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Keeping the flow: hydropower, river ecosystems and governance in northern Sweden

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Contents

Summary

The focus of this report is hydropower generated in the Norrbotten region of Sweden, in the larger context of the Nordic and EU regions. Recognizing hydropower's changing role in meeting growing energy demand is crucial.

Hydropower provides energy security and grid stability for Sweden, which has long relied on the low-carbon energy source for much of its electricity. Industrial expansion, particularly in northern Sweden, is expected to drive a substantial increase in energy demand, leading to more demand for hydropower. At the same time, more renewable energy will be added to the Swedish electricity grid and beyond, and hydropower will play a key role in stabilizing the grid to make space for wind and solar power.

With this increase will come more impact on river ecosystems, particularly through hydropeaking, i.e. where hydropower operation is optimized creating frequent and large changes of river flow, which is of significant concern for environmental impacts. Balancing hydropower production with the preservation of biodiversity and ecosystem health is essential and part of the policy priorities of the EU and Sweden.

To ensure the long-term success of the hydropower industry, efforts need to be emphasized to improve efficiency, promote biodiversity and incorporate community perspectives. Additionally, strategies for adapting to a changing energy landscape, such as accommodating fluctuating renewable energy sources, are vital.

1. Introduction

Hydropower has played an important role in Sweden's electricity mix for over a century, providing a low-carbon source of energy. Extensive infrastructure investments in the previous century led to a broad network of hydropower stations, with a significant portion of them located in the north of the country, where its largest rivers are located.

The construction and operation of dams for hydropower disrupt rivers by impeding the natural movement of water, energy, materials and species (Bunn & Arthington, 2002; Poff et al., 1997). This interference, mainly driven by fragmentation and artificial flow regulation caused by dams, results in significantly reduced connectivity compared to free-flowing rivers. Achieving good water quality and ensuring the sustainability of biodiversity will require understanding and predicting the dynamics between water and energy. In Sweden, damming has led to the loss of fish species and various environmental impacts on rivers and other water bodies.

In northern Sweden, where most of the country's hydropower resources are concentrated in the Norbotten region, the current expansion of industrial activity is developing in parallel with unprecedented challenges to the electricity grid. For example, to mitigate industrial emissions, companies such as HYBRIT or H2 Green Steel in Norrbotten plan to replace the coking coal currently used to make steel with hydrogen that is produced with fossil-free electricity, much of which could be generated through hydropower. This new production process requires significant amounts of electricity, water supply for potential on-site hydrogen production, and energy storage beyond the existing electricity supply for running these plants.

Because of industry expansion, urbanization is also expected to lead to population growth in northern Sweden. Concurrent economic development will further increase energy consumption (Energimyndigheten, 2020a), with knock-on effects to the electricity grid – and the environments of rivers and other water bodies – in Sweden.

Meeting the steep projected increase in renewable energy demand in Sweden while balancing environmental protection is going to be an intricate problem to solve. Despite the challenges, continued expansion of energy and industrial processes will rely on renewables in Sweden, as well as in the whole EU. For example, the EU promotes increased use and production of hydrogen (European Commission, 2020) and highlights that "the strong nexus between water, climate, energy, and food is essential to achieve the objectives of the European Green Deal" (European Commission, 2021). Increased energy requirements will thus result in higher pressures on river networks and their ecosystems across the region. Regulatory frameworks need to reflect and adjust to these changes, locally, internationally and regionally.

Regionally, the EU Water Framework Directive, established protection of inland surface waters, transitional waters, coastal waters and groundwater. The directive aims to prevent further deterioration and protect and enhance the status of aquatic ecosystems, terrestrial ecosystems – with regard to their water needs – and wetlands that depend directly on aquatic ecosystems. Meant to be fully implemented by 2027, in the latest status check, the European Commission established that further efforts were needed to meet the targets of the directive (European Commission, 2019). Required activities can include river restoration measures to improve the "hydro-morphologic status" of water bodies adjacent to hydropower facilities, which means considering their physical character and water content; making these improvements can limit or decrease hydropower production and capacity. Parallel changes to the Swedish political and regulatory landscape also could significantly affect local hydropower.

Ongoing modernization of existing facilities offers great opportunities and also challenges, for governance, meeting electricity needs and protecting water resources and their environments. Such upgrades or technical changes require significant investments but also can lead to more efficient and increased power output in relation to water use. Such upgrades should be combined with river restoration or other forms of environmental protection on water bodies, with proper planning in place – which we discuss in this report in the context of current policy in Sweden and the EU.

Currently, hydropower is a source of baseload capacity for the electricity grid, needed throughout the day at constant levels, particularly in Sweden as well as many other countries; however, applications where hydropower is used for energy storage will become increasingly important for achieving higher system flexibility and balancing intermittent renewable energy sources (United Nations, 2020). We argue here that fundamental work needs to be done to devise models that support decision-making on capacity expansion. These models should explore strategies to meet demand and environmental targets via innovative technologies. The role that such technologies can play, their added value, as well as optimal times of investment can be folded into such models (Heuberger et al., 2017).

Meeting environmental targets in Sweden will be one of the biggest challenges for hydropower in the near future: damming is one of the reasons behind unprecedented rates of decline of freshwater biodiversity in the country's rivers, especially in the north. Hydropower operations on a day-to-day basis have also changed rivers' natural flow variation, which is essential for healthy ecosystem functioning, via hydropeaking practices meant to balance electricity grids, leading to negative impacts overall on biodiversity (Poff & Zimmerman, 2010).

In this report, we explore the status and future of hydropower in the north of Sweden, with particular focus on the Bothnian Bay, in the Norrbotten region, as the home of the largest hydropower stations and the region with the most industrial expansion. We then examine the regulatory context in the Nordic region, with specific context in Sweden for national planning. We investigate hydropower questions for the region from two perspectives: for electricity grids, discussing supply, demand and infrastructure needs, and for ecosystems, discussing climate change and increased demand impacts on freshwater environments and biodiversity.

We explore the following questions: What is the future role of hydropower in the Norrbotten region, given the challenges that electricity grids are facing under increased demand in the area? How can future energy and water demands be addressed, while safeguarding water, ecosystems and biodiversity? We do a basic mapping of stakeholders, work that is required to advance future decisions and development for hydropower in Sweden.

2. Swedish electric power system

2.1 Swedish and Nordic grid dynamics

Sweden has a diverse mix of energy sources for electricity generation, including hydropower, nuclear power, a small share of fossil fuels, and renewable sources such as biomass, wind and solar. This mix of energy sources helps to ensure that the country has a reliable and stable supply of electricity, with implications for the regional network of electricity grids and markets in the Nordic and EU countries.

The national transmission grid (220/400 kV) is operated by the Swedish transmission system operator (TSO), Svenska Kraftnät. High-voltage regional grids (130 KV) are operated by several different companies, for example: E.ON, Ellevio, Skellefteå Kraft, Vattenfall, Jämtkraft and Öresundskraft. There are 172 local grid companies operating low voltage grids (230 V to 40 kV), including municipally owned ones (Energimarknadsinspektionen, 2021). These companies are responsible for building and maintaining the power plants and transmission lines that make up the Swedish grid. They also manage the flow of electricity through the grid to ensure that it is distributed efficiently and effectively.

The Swedish transmission grid is divided into four "electricity regions" (*elområde*). This division is made in line with physical limitations of the grid due to various transmission bottlenecks. This division is also made so that stakeholders from different countries are not discriminated against when handling these bottlenecks, which is a requirement of EU regulations (Svenska Kraftnät, 2022a).

Figure 1. Swedish electricity regions (*elområde*) and the surrounding Nordic grid.

Source: Svenska Kraftnät

Electric grids from the four Nordic countries – Sweden, Norway, Finland and Denmark (the whole of the first three, with the eastern part of Denmark) – are integrated into a synchronous grid (Figure 1). During normal system conditions, the frequency is synchronized across the four grids, which function as one. The four countries' TSOs – Svenska Kraftnät (Sweden), Statnett (Norway), Fingrid (Finland) and Energinet (Denmark) – are responsible for the operational functioning of the overall electricity system, including the balancing of electricity generation and load, in each country.

One of the key challenges facing the Swedish electricity grid is the integration of renewable energy sources. Renewable energy sources such as wind and solar are often intermittent, meaning they may not always be available when electricity is needed. Hydropower, which has been Sweden's main source of electricity, now needs to shift to serve as energy storage, to enable wind and solar resources on the grid, which is further discussed in section 2.2. This has implications in Sweden, the Nordic region and the EU markets overall, where wind and solar are the most common and most variable renewable sources of energy.

To address the challenge of accommodating renewables, Sweden is exploring several different options, including the use of advanced energy storage technologies, such as batteries or hydrogen, and the development of smart grid systems. This can help to better manage the flow of electricity, while still meeting the country's energy needs and assisting in balancing the load across the European markets.

As more intermittent renewable sources such as wind or solar are introduced, the electricity grid becomes more complex to manage. With reduced coal and nuclear production in the electric grid, the overall inertia and stability of the grid decrease on an instantaneous timescale. This increases the risk of significant drops in alternating current (AC) frequency and has consequences for the system when it must handle unforeseen disturbances, such as the "tripping" of a large generator after a break in its power supply.

Given that more renewables will be introduced across Sweden's, Nordic countries' and EU grids, planning becomes more complicated on various timescales. On a seasonal timescale, planning must match generation to higher loads during winter than during summer, which is an economic challenge. It might mean that generating resources remain idle during large parts of the year – a large capital investment that is rarely used – to be able to meet load peaks during periods of high demand. Generally, intermittent renewable energy sources provide the capacity to meet seasonal fluctuations in the load, since there tends to be more reliable wind power during winter and solar power provides higher generation during summer (Heide et al., 2010).

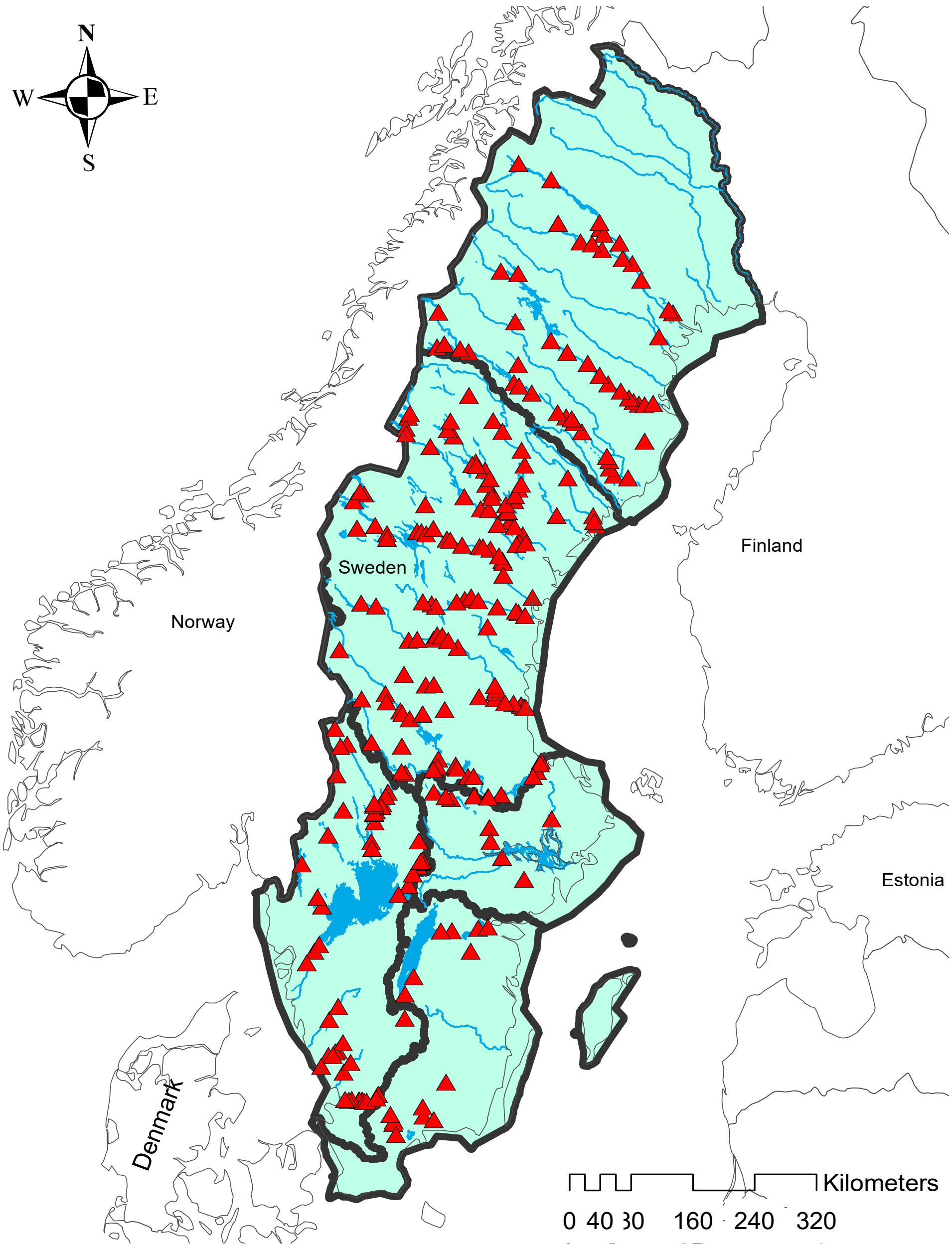
A range of technically viable demand- and supply-side flexibility resources could be employed to tackle the challenges of intermittent renewable power generation. Demand-side management (often referred to as DSM) aims to modify the end-use electricity consumption, or the load, to better match electric generating (Lund et al., 2015). Demand-side management could be part of a more integrated electric power system that would allow for a high integration of variable renewable energy (known as VRE). This integrated system would combine and coordinate electricity, thermal and gas grids for energy storage at various timescales, including seasonal storage (Lund et al., 2016).

2.2 Swedish hydropower flexibility potential

Sweden has an average hydropower production of 65 TWh/year, which represents roughly 40% of total electricity generation in Sweden, and dam storage capacity of 34 TWh, which represents around 25% of annual Swedish electricity consumption (SOU, 2017). Hydropower is generated in roughly 2100 stations with a total installed capacity of 16.2 GW. Around 95% of Swedish hydropower is generated in 208 stations that have an installed capacity exceeding 10 MW (ER, 2014). Figure 2 shows the location of all Swedish hydropower plants with a capacity above 3 MW.

Hydropower dominates grid frequency regulation services delivered in only a few seconds up to a month in the flexibility market. As battery storage deployment in the Swedish grid increases, the share of batteries in some of these frequency regulation services can be expected to increase. Still, hydropower will play a vital role in balancing the system.

Figure 2. A map of all Swedish hydropower plants above 3 MW (red triangles). Regions within the bold black lines are the water districts of Sweden.



Source: SEI, adjusted from eurofresh.se.

Of the three main types of hydropower production – run of river, pumped storage and dam – the dominant form in Sweden is dams, referred to as impoundments in the context of hydropower. Run-of-river hydropower accounts for a limited portion of Sweden's total installed hydropower capacity, in part because of inherent unreliability due to seasonal variation of streamflow; however, it helps to support grid stability. (For discussions of these three types and their different characteristics and flexibility capacities, see Paatero & Lund, 2005; Rehman et al., 2015; Sridhar et al., 2022; WEC, 2016.) Pumped storage hydropower capacity has varied in Sweden, with current capacity at nearly 100 MW from a handful of installations, and in the past, several times that.

The increasing need for energy storage in the Swedish energy system due to the larger share of intermittent renewable energy sources has led to renewed interest in pumped storage hydropower, which can store power for several hours and add flexibility to the grid on operational and short timescales. The largest example ever built in Sweden (335 MW) is in Juktan in the Västerbotten region in northern Sweden, along the Ume River. The Juktan installation was operational from 1978 to 1996; recently its owner, Vattenfall, has been considering restarting operations (Ny Teknik, 2022). The Swedish Energy Agency has also financed a demonstration project for underground pumped storage hydropower (2 MW), using an old mine cave for storage in the island of Åland (Energimyndigheten, 2020b). Other notable pumped storage hydropower in Sweden includes Kymmen (55 MW capacity), Letten (36 MW) and Eggsjön (0.6 MW), according to Fortum, the energy company that runs these installations in the Värmland region.

Hydropower could produce even more electricity if needed, but grid bottlenecks exist. between the north (Elområde 1 and 2) and south (Elområde 3 and 4) electricity regions. Likely the capacity could not be transferred from the production sites to where most demand exists, unless the Norwegian grid were to be used for the exchange of capacity. Regardless, in 2022, dam hydropower produced 72% of the installed power capacity under peak load hours, i.e., when the grid is under most stress, for example, on a cold winter afternoon when people are at home using appliances and turning up household heating (Svenska Kraftnät, 2022b).

2.3 Hydropower's changing role in Norbotten

Recent studies of the Swedish energy system have predicted a significant increase in energy consumption, in the next several decades. Electricity demand in particular will increase as the result of ongoing electrification trends, mainly in industry and transport, but also households. For example, Energiforsk & Profu (2021) estimated electricity use will increase between 65 and 117 TWh/year by 2045.

The Norrbotten region is already experiencing rapid increases in electricity demand as a result of the expansion of industrial activities in the area, e.g. the "fossil-free steel" manufacturing ventures of HYBRIT and H2 Green Steel, conventional steel-making (SSAB), mining (LKAB) and battery production (Northvolt). The latest estimations in an analysis by the North Sweden Energy Agency (Energikontor Norr) indicate that an additional 80 TWh/year by 2028 would be needed to cover the electricity demand of only the aforementioned industries, without including potential expansion of other industries, data centres, or increased household consumption due to increasing population trends as a result of these industrial expansions (Region Norrbotten & Energikontor Norr, 2022).

Currently, the electricity grid area 1 (SE1 – Elområde 1, which represents the northernmost part of Sweden) has an overcapacity of 3000 MW, but planned industrial expansion will reduce that overcapacity to 600 MW. The increase in capacity in the region as a result of industrial expansion will thus be equivalent to 2400 MW by 2028, roughly about the capacity needs of a city as big as Gothenburg (Region Norrbotten & Energikontor Norr, 2022).

As a direct result of these forecasts, the Swedish TSO, Svenska Kraftnät, is planning to enhance the northern Sweden grid with investments of 10 billion SEK (equivalent to approximately 887 million EUR). The project, “Fossil-free Upper Norrland” (*Fossilfritt övre Norrland*), will increase available grid capacity by 5000 MW and allow for the connection of another 4000 MW of renewable energy production, coming mainly from new wind power installations. Grid projects historically have taken 12 to 15 years to be completed, partly due to rigorous environmental regulations, but Svenska Kraftnät is aiming for project completion by 2028, i.e. 8 years from the project start (Svenska Kraftnät, 2022c).

Offshore wind is among the main candidate solutions for delivering this additional power capacity that will be needed in the future. Previous analyses attempted to quantify the potential that on- and offshore wind power could have in balancing mismatches of demand and supply for the Swedish grid. The Swedish Energy Agency’s wind power strategy states that 100 TWh of wind power will be available by 2040 – with 80% coming from onshore wind (Energimyndigheten, 2021a).

The interest in wind power in northern Sweden has increased in recent years. The installed wind power capacity almost doubled between 2018 and 2022, from 7300 to 14 278 MW (Energimyndigheten, 2024). This market expansion, together with technological improvements and economies of scale, has led to a decrease of the levelized cost of electricity generated by wind power, from 50 öre/kWh for a 2- to 2.5-MW_e turbine to 30 öre/kWh for a 6 MW_e wind turbine (Region Norrbotten & Energikontor Norr, 2022).

While wind will continue to expand as a renewable resource, hydropower will continue to play an important role and could even increase its output and balancing role through refurbishment and more effective use of existing plants. Nearly all of the electricity production in the Norrbotten region comes from hydropower, at approximately 15 TWh of the total 15.5 to 18.5 TWh/year(Region Norrbotten & Energikontor Norr, 2022).

One possibility for increasing hydropower capacity in the region to cover future demand is to upgrade existing infrastructure. The National Plan for Hydropower Permit Review (*Nationell plan för omprövning av vattenkraften*) (HaV, 2019b) promotes efficiency upgrades in existing hydropower stations that can be implemented without negative effects on the water bodies currently being used to provide electricity. Previous analyses, however, have not assumed increased hydropower output in the future, expecting business-as-usual hydropower performance (Region Norrbotten & Energikontor Norr, 2022). Svenska Kraftnät expected the same, with total national hydropower energy production assumed to range between 66 and 68 TWh in four scenarios for 2045 (assuming a starting point of 68 TWh in 2025) (Svenska Kraftnät, 2021). The Swedish Energy Agency also assumed that hydropower production remains stable in their scenario analysis for 2050, with a slight overall increase (0.5 TWh), due to the balance between increased production because of climate change, which will bring heavier yet unpredictable precipitation and more water for hydropower on rivers, and decreased production because of stricter environmental regulation (Energimyndigheten, 2021b). Added capacity is assumed to cost 40–50 öre/kWh (equivalent to 0.04–0.05 EUR/kWh) in these scenarios, and small-scale hydropower is also included (Energimyndigheten, 2021b).

The projections of Svenska Kraftnät and Energimyndigheten can be considered to be overly cautious, since they do not appear to include efficiency gains from the ongoing refurbishment of Swedish hydropower nor projected effects from climate change. Refurbishment of existing hydropower stations is set to increase hydropower production by 3 TWh/year in the coming decades (Bernhoff et al., 2003; P. M. Rudberg, 2013). Various studies on climate change effects in a Nordic setting also indicated an increase in precipitation and a better match between flow and electricity consumption with warmer winters, which should lead to significantly increased production of Nordic and Swedish hydropower (Chernet et al., 2013; Shevnina et al., 2018).

Furthermore, a recent study has simulated the effects of various global warming scenarios on Swedish hydropower's production capacity, which could increase by 2.8 to 4.4 TWh/year, while its balancing capabilities would not be negatively affected. Based on energy market model simulations for Sweden, it would be cost-effective to have hydropower play a complementary role to wind and to some extent solar power, both of which would be delivering the majority of electricity in a carbon-neutral northern European system (Scharff et al., 2023).

In light of these estimated changes in energy and power demand and supply dynamics in the future, previous studies have looked into how capacity of existing hydropower can be improved. It is worth noting that existing hydropower stations were built from an energy optimization perspective, i.e., maximizing energy output, while today and in the future, more focus will be placed on flexibility and optimized power output. It may be possible to optimize infrastructure upgrades to maximize power and flexibility on currently used waterways without needing to exploit new flows, by building new dams, for example. Such infrastructure upgrades would not lead to increased energy production, but instead they could strengthen hydropower balancing potential for the electric grid with an increasing share of intermittent renewable energy sources such as wind power added to the grid. The overall potential for such power capacity increases from hydropower has been estimated to be 3400 MW for the top 10 hydropower-producing Swedish rivers, which is equivalent to the power needed for 10 medium-sized cities (assuming a 300 MW power demand). On average, capacity per river can be increased by 24% (Molin et al., 2016).

The realization of such potential depends on the political question of the re-examination of environmental permits for hydropower (see Section 3), as well as market conditions (electricity prices, grid tariffs, facility taxations, etc.) and the implementation of the EU Water Framework Directive (2000/60/EC) (Molin et al., 2016). Increased electricity price variations and the emergence of flexibility markets have led to favourable market conditions and some capacity upgrades and reinvestments in hydropower stations in the past 10 years. These have led to increased production efficiency and decreased energy losses (Energiforsk, 2021). However, the full potential to upgrade infrastructure and improve efficiency of existing hydropower plants has yet to be realized.

The above discussion highlights the significant pressures on the Swedish electricity grid to come in the near future, especially with the expansion of industries in northern Sweden. Hydropower and wind power can play a key role in delivering power capacity and flexibility where most needed, but certain upgrades would be needed to optimize systems and equip the grid for new intermittent energy sources.

3. Swedish regulatory context and revised environmental code

In the previous section, we explored the ongoing changes to the role of hydropower in northern Sweden and the Nordic electricity grid. Below we consider the regulatory context surrounding the future of hydropower in the country.

3.1 Overview of Nordic hydropower governance

The three Nordic countries exhibit similarities that impact governance of hydropower, including for modifications to improve operations. The bulk of their hydropower capacity was constructed during the middle of the last century, and licences to operate hydropower were, as a rule, granted without an expiration date (Sweden and Finland) or with a very long tenure (Norway) (Darpö, 2016; Soininen et al., 2019). Significant adjustments to the operating conditions of hydropower plants to cater for additional flexibility or environmental requirements necessitates a modification of the original licence. However, the possibilities for modifying such hydropower licences, particularly for environmental improvements, have been limited under existing regulatory frameworks in Nordic legislation. Such restrictions are a significant reason behind the limited modifications made to existing hydropower production in the Nordic countries (Darpö, 2016; P. M. Rudberg, 2013; Soininen et al., 2019).

In Norway, for example, despite a significant amount of hydropower licences that can be revised, the pace of hydropower licence reviews is very modest. A change to legislation in 1992 made licence revisions possible 30 years after issuance (Darpö, 2016). The concerned municipality can make a request to revise a hydropower licence to the Norwegian Water Resources and Energy Directorate. Hundreds of hydropower licences issued more than 30 years ago could be reviewed. By 2022, this amounted to 430 hydropower licences (NVE, 2013), yet between 1992 and 2018, only 9 granted hydropower licences were reviewed (Darpö, 2016; NVE, n.d.).

In Finland, the National Water Act of 2011 is based on a strict ex-ante ideology, in that once a hydropower operation has been granted a licence, it cannot be revoked or greatly adjusted without the consent of the hydropower operator (Soininen et al., 2019). As a result, new environmental measures linked to hydropower are limited.

3.2 Modifications to Swedish hydropower governance

Starting in 2016 the Framework Agreement on Energy Policy was passed with the objective of reaching 100% renewable electricity production by 2040 (Regeringskansliet, 2018a). This cross-party agreement is one of the reasons why Sweden is leading the way towards a low-carbon economy (International Energy Agency, 2019) .

The agreement has led to significant modifications to Swedish legislation, the creation of the National Plan for Hydropower Permit Reviews, and the setting up of a private fund to finance environmental measures at hydropower stations and dams. These developments reflect a significant shift in Sweden to adapt existing hydropower to cater for both flexibility and environmental requirements.

In Sweden, up until 2018, changes were not often made to existing hydropower production facilities (P. M. Rudberg & Smits, 2018). However, that year, the Swedish parliament decided on important legislative and administrative changes affecting hydropower production and river restoration that came into effect in January 2019. These modifications were partially a response to infringement procedures initiated by the EU Commission, due to what they saw as an incomplete implementation of the EU Water Framework Directive (Regeringskansliet, 2018b). Although the extent these legislative and administrative changes are sufficiently ambitious to implement existing environmental policy can be debated, they do represent a major break with the system that was in place until 2018 in Sweden, and they will most certainly accelerate the speed and scope of flexibility and river restoration measures.

Important administrative and financial modifications accompany the legislative modifications of 2018. In a joint national strategy planning document, the Swedish Agency for Marine and Water Management (Havs- och Vattenmyndigheten, HaV) and the Swedish Energy Agency established a planning limit: river restoration measures related to hydropower production should be allowed to cause up to a 2.3% loss of annual hydropower production, equal to 1.5 TWh/year, on a national level (Energimyndigheten & Havs- och Vattenmyndigheten, 2014). A greater extent of river restoration measures is deemed to cause a substantial negative impact on the Swedish energy system.

Sweden's national strategy for hydropower is to focus on flexibility and efficiency-increasing measures at existing large-scale >10 MW hydropower installations. Passage facilities for fish and minimum flow conditions will be required across the board, for the 60 large hydropower stations with conditions favourable for fish passage and for all smaller hydropower stations (<10 MW) (HaV, 2019a). The strategy document also provides a classification of the main river basins in Sweden, based on their value for the energy system due to existing hydropower production, environmental values and significance for reaching EU and Swedish environmental objectives. The strategy document is intended to show in which river basins environmental measures should be prioritized and in which basins measures should be focused on intensified electricity production in existing hydropower facilities.

National Plan for Hydropower Permit Reviews

A key development for the hydropower sector is the permit review process. The Swedish Agency for Marine and Water Management, the Swedish Energy Agency and Svenska Kraftnät have created the National Plan for Modern Environmental Conditions for Hydropower (NAP), intended to organize and coordinate the permit review process on a national scale (HaV, 2019a). The review process should take 20 years.

A private fund, financed by eight of the biggest hydropower producers in Sweden, is meant to cover roughly 90% of all costs – including administrative, construction and loss of hydropower production costs – from river restoration measures that result from the implementation of the National Plan for Hydropower Permit Reviews (Vattenkraftens Miljöfond, n.d.). A total of 42 million EUR/year, during a 20-year period, will be set aside by these private companies to finance river restoration measures related to hydropower production. As part of the Framework Agreement on Energy Policy, the property tax on hydropower facilities was reduced by an estimated 163 million EUR/year (Finansdepartementet, 2017).

The NAP also promotes the modification of existing hydropower stations to increase their installed effect and production capacity (HaV, 2019a), which, as discussed in Section 2, will be important for balancing the electricity grid. The intent of the NAP is that environmental and efficiency-increasing measures are to be evaluated and implemented across various stations in the same river basin, as well as guiding work on the national level, in basins where there is the highest potential for these measures to have the desired effect. Given these intentions of the national plan, and the political, legal and financial adjustments that have been made in Sweden, it is likely that the coming modifications to existing hydropower stations and operations in Sweden will be carried out in a synergetic and effective way in the coming 20 years.

The suggested balance between environmental and hydropower flexibility in the NAP are, however, the result of significant and contested trade-offs in Sweden. The planning limit for environmental measures at hydropower stations in Sweden is 1.5 TWh/year. This means that, on a national level, electricity production should not go below this limit due to environmental measures at hydropower stations, including mandatory minimum flow and fish passages, as mentioned earlier. The scope for environmental measures at large-scale >10 MW hydropower stations is thus severely restricted (Energimyndigheten & Havs- och Vattenmyndigheten, 2014).

3.3 Swedish political processes and stakeholders

The implementation of the NAP will face important questions, trade-offs and hurdles, as hydropower operators and regulators at different levels coordinate electricity production with environmental protections. Increasing the installed efficiency and production capacity of existing large-scale hydropower stations will also increase hydropeaking, the rate and scale of change of river flow, which potentially augments any ecological damage in the affected river basins (Bejarano et al., 2017).

In the past, various stakeholders have taken different positions on the issues. For example, the Swedish River Basin District Authorities have taken partially different standpoints regarding the restoration requirements at large-scale hydropower stations, compared to the NAP provisions (Vattenmyndigheterna, 2018), illustrating the complexity of multilevel governance of hydropower in Sweden and its multi-stakeholder framework.

In February and September 2022, the owners of hydropower installations in 25 river basins submitted permit review documents to the Swedish Land and Environmental Court. These submissions were preceded by a stakeholder collaboration process led by the corresponding County Administrative Board (CAB, *Länsstyrelsen* in Swedish), where each installation is located. These first rounds of implementation of the NAP included only a few involved basins and hydropower installations – a hydropower station in Enningsdalsälven to 18 hydropower installations in Rönne Å, where the municipality of Klippan has bought and will decommission the three largest hydropower stations in the basin (Rudberg & Karpouzoglou, 2022). For now, few rulings are definite and can be deemed to constitute legal precedent to guide the application of how to interpret and apply existing legislation.

In parallel to regulatory processes discussed above, the Swedish political landscape affects the outlook for hydropower in the country. On 12 December 2022, the government declared that it aimed to postpone the implementation of the NAP for one year, for the hydropower projects that had not yet submitted their permit review documentation to the Land and Administrative Court (Regeringskansliet, 2022). From the adjoined documentation to the decision, it appears that the consultation processes not yet submitted to the court are meant to continue but will finish one year later than previously planned. The processes that are already in the Land and Administrative Court are meant to continue without any pause (Miljödepartementet, 2022; Rudberg & Karpouzoglou, 2022).

Stakeholder mapping

To address the Swedish context with an inclusive perspective, we mapped stakeholders according to representation (see Table 1). Given the many different stakeholder mapping methodologies available (Reed & Curzon, 2015), we followed a method tailored to inclusive mapping (Barquet et al., 2022).

Stakeholder mapping helps organizations understand and manage their relationships with various stakeholders. It involves answering questions such as:

- What is the problem or solution being addressed by a system? This can refer to a group of interconnected things, processes and actors.
- How are these issues being affected by or affecting the system?
- What are the interests and beliefs of stakeholders in relation to these issues?
- How can stakeholders be prioritized in the decision-making process?

Furthermore, stakeholder analysis looks at stakeholders' perceptions of risks, viable solutions to problems, the distribution of resources among stakeholder groups, the interactions between these groups, and the opportunities for influencing policy. Based on this analysis, strategies and plans can be developed to achieve objectives and facilitate collective agreements (Barquet et al., 2022).

Stakeholder mapping often focuses on actors who have influence over a system, potentially overlooking those who may be affected by an intervention but lack the resources or power to influence decision-making processes (Bresney et al., 2023). Our method ensured broader identification of stakeholders, to avoid reinforcing existing inequalities.

Our initial mapping process showed that the government agencies, large TSOs and other such organizations have higher influence. Other stakeholder organizations and interest groups are not often consulted.

Some stakeholders are quite focused regionally: for example, the organization Vattenregleringsföretagen is owned jointly by various hydropower producers. It aims for optimizing hydropower production for rivers with different power station owners, on the Umeälven, Ångermanälven, Indalsälven, Ljungan and Dalälven. Others could be considered regional to global, such as the World Wide Fund for Nature (WWF Sweden).

This stakeholder framework has implications for future decision-making: sociotechnical innovations and regulatory process consultations need to span multiple scales (both in time and geography) and involve several stakeholder groups. At the same time, most decisions are taken at the national level (see Table 1), which might be a barrier for smaller organizations that represent, for example, local communities and civil society to contribute with knowledge or express their potential concerns.

Table 1: Stakeholder mapping according to representation.

Stakeholder group	Organization	Role			
		Decision-makers (making strategically important decisions)	Implementers (puts the agreed decisions/plans into effect)	Coordinators (organizing people and activities for effective cooperation)	Knowledge provider (provides knowledge on solutions and development experiences)
SH1: National authorities	Swedish Agency for Marine and Water Management	X		X	X
	Swedish Energy Agency	X		X	X
	Svenska Kraftnät	X	X	X	X
	Swedish River Basin District Authorities	X	X	X	
SH2: Regional authorities	Regional Water Authority (Bothnian Bay)	X		X	
	County administrative board (Länsstyrelsen)	X		X	X
	Region Norrbotten				
SH3: Local authorities	Norrbotten municipalities: Arjeplog, Arvidsjaur, Boden, Gällivare, Haparanda, Jokkmokk, Kalix, Kiruna, Luleå, Pajala, Piteå, Älvsbyn, Överkalix och Övertorneå	X	X	X	
SH4: Research Community	Kungliga Tekniska Högskolan (KTH)				X
	Chalmers				X
	Luleå Tekniska Högskolan (LTH)				X
	Energiforsk				X
	Profu				X
	Umeå University				X
SH5: Energy companies	Vattenfall		X		X
	Skellefteå Kraft		X		X
	Jämtkraft		X		X
	Vattenregleringsföretagen				X
SH6: Civil society	Sámi Reindeer herding communities				X
SH7: Environmental NGOs	Naturskyddsföreningen				X
	Älvräddarna				X
	WWF				X
	Sportfiskarna				X

4. Hydropower and the freshwater environment

The ongoing technical and regulatory changes discussed in Sections 2 and 3 will have significant impacts on the freshwater environment. In this section, we explore the relationship between hydropower, the freshwater environment and ecosystem biodiversity from a Swedish as well as Nordic perspective, since river ecosystems should be seen from a more holistic, regional point of view.

4.1 Norrbotten rivers' hydrologic and ecological status

The detailed reconstruction of natural flow regimes across Sweden reveals an impact of hydropower production on both the local and national flow regimes (Arheimer et al., 2017). According to the model results for the whole of Sweden, hydropower has a significant impact on the seasonal distribution of flow, as water is stored during the high flow of the spring snowmelt from May to July and released during winter when electricity is needed most (Arheimer & Lindström, 2014). This study was done on eight hydropower stations located on six Swedish rivers, which included the biggest ones, Luleälven, Umeälven, Ångermanälven and Indalsälven, as well as Motalaström and Göta älv; it showed that hydropower production has changed the total river-flow regime in Sweden (Arheimer & Lindström, 2014). In an average year, Sweden redistributes water by 19% due to dam regulation (including rivers that are regulated as well as rivers that are not). As a result of dam storage, spring peak flows have been diminished by 15%, while winter flows have increased considerably. Also, flow duration curves show dampening of both high and low flow extremes due to regulation (Arheimer & Lindström, 2014).

Short-term regulation has also altered the sub-daily flow regimes of regulated rivers. When compared to the free-flowing (unregulated) Vindel River, hydropower sites on the Ume River have shown higher sub-daily flow fluctuations and lesser periods of stability (Bejarano et al., 2017). The frequency with which hourly river flow changed was remarkably higher in the Ume River than in the free-flowing river. But these frequent changes in the flow on the regulated river were smaller in magnitude than on the free-flowing river. The impact on the sub-daily flow patterns also varied seasonally. Hence, the short-term flow regime of Ume River is strongly impacted by hydropower production.

Long-term changes to river flow in northern Swedish rivers due to hydropower exploitation have led to a loss of biodiversity and have increased threats to iconic fish -- salmon, brown trout and grayling, especially (Heggenes et al., 1996; Rivinoja et al., 2001; Saltveit et al., 2001). Studies of the tributaries to two impounded Arctic rivers, the Ume and Lule rivers, showed low fish diversity and losses of almost all running water habitat in the main stem of the Ume River during times when hydropower production uses up all the flow(Näslund et al., 2022; Widén et al., 2021). Brown trout, which is known for its ecological and recreational significance, has faced severe population declines and is nearly entirely gone from the main river stem of the Ume River, while only remnant grayling populations remain (Widén et al., 2021).

4.2 Load balancing and hydropeaking

The role of hydropower as an intermittent load balancing energy source must balance with opportunities for improving environmental conditions in river systems in Sweden. Long-term river use for hydropower removes or dampens natural river flow variations, and the implementation of a free market for electricity production already has led to more variable flows because of more intense hydropeaking practices (Ashraf et al., 2016, 2018).

On larger timescales, such as annually or seasonally, hydropower plants regulate and dampen river flows by storing river water in large reservoirs to ensure a consistent supply for hydropower generation. This regulation smooths out the natural long-term extremes of high and low flows; however, at sub-daily levels, hydropower generation increases flow variations downstream due to hydropeaking (Ashraf et al., 2018). Facilities often adjust their outflow in response to electricity demand, which fluctuates on sub-daily time periods, leading to sudden increases (“peaks”) in water discharge. These artificial fluctuations in flow downstream of hydropower reservoirs, ranging from phases of very low to no base flow when there is no electricity generated to high ramping rates when electricity demands increase, result in faster and erratic flow changes (Bruder et al., 2016).

Hydropower operating rules under the influence of energy market dynamics determine when and how long these phases last, as well as how much and how quickly the discharge changes during each phase. This, in turn, affects hydrologic, hydraulic and water quality parameters (Pulg et al., 2016; Shen & Diplas, 2010; Vanzo et al., 2016; Zolezzi et al., 2011) both downstream and upstream of the hydropower installation. Because of the oscillating cycles of water storage and discharge downstream, water levels in impoundments upstream of power stations can fluctuate greatly. These changes in fluvial processes trigger biological changes in river reaches affected by hydropeaking, exacerbating negative ecosystem impacts.

Downstream, these negative impacts include impact on aquatic organisms (Casas-Mulet et al., 2016; Harnish et al., 2014), fish habitat destruction (García et al., 2011), streambed habitat alteration (Cristina Bruno et al., 2010), thermal regime disturbances (Choi & Choi, 2018) and degradation of recreational services (Brown et al., 1991; Brunson & Shelby, 1993 , Virk et al., 2024). Most studies quantifying the effect of hydropeaking on riparian ecological status include only fish and macroinvertebrates, but hydropeaking has also been shown to affect riparian vegetation, which is also a key element of fluvial ecosystems. As a result of rapid and frequent changes in discharge and water level, inundation and drawdown, the resulting sediment scouring and ice disturbance may affect seed germination and plant growth, or destruction of plants (Bejarano et al., 2018).

Hydropeaking also can lead to the homogenization of riparian vegetation, by filtering out species that lack traits required to bear this artificial phenomenon and opening spaces for invasion by exotic species. Among riverine plants, terrestrial wetlands and submerged and floating aquatic species are most susceptible to hydropeaking conditions, potentially being removed or shifted towards the upper or lower river-margin limits (Bejarano et al., 2018).

Where the implementation of environmental adaption measures reduces the possibility for hydropeaking, hydropower installations will have reduced capacity and flexibility to contribute electricity to the grid; this means that investments in other power sources or technologies for storage might be necessary, according to recent modelling studies. The environmental effects of such choices will depend on the type of technologies used to replace the lost hydropower potential (Gode et al., 2022).

These investments may turn out to be necessary no matter what, given climate changes and the increasing demand for electricity. In Europe, the gross hydropower potential because of hydrologic change is expected to increase in the north but decrease in most of central and southern Europe, as climate change leads to precipitation shifts and droughts (Lehner et al., 2005). For Sweden, the gross hydropower potential is projected to increase by more than 30% to the 2070s. Potential power production will rise because of the predicted increase in the run-off in central and northern Sweden, where most of the hydropower capacity is installed.

Increases in river flows could mean an increased generation of electricity and bring new opportunities for dam operation and meeting environmental and recreational needs (Arthington et al., 2006). However, such climatic shifts also could require other changes: current hydropower installations were not built for projected run-off conditions in a changing climate, which would fit better to run-of-river projects than damming and pumped hydropower that currently dominate Sweden’s current hydropower production (Ashraf et al., 2018).

4.3 Needs, methods and knowledge gaps

There is currently a knowledge gap regarding the impacts of the major changes currently affecting the energy industry on hydropower reservoir operation practices. As energy systems incorporate more variable sources (e.g. wind, sun), hydropower will become more important as a load balancing source (Gaudard & Romerio, 2014), given the widely variable nature of these resources on a short timescale (Raynaud et al., 2018). This will lead to more hydropeaking as a method to balance the electricity grid and energy demands, leading to more environmental damage – thus the potential effects of more hydropeaking need to be evaluated in more detail for Nordic rivers (Ashraf et al., 2018).

Such evaluations will need to consider ecological conservation, economic development and social impacts; they will also need to find ways to adapt hydropower operational practices that take into account all of these aspects (Couto et al., 2021; Sabo et al., 2017; Winemiller et al., 2016). Thus, sustainable river management calls for methodologies to quantify hydropeaking and its relationship with power market demands.

The need for more efficient hydropower should be coordinated with efforts to protect biodiversity. A place to start could be identifying solutions like efficient fish passages, which have significant ecological benefits with relatively small losses in power production. If such measures are implemented, fisheries could be compensated and the negative externalities of hydropeaking would be internalized by the positive effects of improved hydropower output.

Finding ways forward will also require deeper stakeholder mapping and efforts to examine where stakeholders may have more or less opportunity to inform decisions, and how that could imbalance future plans for hydropower. Better mapping will improve decisions made for the environment, efficiency and other aspects of hydropower.

5. Conclusions

Under such circumstances as described above, hydropower can be complementary to future baseload wind power, necessary to cover industrial needs, and play a significant role in meeting the growing energy demand in northern Sweden. But upgrades may be needed to optimize systems and handle new energy sources, and these changes must be made with environmental protections in mind.

We recommend decision-makers consider the following two aspects when making assessments regarding hydropower's future role in northern Sweden (Xylia et al., 2023):

- enhancing efficiency and coherence when it comes to hydropower station operation;
- addressing synergies and trade-offs that occur in the pursuit of achieving sustainability goals, environmental targets and socioeconomical development plans.

There is a clear need for an integrated economic and ecological framework to regulate hydropower operations on Nordic rivers. The decisions on how to go about achieving it are political, with river conservation, restoration and environmental flow actions being crucial components. Addressing these issues, which could include better design, "smart" water management and active monitoring, might make it possible to operate or even expand hydropower production sustainably. This can even be facilitated by the predicted increase of run-off in a changing climate, creating enough water for both hydropower production and ecosystem functioning.

One place to start would be more systemic environmental assessments of water and energy infrastructures and their implications for the river ecosystems at their locations, as water and energy infrastructures share the same water resources. Such assessments enhance efficient and coherent planning for dam operation, energy generation and industrial output, while also addressing synergies and trade-offs between sustainability goals, environmental targets, economic policies and social development. These may evolve based on various hydropower dam operation scenarios, hydroclimatic conditions and socio-economic development pathways.

Given the necessary trade-offs required to preserve and enhance hydropower's production and flexibility capacity, the Swedish government in collaboration with its Nordic counterparts should explore and implement various strategies to increase the flexibility of the electricity system to cater for increased intermittent renewable energy sources. Some of these changes are already under way, such as the Nordic balancing model, and there is significant flexibility potential in combining electricity and other energy sectors, such as heating, as well as promoting active demand-side response. However, efforts need to accelerate.

In summary, the changing climate and increasing energy demand are transforming the hydropower industry, creating new pressures and opportunities for ecosystems. As hydropower becomes a flexibility source and wind power serves as the baseload, the implications for water systems and biodiversity must be considered. Efforts to improve efficiency and promote biodiversity should be pursued, and social and community perspectives should be included in hydropower planning to ensure future sustainability. Hydropeaking levels must also be evaluated to maintain and, as far as possible, improve current river ecological status, while balancing ecological conservation, economic development and social impacts. To achieve sustainable river management, methodologies must be developed to quantify hydropeaking and its relationship with power market demands, and a broader dialogue with actors beyond the energy industry is necessary. Ultimately, incorporating biodiversity preservation and community consultation in hydropower planning is essential for the long-term success of the industry.

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