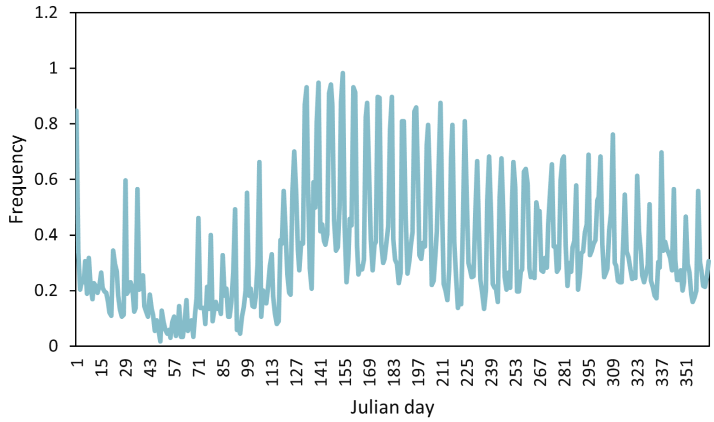
For frequency, we counted the number of days in the simulated cases with down-ramping or up-ramping episodes where the rate of change was > 5 cm/h as hydropeaking episodes. For cases S2 and S3, there are defined periods in which hydropeaking can occur that sets the maximum number of days; down-ramping of > 5 cm/h is not allowed to occur in daytime during winter in both cases S2 and S3. There are a total of 30 weeks (week 11 through 40), i.e., 210 days, where ramping > 5 cm/h are allowed to occur regardless of night and day, while, for simplification, the constraint of 5 cm/h was set to apply for both day and night during week 1-10 and 41-52 (Table 4). The production model did however predict that abrupt flow changes would occur on average only 143 and 139 days in Case S2 and Case S3, respectively (Table 14).

Table 14. Effect factor E4 hydropeaking frequency.

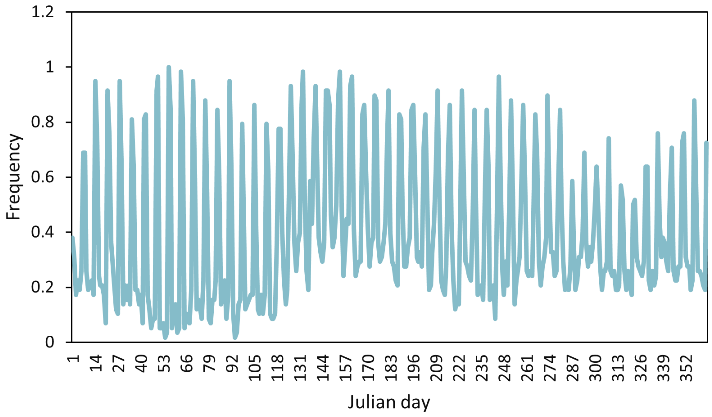
	# days with hydropeaking	E4 category	E4 score
Case 1	124	Large	3
Case 2	143	Large	3
Case 3	139	Large	3
Case 4	0	Small	1

E5. Distribution of hydropeaking events throughout the year

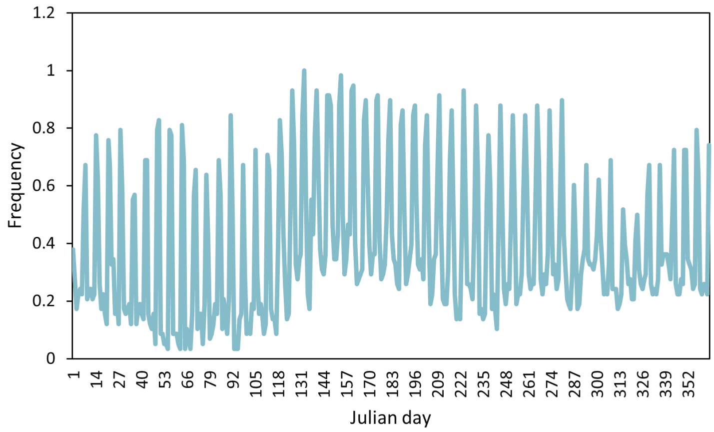
The distribution effect factor describes whether hydropeaking occurs in patterns throughout the year. For the simulated Case S1, with no environmental constraints, there is no consistent pattern in what time of year flow changes corresponding to > 5 cm/h occurs, but generally, there are a few periods in the beginning of the year when rapid flow changes seem to appear less frequent (Figure 19). We therefore classify Case S1 as "irregular in certain periods" (Table 15). It is the same for Case S2 and Case S3 as there are weeks in the winter without ramping rates > 5 cm/h in the simplified constraint for the model. For Case S4, there is no hydropeaking, so the effect is at the bottom end of the scale, i.e., "small" effect.



S1



S2



S3

Figure 19. Frequency of hydropeaking episodes on a given day of the year 1958-2015 for cases S1, S2 and S3.

Table 15. E5 Distribution of hydropeaking events.

	Distribution of hydropeaking	E5 category	E5 score
Case S1	Irregular in certain periods	Large	3
Case S2	Irregular in certain periods	Large	3
Case S3	Irregular in certain periods	Large	3
Case S4	No hydropeaking	Small	1

E6. Timing of hydropeaking

The last hydro-morphological effect factor concerns whether hydropeaking occurs in especially vulnerable periods for salmonid fish. There are no constraints on case 1, where hydropeaking can occur even in daylight during winter, which is considered the most severe period [17]. For Case S2 and Case S3, our simplified constraints make hydropeaking allowed during summer and fall, but not in darkness in winter. If we followed the constraints in the licence 100%, "in darkness in winter" would be the most severe category for Case S2 and Case S3, but instead we have used the same constraints as in the flexibility model to ensure comparability.

Table 16. Timing of hydropeaking events.

	Timing of hydropeaking	E5 category	E5 score
Case S1	In daylight in winter	Very large	4
Case S2	Summer and fall (in darkness in winter)	Moderate	2
Case S3	Summer and fall (in darkness in winter)	Moderate	2
Case S4	No hydropeaking	Small	1

4 Results

4.1 Aura

4.1.1 Equivalent electricity storage

The parameters for the equivalent electricity storage for the Aura cases described in Table 2, relative to Case A1, are shown in Table 17. For Case A3 relative to Case A1, the equivalent storage size is 11% of the total storage for Aura in GWh, which is 1413.84 GWh. The capacity of that equivalent storage is 64% of the maximum production for Aura, which is 310 MW. It would take 812.42 hours to empty the equivalent electricity storage. However, the yearly flexibility loss that the environmental constraint inflicts on the system is negative, meaning that the total lost revenue of the system with the constraint, compared to the system without the constraint, is smaller than the average production loss times the price of that time step. A negative loss in Case A3, or in fact a positive change, indicates that the flexibility is increased with the introduction of the constraint. So, for Case A3, the net yearly flexibility income of the system increases with an income that is 0.07% of the yearly income for the unconstrained case. For Case A4 relative to Case A1, the equivalent storage size is 19% of the total storage for Aura in GWh. The capacity of the equivalent storage is 96% of the maximum production for Aura. For Case A4, the net yearly flexibility loss is positive, indicating that the constraints have reduced the flexibility of the system, which could be expected with the introduction of the environmental constraint. The flexibility loss is 0.05% of the yearly income for the unconstrained case. Figure 20, Figure 21, and Figure 22 show the reservoir operation for the biggest reservoir in the system, Aursjøen, for cases A1/A2, A3 and A4. Figure 23 and Figure 24 show the equivalent electricity storage size for cases A3 and A4 when the 58 scenarios are parallelised, and the balancing energy and net yearly flexibility loss are calculated for each scenario.

Table 17: Parameters for the equivalent electricity storage

Case	Storage Size [GWh]	Capacity [MW]	Utilization time [h]	Net yearly flexibility loss [MNOK]
A2	NA	NA	NA	NA
A3	161.20	198.42	812.42	-0.46
A4	267.36	296.56	901.54	0.38

4.1.2 Flexibility factor and change in power production

The flexibility factors for the Aura cases are shown in Table 18, using the definitions of the flexibility factor in Section 2.1.1. The average price is 0.4044631 NOK/kWh. The change in power production relative to Case A1 are shown in the same table. We see that the flexibility factor increases from Case A1/A2 to Case A3, and again to Case A4. However, we also see that there is less power produced. Indeed, in Case A3, the loss is 3.7% of the total production for Aura in the unconstrained case, and in Case A4, the loss is 10.2% of the total production for Aura in the unconstrained case.

Table 18: Flexibility factors and change in power production for the Aura cases.

Case	Yearly produced energy [GWh]	Yearly income [MNOK]	Reservoir difference (start-end) [GWh]	Flexibility factor	Change in power production [GWh]
A1	1605.3	694.9	-4.9	1.070	0
A2	1605.3	694.9	-4.9	1.070	0
A3	1546.4	672.3	-5.6	1.075	-58.9
A4	1441.9	629.9	-5.9	1.080	-163.4

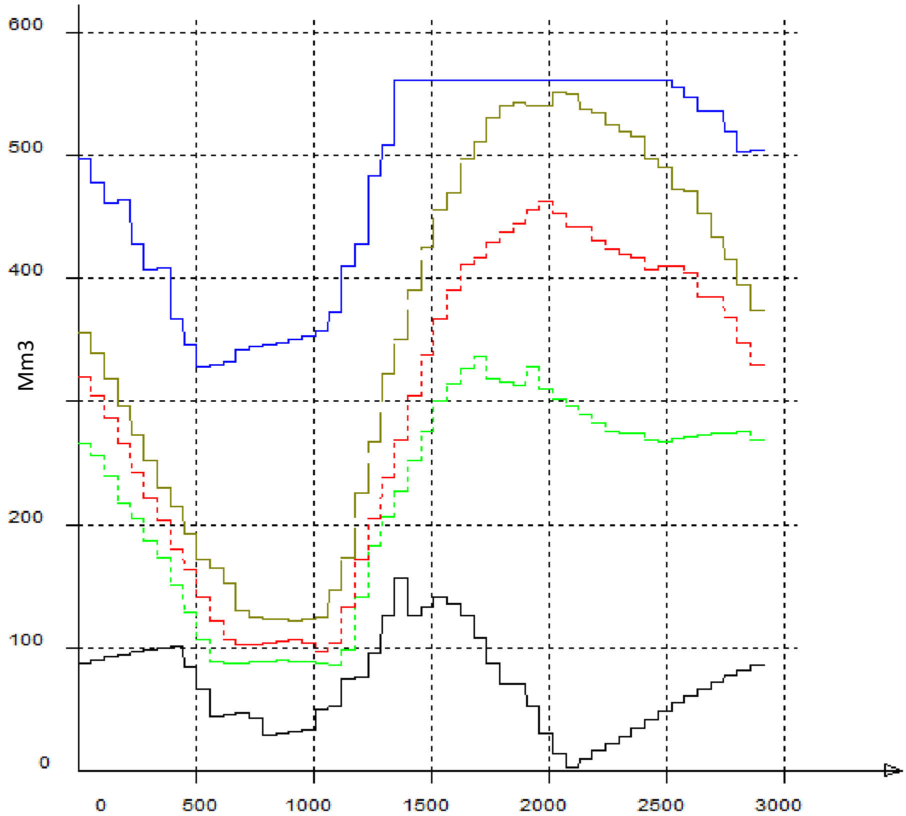


Figure 20: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Aursjøen, plotted over one year, for Case A1/A2. The quantiles are calculated based on all 58 scenarios.

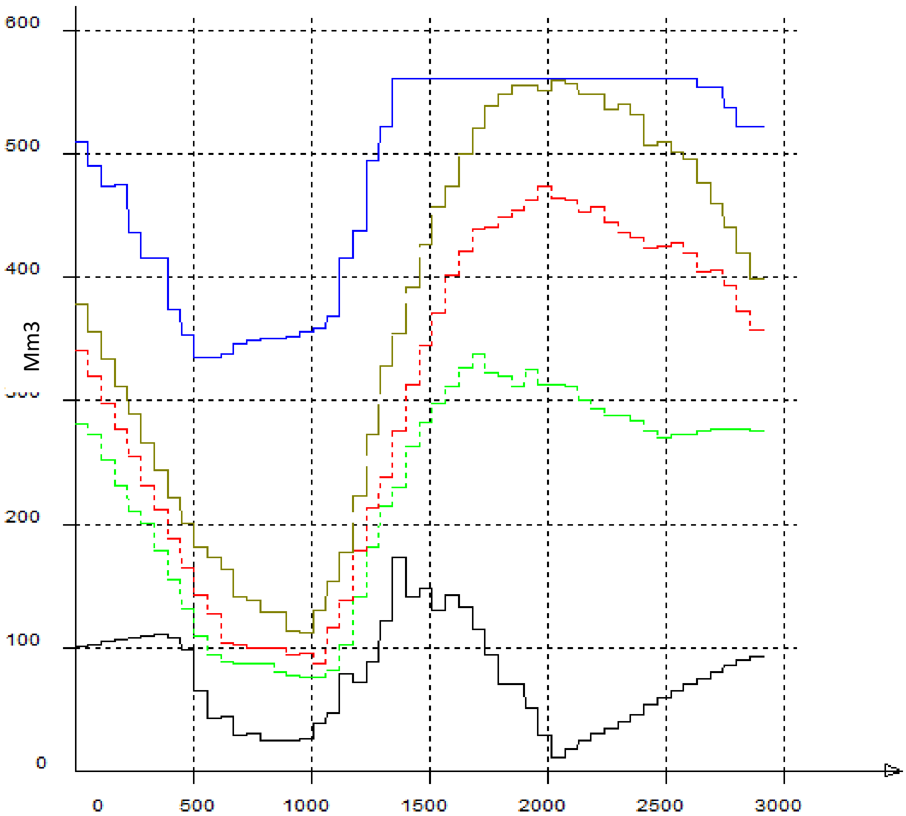


Figure 21: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Aursjøen, in Mm3 plotted over one year, for Case A3. The quantiles are calculated based on all 58 scenarios.

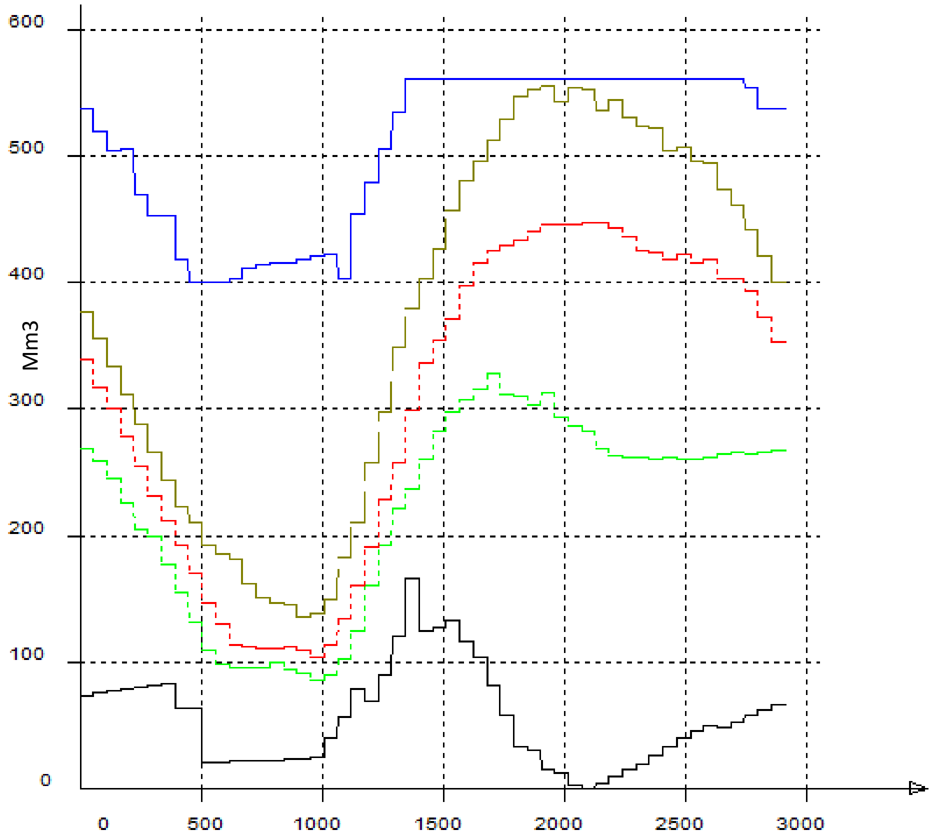


Figure 22: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Aursjøen, in Mm3 plotted over one year, for Case A4. The quantiles are calculated based on all 58 scenarios.

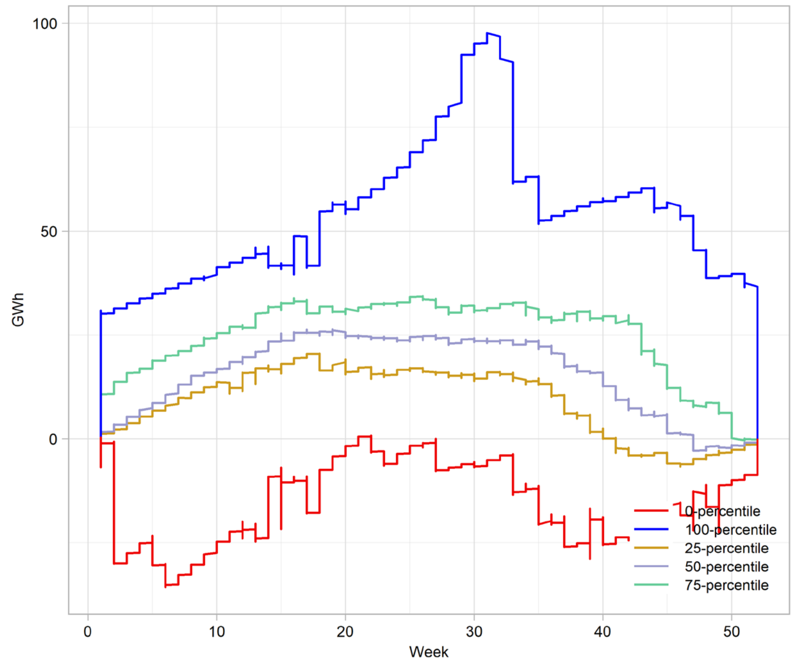


Figure 23: The percentiles of the balancing energy across the 58 scenarios in Aura Case 3. The average storage size across the scenarios is 47.196GWh while the maximum storage size is 117.033GWh. The maximum flexibility loss is 6.362MNOK, the minimum flexibility loss is -5.489MNOK and average flexibility loss is -0.029 MNOK.

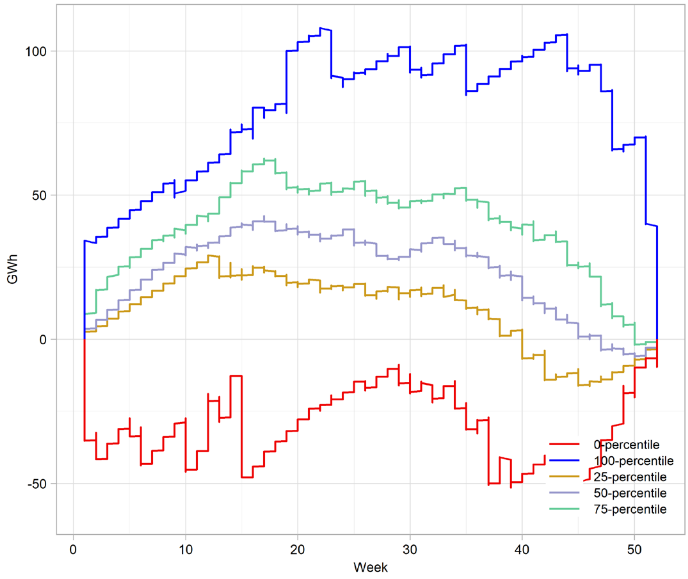


Figure 24: The percentiles of the balancing energy across the 58 scenarios in Aura Case 4. The average storage size across the scenarios is 80.169GWh while the maximum storage size is 125.471GWh. The maximum flexibility loss is 19.669MNOK, the minimum flexibility loss is -27.201MNOK and average flexibility loss is -0.657MNOK.

4.1.3 Smolt production

With only the residual flow (Case 1-2) in Aura, habitat productivity and hydrological bottlenecks during summer and especially winter will lead to an expected smolt production of at least 6176 individuals. For comparison, the minimum smolt production potential is expected to be at least the double with the release of a minimum flow from lake Aursjøen (Case A3 and A4) (Table 19). Note that there is considerable uncertainty in the calculated numbers of smolt production and the important result is the difference between the cases.

Table 19. Calculated minimum and maximum smolt production potential for the different cases.

	Minimum smolt production potential	Maximum smolt production potential
Case 1	6 176	11317
Case 2	6 176	11317
Case 3	12 405	22731
Case 4 (A220)	17 412	31904

4.1.4 Discussion

The smolt production is scaled with the unconstrained Case A1 as the worst option and the best-case scenario when allowing power production in the same hydropower system, Case A4, as the best option. Case A3 is somewhere in between. This result is as expected since smolt production should increase with the flow release, and the suggested release of water in case 3 was higher than cases A1 and A2, but lower than Case A4 (Table 7).

For all Aura cases, we introduce a bypass constraint only, using a constant flat constraint in Case A3 and a time-dependent and stricter constraint in Case A4. The flexibility factor indicates that the progressing constraint increases the flexibility, as the number increases. Constraints of type minimum discharge or minimum bypass will remove water from the system and will tend to increase the water values, or value of storing water. This will cause the strategy to be more careful with maximum discharge, which in turn very often will lead to a higher flexibility factor. We have a lower chance of spillage if there is a bypass. However, this increased flexibility factor must be balanced with the change in power production as explained in Section 2.1.3. Here, we see that the progressive bypass constraint diminishes the change in power production: We lose produced power due to the constraint. As the bypass is inflicted on the upper reservoir in the system, the loss of water from Aursjøen will have a high energy equivalent relative to the ocean. The power loss of Case A4 is approximately 10% of the total production of the Aura system, and therefore a considerable size. The net yearly flexibility income is zero in the unconstrained case, and for the constrained cases, the value relative to the yearly income of the total system is used. Here we notice that Case A3 causes a negative net yearly flexibility loss or a positive net yearly flexibility income for the system, and Case A4 causes a net yearly flexibility loss for the system. For Case A3, this corresponds to the positive change in flexibility factor, indicating that the case has indeed a positive effect on the flexibility of the system. The loss in power production of approximately 4% is the cost of an increased smolt production. Or, likewise, the reduction in smolt production from Case A4 to Case A3 is the price of the increased power production from Case A4 to Case A3. Case A1/A2 gives the maximum power production, but a reduced flexibility compared to cases A3 and A4 and also a considerably reduced smolt production.

4.1.5 Graphical illustration with all parameters included

To be able to plot all parameters on the same axes, the resulting values for the net yearly flexibility income, flexibility factor, power production and smolt production have been scaled with a set minimum and maximum value. To be able to compare cases with each other, it would be advantageous to use the same minimum and maximum flexibility factor.

The flexibility factor has been scaled with a minimum value of 1.0 and a maximum value of 1.1, as this scale covers both the Aura and the Surna cases and is still fine grained enough to show the difference between the two. The power production is percentage wise relative to the power production of the unconstrained case, and thus has a maximum of 100. We choose a minimum of 75, as a more extensive production loss is less relevant for realistic cases. The smolt production uses the value for the unconstrained case as the minimum value, and the value for the ideal case as the maximum value. The net yearly flexibility income is here relative to the total revenue of the unconstrained case. In order to more clearly see the variation in the flexibility between the different cases, the limitations for the scaling are adapted to the case. The flexibility factor and power production can use general scales, but the smolt production and the net yearly flexibility income are case specific, so universal scaling will not make sense.

All parameters that are included in the spider chart for the Aura cases are shown in Table 20, and the spider chart is shown in Figure 25.

Table 20: Parameter values for the Aura cases. The unscaled change in power production and net yearly flexibility income are percentages relative to the total yearly production and income in Aura.

	Scaled values					Unscaled values		
	A1/A2	A3	A4	Min	Max	A1/A2	A3	A4
Flexibility factor	0.7	0.75	0.8	1	1.1	1.07	1.075	1.08
Power production	0	0.85	0.59	75	100	100	96.33	89.82
Smolt production	0	0.55	1	6176	17412	6176	12405	17412
Net yearly flexibility income	0.5	0.85	0.25	-0.1	0.1	0	0.07	-0.05

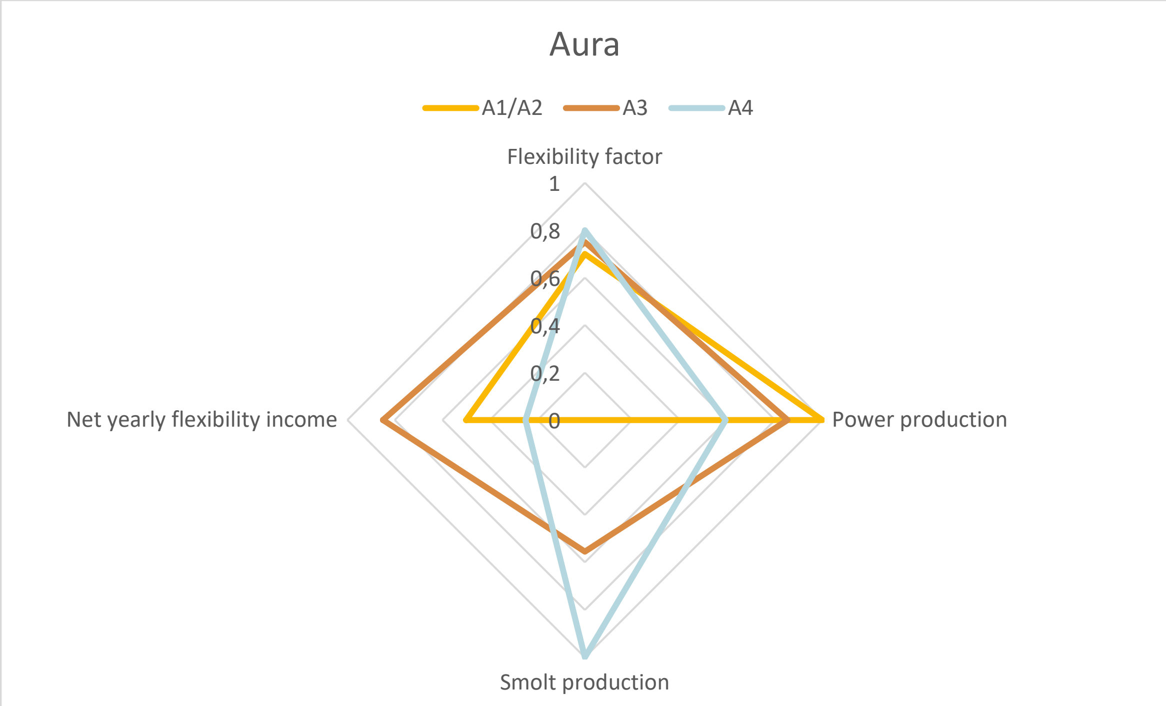


Figure 25: Graphical illustration of the sustainable flexibility parameter values for the Aura cases.

4.2 Surna

4.2.1 Equivalent electricity storage

The parameters for the equivalent electricity storage for the Surna cases described in Table 2, relative to Case S1, are shown in Table 21. For Case S2 relative to Case S1, the equivalent storage size is 27% of the total storage for Surna in GWh, which is 393.0 GWh. The capacity of that equivalent storage is 65% of the maximum production for Surna, which is 143.3 MW. The storage size increases for cases S3 and S4 to 36.1% and 37.7%, respectively of the total storage for Surna in GWh, as well as the capacities for cases S3 and S4, which are 69.5% and 70.6%, respectively of the total capacity for Surna in MW. The net yearly flexibility loss for Surna with the constraints in Cases S2, S3 and S4 increases with the introduction of new constraints, however only slightly from Case S2, with 1.041% of the total yearly income in the unconstrained case, to Case S3, with 1.044% of the total yearly income of the unconstrained case, and noticeably from Case S3 to Case S4, with 1.44% of the total yearly income of the unconstrained case. The constant, strict ramping constraint appears to influence the flexibility of the system severely, and the bypass constraint does not appear to reduce the flexibility much.

Figure 26, Figure 27, Figure 28, and Figure 29 show the reservoir operation for the biggest reservoir in the system, Trollheim, for cases S1, S2, S3 and S4. Figure 30, Figure 31 and Figure 32 show the equivalent electricity storage size for cases S2, S3 and S4 when the 58 scenarios are parallelized, and the balancing energy and net yearly flexibility loss are calculated for each scenario.

Table 21: Parameters for the equivalent electricity storage

Case	Storage Size [GWh]	Capacity [MW]	Utilization time [h]	Net yearly flexibility loss [MNOK]
S2	105.92	92.58	1144.09	3.81
S3	141.74	99.63	1422.66	3.82
S4	148.32	101.13	1466.63	5.26

4.2.2 Flexibility factor and change in power production

The flexibility factors for the Surna cases are shown in Table 22, using the definitions of the flexibility factor in Section 2.1.1. The average price is 0.4044631 NOK/kWh. The change in power production relative to Case S1 are shown in the same table. We see that the flexibility factor decreases from Case S1 to Case S2, and again to Case S3. From Case S3 to Case S4 we see an increase in the flexibility factor, indicating a higher flexibility in Case S3 than in Case S2. However, we also see that there is less power produced in Case S4 than in Case S3. The loss in Case S2 relative to Case S1 is only 0.07% of the production for Surna in the unconstrained case. The loss in Case S3 has increased to 3.26% of the production for Surna in the unconstrained case, and the loss in Case S4 is 3.30% of the production for Surna in the unconstrained case.

Table 22: Flexibility factors and change in power production for the Surna cases.

Case	Yearly Produced energy [GWh]	Yearly Income [MNOK]	Reservoir difference (start-end) [GWh]	Flexibility factor	Change in power production [GWh]
S1	857.9	365.9	-2.1	1.054368	0
S2	857.3	361.9	-2.2	1.043591	-0.6
S3	829.9	350.8	-2.4	1.044963	-28
S4	829.6	349.2	-2.4	1.040585	-28.3

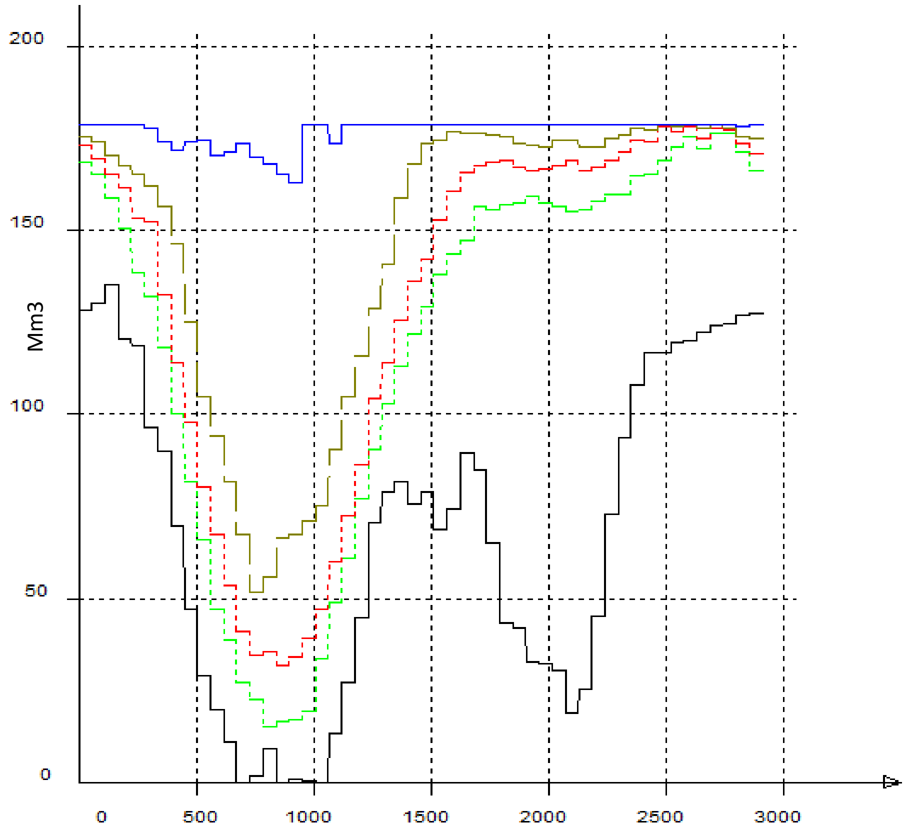


Figure 26: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Trollheim, plotted over one year, for Case S1. The quantiles are calculated based on all 58 scenarios.

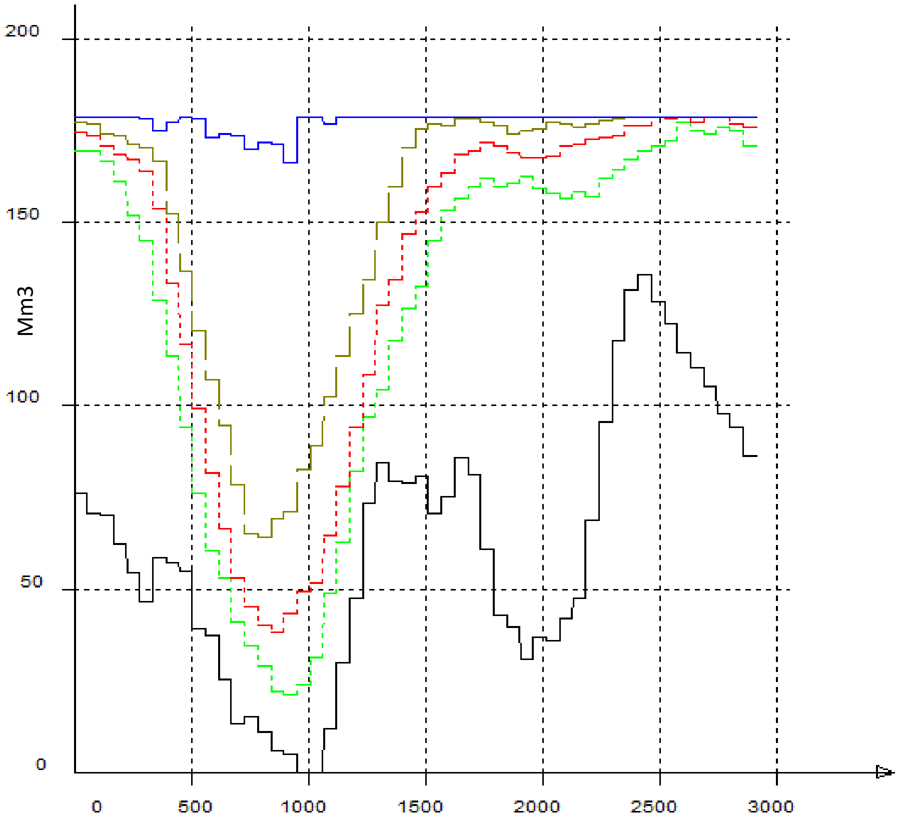


Figure 27: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Trollheim, plotted over one year, for Case S2. The quantiles are calculated based on all 58 scenarios.

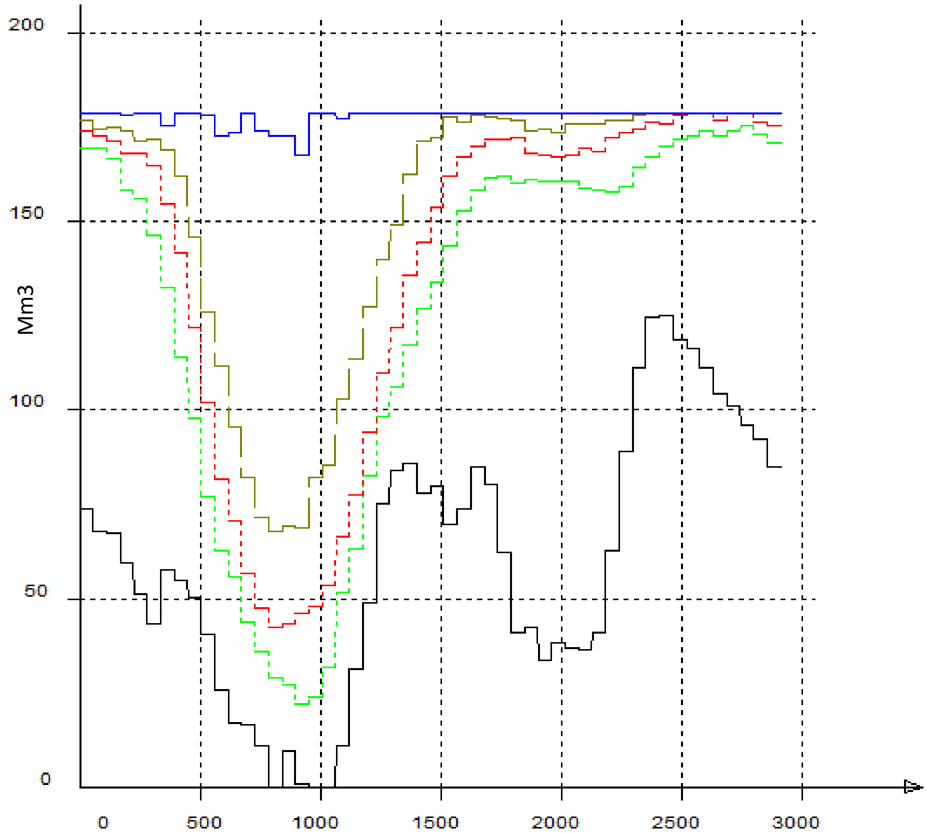


Figure 28: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Trollheim, plotted over one year, for Case S3. The quantiles are calculated based on all 58 scenarios.

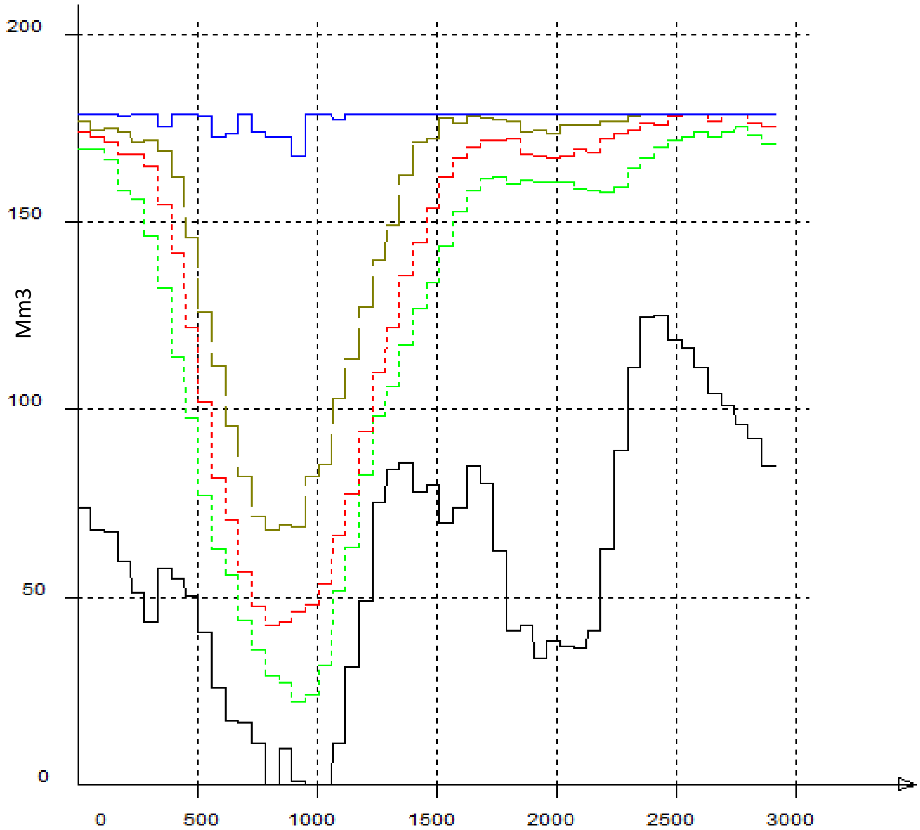


Figure 29: The plot shows the 100-, 75-, 50-, 25- and 0-percentiles for the reservoir Trollheim, plotted over one year, for Case S4. The quantiles are calculated based on all 58 scenarios.

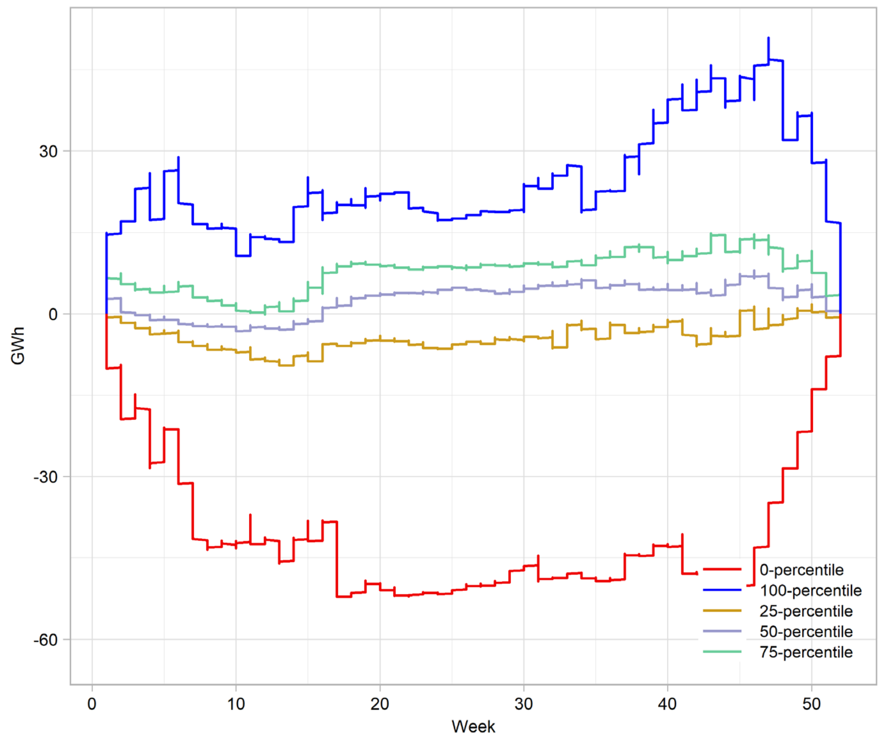


Figure 30: The percentiles of the balancing energy across the 58 scenarios in Surna Case 2. The average storage size across the scenarios is 33.146GWh while the maximum equivalent storage size is 85.472GWh. The maximum flexibility loss is 1.945MNOK, the minimum flexibility loss is -20.265MNOK and average flexibility loss is -3.812MNOK.

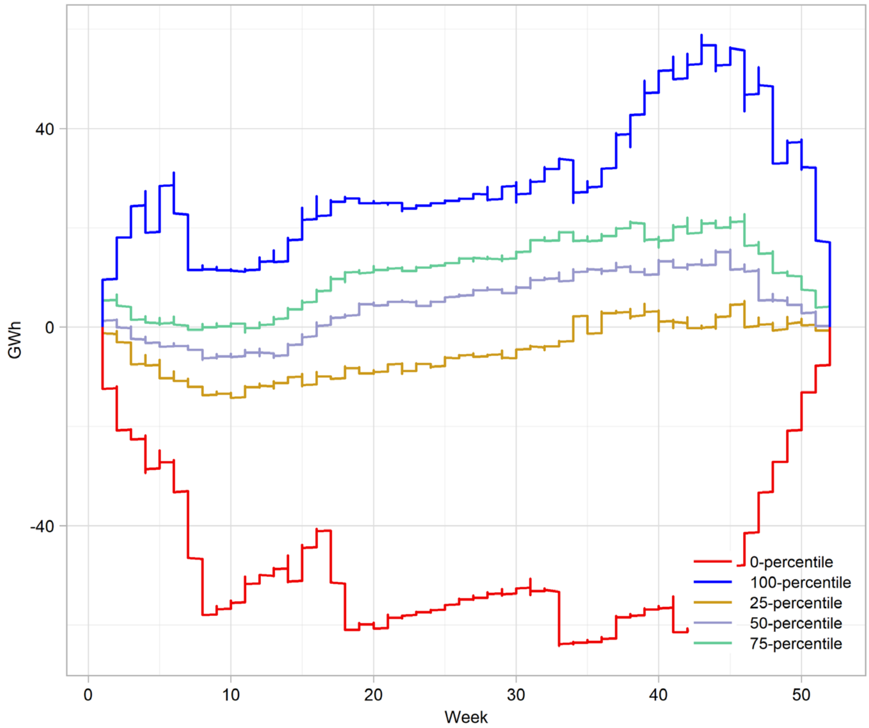


Figure 31: The percentiles of the balancing energy across the 58 scenarios in Surna Case 3. The average E across the scenarios is 40.704GWh while the max E is 86.009GWh. The max revenue is 1.546MNOK, the min revenue is -20.176MNOK and average revenue is -4.063MNOK.

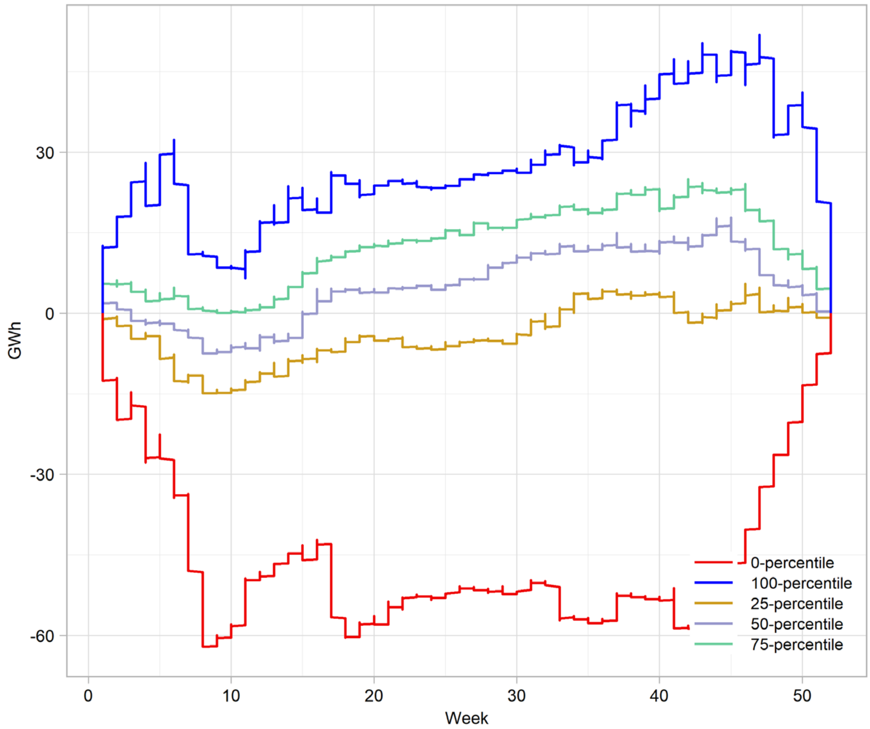


Figure 32: The percentiles of the balancing energy across the 58 scenarios in Surna Case 4. The average E across the scenarios is 41.91GWh while the max E is 82.703GWh. The max revenue is 0.894MNOK, the min revenue is -23.427MNOK and average revenue is -5.415MNOK.

4.2.3 Environmental score

With the hydro-morphological effect factors E1-E6 taken together, the combined score shows that Case S1 has a very large effect, while cases S2 and S3 have a moderate effect and case 4 has a small effect (*Table 23*).

Table 23. *Combined hydro-morphological effect.*

	Case 1	Case 2	Case 3	Case 4
E1: Rate of change	4	2	2	1
E2: Dewatered area	4	2	2	2
E3: Magnitude of flow changes	4	2	2	2
E4: Frequency	3	3	3	1
E5: Distribution	3	3	3	1
E6: Timing	4	2	2	1
Combined hydro-morphological effect	**30 (very large)**	**14 (moderate)**	**14 (moderate)**	**7 (small)**

4.2.4 Graphical illustration with all parameters included

As for the Aura case, the parameters used to illustrate the relationship between flexibility and sustainability for Surna must be scaled to reasonably reflect the changes between the four cases.

The flexibility factor has been scaled with a minimum value of 1.0 and a maximum value of 1.1, just like for the Aura cases. The change in power production has a maximum of zero, which corresponds to the unconstrained case, and a minimum of -50. The combined hydro-morphological effect has a minimum value of 4 and a maximum value of 24, which corresponds to the sum of 6 sub parameters ranging from 1 to 4 production. However, these values are negated, to reflect that a higher value means a higher negative effect on the environment. The net yearly flexibility income is presented as the share of the total revenue, as in the Aura cases. The minimum is set to go well beyond the lowest value.

All parameters that are included in the spider chart for the Aura cases are shown in Table 24, and the spider chart is shown in Figure 25.

Table 24: Parameter values for the Surna cases. The unscaled change in power production and net yearly flexibility income are percentages relative to the total yearly production and income in Surna.

		Scaled values					Unscaled values			
	S1	S2	S3	S4	Min	Max	S1	S2	S3	S4
Flexibility factor	0.54	0.44	0.45	0.41	1	1.1	1.054	1.044	1.045	1.041
Power production	1	0.99	0.44	0.43	75	100	100	99.93	96.74	96.7
Combined hydro-morphological effect	0.1	0.5	0.5	0.85	-24	-4	-22	-14	-14	-7
Net yearly flexibility income	1	0.37	0.36	0.12	-1.5	0	0	-1.04	-1.04	-1.44

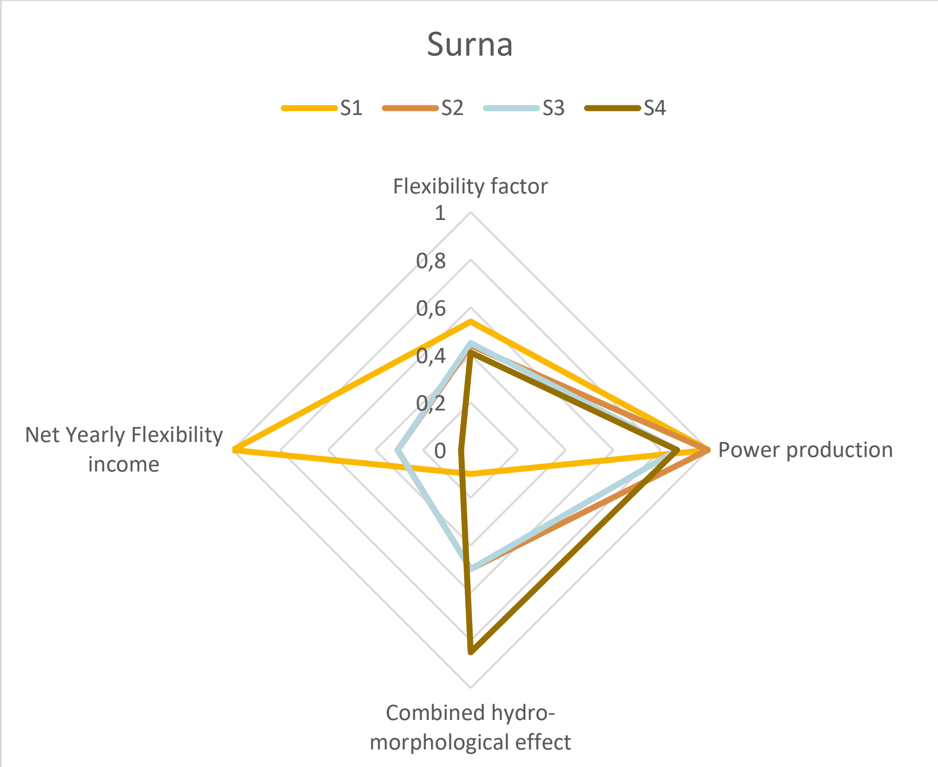


Figure 33: Graphical illustration of the sustainable flexibility parameter values for the Surna cases.

4.2.5 Discussion

We notice that for the combined hydro-morphological effect and also for all parameters, Case S2 and Case S3 results are identical. The reason for this is that they are identical for the section downstream Trollheim hydropower plant. If we would have considered the whole anadromous river stretch, then Case S3 would have come significantly better than Case S2 because of the minimum flow constraints in the side rivers Rinna and Bulu.

For the flexibility factor, we see a slight improvement from Case S2 to Case S3, and then a deterioration from Case S5 to Case S3. However, the improvement in flexibility factor from Case S2 to Case S3 is accompanied by a loss in power production of 3.26%. The net yearly flexibility loss increases with 38% from Case S3 to Case S4. Also, the flexibility loss is much higher for the Surna Case S4 than for the Aura Case A4 – the losses are 5.26 MNOK and 0.38 MNOK per year, respectively. Relative to the total system revenue of the unconstrained cases, the Aura Case A4 flexibility loss is 0.05%, and the Surna Case S4 loss is 1.44%.

When balancing the hydropower flexibility with sustainability, we see in Figure 33 that only a consideration of power production loss indicates an advantage in choosing Case S2 over Case S3. The combined hydro-morphological effect, the flexibility factor and the net yearly flexibility income are unchanged or almost unchanged. However, the cost in hydro-morphological effect of moving to the unconstrained Case S1 is large, whereas the change in power production is unnoticeable, and the change in flexibility factor is also little. The net yearly flexibility lossis however large – a net yearly flexibility loss of 3.81 MNOK yearly is the cost of Case S2 compared to Case S1.

5 Workshop

One objective of the SusFlexMet project is to achieve interdisciplinary collaboration and consolidating knowledge from different fields into a coherent framework. To reach beyond the project working group, a workshop was hosted online on September 27th with the aim to discuss and refine metrics with researchers and relevant HydroCen industry partners. In addition to the project working group, the participants of this workshop covered representatives from the power producers Hafslund-Eco, Å Energi, Lyse, Eviny, Statkraft and Aneo, from the Norwegian Environment Agency, and from the relevant research community at NTNU, NINA and SINTEF Energi.

5.1 Agenda

12:00	INTRODUCTION OF THE PROJECT	SIRI MATHISEN, SINTEF ENERGI
12:10	PRESENTATION OF PARAMETERS	KRISHNA PANTHI, NTNU KRISTINE BJØRNÅS OG TONJE ARONSEN, NINA SIRI MATHISEN, SINTEF ENERGI
12:35	THE VALUE OF FLEXIBILITY	VEGARD KYLLINGSTAD, LYSE
12:40	DISCUSSION	
13:00	BREAK	
13:10	INTRODUCTION OF RAMPING CONSTRAINT	TONJE ARONSEN/KRISTINE BJØRNÅS, NINA
13:20	DISCUSSION	
13:50	SUGGESTIONS TO FUTURE WORK IN THE PROJECT	KRISTINE BJØRNÅS, NINA

5.2 Important take-aways

During the workshop, the project was recommended to consider another version of the flexibility factor, which considers the resources available, as an alternative to the common flexibility factor.

It is pointed out that it is important to balance flexibility and with society's demand for power, with necessity to conserve nature. It is pointed out that using a battery as illustration for the equivalent electricity storage could be misleading, as it can give the impression of a solution that is without disadvantages for the nature.

5.2.1 Concerning which parameters to use for a sustainable flexibility metric

The metric should represent socio-economic interests, and it is pointed out that tunnel costs should not be a separate metric, as it should be ensured by the costs presented in production planning and the production planning should consider this effect. One suggestion is made to design environmental constraints in a way that gives the system lower flexibility in times when demand for flexibility is not too high – and thus use the water with lowest monetary value to ensure that environmental constraints are kept. HydroCen is currently working with this problem. The use of smolt production is encouraged as a parameter for sustainability, and it is pointed out that there exists an overview of factors to describe ramping and factors to describe vulnerability of a river in question [17].

5.2.2 Concerning downwards ramping

It is important to consider the part of the river that is affected by the ramping, and how much water is needed to cover the riverbed. It is suggested that downward ramping should be dependent on the state of the river, but this would depend on available measurement points well distributed in the river. Physical measures like a damping reservoir could reduce the demand for downwards ramping constraints. Lack of good models of the river makes measurement points far downstream difficult to include in production planning models. It is pointed out that although the river is sensible to changes in downwards flow ramping, the upwards ramping can be naturally high.

6 Discussions

6.1 Evidence-base for environmental constraints

The Aura and Surna cases show that the graphical illustration introduced in Section 2.4 is a useful tool to balance between different parameters and can therefore be used to evaluate sustainability and flexibility in case studies. We saw that the visual effect is influenced by the range used to scale the values. For instance, the range used for the net yearly flexibility income in the Surna cases is [-1.5,0] and the range used for the Aura cases is [-0.1,1.1]. Therefore, it is necessary to include the table with scaled and unscaled numerical values as well as the illustration in the assessments. We can also observe that the number of parameters supporting each side of the discussion has significance. For Surna, the net yearly flexibility income, power production and flexibility factor can show the benefits of reduced constraints, and only the combined hydro-morphological effect shows the benefits of increasing the constraints. The parameters can also be weighted to emphasize the importance of each parameter, or the scales could be universal for all comparisons.

The Surna cases and the Aura cases show different types of environmental constraints. For Aura, the only constraint is a constant or time varying bypass constraint from the upper reservoir and out of the system. For Surna, there are combinations of minimum flow/discharge constraints, water bypassing a hydropower plant but to a measuring point, and the ramping constraint. Based on the interpretations of the results, the ramping constraint influences the flexibility more than the bypass constraint, although the bypass constraint causes a loss of produced power. That is also intuitive as the bypass constraint will not be seen by the Trollheim hydropower plant in the daily operation, but the ramping constraint will limit the control options on an hourly basis. The Surna and Aura cases also show two different environmental metrics, I.e., Salmon smolt production and the combined hydro-morphological effect. It would be useful in future studies to see if the two metrics could be combined in a case to show their correlation. It is also important to note that the metrics in the Aura and Surna cases are more complicated with respect environmental concerns than outlined in this report. In a reality, both rivers have complicating factors such as the effect of water temperature on salmon growth in Surna, and how the topography/geology of the riverbed will influence the wetted area from the minimum flow regime in Aura. Additionally, production of salmonids is also dependent on sufficient suitable habitat, the presence/absence of migration barriers and other biological factors such as density dependence and the predators.

The metrics for flexibility provide different simplifications of the real world and will consequently have different defects. This may cause a flexibility factor that decreases at the same time as the net yearly flexibility income is positive, or vice versa. Besides, a run-of-river hydropower plant without water storage can provide a high flexibility factor without the possibility to store water and use it at a better time. Although the equivalent electricity storage presents more dimensions to the change in flexibility between two cases by calculating how this could be compensated, the metric can be difficult to understand and use as it requires some understanding of the method. The choice of scheduling tool – between a deterministic and a stochastic tool – can also influence the result. The consequences of the equivalent storage must be better explored by including this storage unit in the scheduling tool. The operational pattern and economic results of the resulting constrained system including the storage unit will give useful insight into how well the equivalent storage unit replaces the lost flexibility in the constrained system. It would also be useful to further explore the possibilities for new good and easily explainable flexibility metrics to be used in hydropower planning. However, the metrics may still help to analyse the case and create a useful discussion. Although the change in power production is not a flexibility metric, it is useful to include because of its reflection on the flexibility factor. Indeed, without the change in power production, the flexibility factor itself will be without context. The equivalent storage on the other hand will capture the power loss and is therefore not dependent on including the power loss. The planning and simulation tool used to assess flexibility also influences the results. For fast changing time-dependent constraints, a high time resolution is necessary. In addition, a flexible operation of a powerplant with more frequent start-stop sequences will create oscillating waves in the waterways systems which may change the downstream river flow from the side intakes. Such frequent changes, which may have direct impacts on the aquatic ecosystem downstream due to frequent fluctuation in the spill of water discharge. Hence, to be able to use the same simulations to assess the sustainability and flexibility, the dynamics of the watercourses (both river course and pressure tunnel systems) must be captured. For future studies, it could be interesting to include other environmental metrics (e.g., based on diversity of benthic macroinvertebrates) and a multi-market model that can include reserve markets. That could show a more complete picture of the environmental impact and economic value of flexibility than a model including only salmon-related metrics and the day-ahead market. It is important to note that sufficient background knowledge about responses to changes in discharge and wetted area is needed to include more species/species group as environmental metrics. Such data/knowledge is currently lacking for many species/species groups.

This study has clear limitations in the assessment of flexibility when considering a specific hydropower system as a component in the power system. Ideally speaking, the flexibility of the specific hydropower system should refer to its overall ability to assist in providing cost-efficient and technical feasible operation of the power system. In the liberalized Nordic power market, this can be translated into the hydropower system's ability to respond to prices in the various markets that are organized by the market operators and transmission system operators. An overview of such market sequences is provided in [74]. It is fair to assume that the hydropower operator will seek to optimize the expected revenue in these markets acting as a price-taking and risk-natural market player.

In this study we have limited focus to the energy market assuming a set of energy price scenarios for the future. This energy market can be seen as a proxy for the day-ahead market operated by the market operator Nord Pool. Thus, we neglect participation in other markets, e.g., all markets dealing with procurement and activation of reserve capacity and also the set of ancillary services to the power system that is are not (yet) explicitly covered by a separate market. As a consequence of this simplification, an important part of the true flexibility of the hydropower system is not measured. If we were to consider these aspects as well, more data regarding the transmission grid, the predicted need for various power system ancillary services, finer time resolution on input data and different scheduling tools would be needed.

7 Conclusions and recommendations

In this report, five different metrics for flexibility of hydropower production and sustainability have been assessed in 8 cases distributed on 2 watercourses: Aura and Surna. The assessed metrics are the flexibility factor supported by the produced power, the equivalent electricity storage using the net yearly flexibility income parameter, the salmon smolt production and the combined hydromorphological effect (Envi-PEAK classification system). The cases consist of different combinations of environmental constraints including constant and time varying constraints on water bypassing a hydropower plant out of the system or to a downstream part of the system, constraints on the minimum flow in part of a river and constant and time varying constraints on the run-down, or downwards ramping, of the flow in part of a river. The assessment framework combines the chosen metrics for the respective case study, scales the metrics, and presents them visually to improve the understanding of the balance between the metrics.

Based on the discussion, the assessment framework promotes the understanding of how the conditions in a case study influence the different metrics, and how the metrics influence each other. The choice of hydropower production planning metrics – the flexibility factor, produced power and the net yearly flexibility income – complement each other and give different perspectives on the flexibility of the case. A natural next step would be to test the framework on the industry or regulatory authorities, to find out how useable the framework is and how well the parameters cover the users' need. We also recommend that more research should be done to search for complimentary good and easily understandable flexibility metrics. A more extensive testing on several systems could help to illustrate the shortcomings of the flexibility factor and equivalent electricity storage, and also point out where other metrics could be found. In addition, research on the frequent fluctuation in downstream flow from the side intakes caused by the operation of a powerplant with frequent start-stop sequences and its impact on the flora and fauna (fish and other organisms) is recommended to be carried out.

The environmental metrics must be chosen separately for each case: Each watercourse has different qualities, keystone species, differences in available data and different constraints required to provide sustainability, so consequently, the metrics required to measure this sustainability must be case dependent. However, the methods used to assess the metric and the procedures for including the metric in the assessment framework can be transferred to other cases using the same metrics – for instance will the combined hydromorphological effect be interesting to use in other cases with a ramping constraint, but the metrics must be scaled for each case separately. In the two systems described in this report, the metrics point out a difference in power loss and flexibility loss: The Surna cases lost more flexibility, and the Aura cases lost more power, relative to the total production. It would be beneficial to test the metrics on other systems with similar environmental constraints and see if they can capture a similar effect there, or if it is dependent on the topology of the system.

The research in this project has made the foundations for an assessment framework for systematic quantification of the regulation capabilities of hydropower in terms of a set of metrics and the trade-offs between them. We recommend that this assessment framework is further tested with different combinations of environmental constraints on the hydropower production planning and with different environmental considerations. Within this project, only environmental metrics related to salmon were included, due to the availability on data on this species. Other keystone species or taxa should be investigated in further development of this framework. Furthermore, this framework could be expanded to include environmental metrics in the reservoirs. The assessment framework contributes to a quantification of the cost in terms of flexibility of preserving the environment around a watercourse. We recommend that further research should be undertaken to quantify the impact in terms of environment on the flexibility of hydropower planning, especially with future value and use of nature in mind.

A multidisciplinary project is interesting as it requires the ability to discuss technical details with experts in different fields. While working together in a project group, a multilateral learning process may efface some of the difficulties of understanding each other within the project group. Therefore, it will be useful to test the results on the industry and see if it is comprehensible to them as well. Within this project, one workshop with the industry and technical experts in different fields was conducted, to discuss the suggested metrics to use in the assessment framework and planned presentation of the metrics. However, we recommend getting an evaluation from different disciplines of the industry on the report's use of the metrics, and on the useability of the framework: How well do other disciplines understand the metrics for flexibility and environmental concerns. As the environmental metrics are case specific, the framework will require expert guidance, but more industrial contributions in further research would give insights to how easy the framework is to use and whether it provides the information that is needed. Multidisciplinary research is demanding as it requires the researchers to be experts in their own field, understand other narrow research fields and also explain their own field and findings in a pedagogic and easily understandable way. However, to get the whole picture, it is necessary to have an understanding of relevant findings in other fields and understand the consequences of choices made in your own research field. Therefore, we recommend more research projects that increase the experience in this way of working and pave the way for more multidisciplinary research and research between other fields.

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