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Hydropower development in the energy transition

Perspectives from northern Sweden

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Key messages

- **Policymakers should recognize the need for a comprehensive approach to hydropower that balances environmental protection with renewable energy goals.**
- **A potential shift towards utilizing wind power as baseload and hydropower as a flexibility source will change flow release patterns from reservoirs and affect aquatic life.**
- **Increased hydropeaking levels may pose challenges to maintaining the ecological status of rivers, which are rich in biodiversity and ecosystem services.**
- **The knowledge gap of how major changes in the energy industry will potentially change hydropower reservoir operation practices and our river flows should be addressed.**

Hydropower can serve as more than a source of baseload electrical capacity, and its storage applications are increasingly vital in achieving greater system flexibility and balancing intermittent renewable energy sources (United Nations, 2020). Upgrading existing hydropower facilities to increase power output and optimize multiple water demands, however, requires significant investments. Therefore, it is essential to develop models that aid in decisionmaking regarding hydropower capacity expansion by exploring strategies that meet both energy demand and environmental targets. This includes examining the role and added value of innovative technologies, as well as identifying the optimal time to invest (Heuberger et al., 2017).

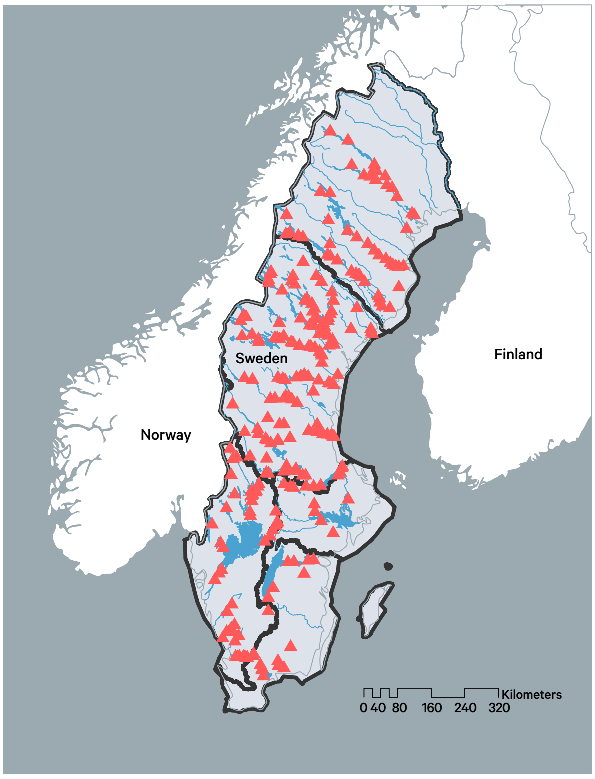
Sweden is a representative case for countries where hydropower is important in the energy transition. Traditionally a source of baseload electricity, hydropower's role will change in the future as the share of other renewable energy sources (wind, solar) increases in the energy mix, thus requiring its flexible load balancing capabilities for a well-functioning, balanced grid.

At the same time, pressure on water ecosystems and biodiversity can increase due to these changes. Hydropower regulations in Sweden are under revision in order to balance these two perspectives, but key questions to address in this context remain: What is the future role of hydropower with regards to the challenges that electricity grids are facing under increased demand? What social, technical and organizational innovations are needed to address future energy and water demands while safeguarding water, ecosystems and biodiversity?

IMAGE (ABOVE): Hydropower, Sweden

In this brief, we discuss the trade-offs and challenges Swedish hydropower is facing in recent years and offer policy recommendations on how to balance them. These insights are based on literature review of the latest academic and grey literature, as well as material from stakeholders and authorities directly involved with the energy transition in northern Sweden. More specifically, we look into three major aspects: the changing role of hydropower in the energy transition, challenges related to hydropower's impacts on the freshwater environment, and how recent changes to governance frameworks can lead to new trade-offs between energy and biodiversity to consider. Finally, we offer policy recommendations addressing the main issues we see as necessary to address for improving hydropower planning processes.

Figure 1. Swedish hydropower plants above 3 MW (red triangles) and water districts (black lines).



Source: SEI, adjusted from eurofresh.se.

1. Hydropower in Sweden

Sweden's hydropower production averages 65 Terawatt-hours (TWh)/year, with a dam energy storage capacity of 34 TWh, accounting for 25% of the country's annual electricity consumption. Hydropower is generated across approximately 2100 stations across the country (see Figure 1) with a combined installed capacity of 16.2 Gigawatts (GW). Most of the Swedish hydropower (around 95%) is produced in 208 stations (less than 10% of the total number of hydropower stations) (Energimyndigheten & Havs- och Vattenmyndigheten, 2014).

The Swedish energy market is supported by a very high share of dam hydropower generation capacity which has high flexibility potential at various timescales (Svenska Kraftnät, 2022a). Hydropower also dominates the electricity grid's frequency regulation services in the flexibility market, delivering energy in only a few seconds to meet immediate needs or up to a month ahead, which help energy networks create necessary signals to adjust energy supply and demand. Such markets will be very important for efficiently utilizing intermittent renewable energy sources and further promoting grid decarbonization.

As battery storage deployment in the Swedish grid increases, it can be expected that the share of batteries in some of these frequency regulation services will increase, but hydropower will still play a vital role in balancing the system.

2. The role of hydropower in the energy transition

Northern Sweden will probably experience extreme increases in energy demand due the expansion of industrial activities in the area, such as the fossil-free steelmaking ventures of HYBRIT and H2 Green Steel, steelmaking (SSAB), mining (LKAB), and battery production (Northvolt).

About 80 TWh/year are needed to cover northern Swedish industrial electricity demand by 2028, without considering data centres or household consumption expansions (Region Norrbotten & Energikontor Norr, 2022). For reference, the total electricity use in the country was 135 TWh in 2020 (Energimyndigheten, 2022), so that would be approximately 60% of today's use. There are plans to increase electricity grid capacity by 5000 MW to connect 4000 MW of renewable energy production, mostly from new wind power installations (Svenska Kraftnät, 2022b). The goal is to have 100 TWh of wind power by 2040, with 80% coming from onshore wind (Energimyndigheten, 2021a).

Table 1. Glossary of useful terms in the energy-water nexus field.

Term	Explanation
River regulation	The management and control of river flow through the construction of hydraulic structures like dams, reservoirs, and weirs, or through the implementation of various water management practices.
Baseload power	The lowest amount of electricity demanded by an electrical supply system, usually throughout a 24-hour period. Baseload power sources are plants capable of consistently producing power to meet steady demand. Hydropower and nuclear plants are usually producing baseload power.
Electricity grid	An interconnected network of power generation, transmission and distribution facilities that enables supply of electricity from power plants to consumers.
Intermittent energy sources	Intermittent power sources refer to renewable energy generation technologies that produce electricity in an unpredictable or varying manner due to their dependence on environmental conditions. Solar and wind power are common examples of intermittent energy sources.
Hydropeaking	An artificial pattern of river flow that occurs when the output of a hydroelectric dam is increased during periods of peak electricity demand.
Multi-stakeholder platforms	These physical or digital (often a mix) spaces where stakeholders from across society participate in the decisionmaking process and information sharing at the country level. Platforms can have different levels of formality, including supporting and advising a process or an organization, or taking decisions at one or several stages in a process.

Increased hydropower output can be achieved in two ways: by upgrades and more effective use of existing plants, or by exploiting protected rivers. Improvements in turbine design and control systems, implementation of machine learning and predictive algorithms, and better resource management, for example, are estimated to lead to an 8–10% increase in power generation (O'Connor et al., 2016). Major increases in hydropower output, though, should not be expected for countries like Sweden which have a strongly established capacity and environmental regulations that seek to protect unexploited rivers. In Sweden, this is a recent and long-term process encapsulated in The National Plan of Hydropower Permit Review (NAP) to promote efficiency upgrades in existing hydropower stations while limiting negative effects on the existing water bodies.

The Swedish electricity grid faces pressure for quick upgrades to the transmission lines due to industry expansion; hydropower and wind power can provide capacity and flexibility, but upgrades are needed for intermittent sources. The current situation also presents opportunities to modernize hydropower plants and enable them to provide vital services to power systems, including pumped hydropower which has received increased attention in recent years with more abundant intermittent renewable energy sources that benefit from its storage potential (IRENA, 2023).

Another factor to weigh in the equation is climate change, which will shift snow timing and glacier melt as well as precipitation patterns (Mishra et al., 2020). Swedish hydropower production, for example, is predicted to be similar to today's levels by 2050, with slight net increase (0.5 TWh) balancing climate change impacts and stricter regulations (Energimyndigheten, 2021b; Svenska Kraftnät, 2021). However, other studies point out an increase in hydropower potential in the Nordic region based on hydrological projections, as climate models like CaEMS2 and MPI-EMS-LM project a large increase in precipitation (Chernet et al., 2013; Shevnina et al., 2018). Questions remain as to whether current governance models are prepared for the future role of hydropower. Increased hydropower production will also have consequences for ecosystems' biodiversity.

3. Impact of hydropower on the freshwater environment

Hydropower production has a significant impact on the seasonal distribution of flow and alters sub-daily flow patterns, causing a loss of biodiversity and negatively affecting river ecosystems (Arheimer et al., 2017). In an average year, Sweden redistributes 19% of its river waters by regulation, including both regulated and unregulated rivers (Arheimer & Lindström, 2014). As a result of dam storage, spring peak flows have been diminished by 15%, while winter flows have increased considerably (Arheimer & Lindström, 2014). Also, flow duration curves show dampening of both high and low flow extremes due to regulation.

Long-term river regulation of large boreal rivers in northern Sweden by hydropower dams has resulted in the loss of biodiversity, including the loss of a large proportion of main stem shallow flowing habitats (Englund & Malmqvist, 1996; Jansson et al., 2000; Nilsson et al., 1991). The upstream migration of Atlantic salmon in many Baltic Sea rivers has been eliminated or substantially reduced due to damming and hydropower generation (Rivinoja et al., 2001). There have been notable declines in the populations of brown trout and grayling (Heggenes et al., 1996; Saltveit et al., 2001). Brown trout is no longer present in the main stem, and only remnants of grayling populations remain, as reported by Widén et al. (2021).

Another issue is how hydropeaking, the sudden release of water from hydropower reservoirs to meet energy demand, is deployed. Northern Swedish rivers like the Ume, for example, have shown high levels of hydropeaking (Alonso et al., 2017). Because of the detrimental environmental impacts of hydropeaking, there are growing concerns about escalating trends in hydropeaking associated with the rise in wind energy penetration, both in the Nordics and globally (Ashraf et al., 2018; Haas et al., 2015; Jager et al., 2022) .

Hydropeaking causes artificial fluctuations in downstream flow, affecting hydrologic parameters and water quality. Hydropeaking on downstream ecosystems negatively impacts aquatic organisms (Casas-Mulet et al., 2016; Harnish et al., 2014); destroys fish habitats (García et al., 2011); alters hyporheic habitats, the areas of the streambed and near-stream aquifers through which stream water flows (Cristina Bruno et al., 2010); causes thermal regime disturbances (Choi & Choi, 2018); and degrades recreational services (Brown et al., 1991; Brunson & Shelby, 1993). River regulation may also cause riparian vegetation homogenization by filtering out species that lack traits required to bear this artificial phenomenon and cause invasion by exotic species (Jansson et al., 2000).

As a result, recent discussions have focused on restoring ecological flows in constructed rivers to achieve good ecological status as required by the EU Water Framework Directive (Voulvoulis et al., 2017). As the demand for hydropower increases, water management in the Nordic countries has become an important issue to improve hydropower production and balance load demands (Latola & Savela, 2017).

4. Hydropower governance in Sweden

In 2018, Sweden made changes to legislation affecting hydropower production and river restoration. In a joint national strategy planning document, the Swedish Agency for Marine and Water Management (SwAM) and the Swedish Energy Agency (STEM) set a limit of 2.3% loss of the annual hydropower production, equal to 1.5 TWh/year, that river restoration measures related to hydropower production should be allowed to cause on a national level (Energimyndigheten & Havs- och Vattenmyndigheten, 2014). Sweden's national strategy for hydropower is geared towards flexibility and efficiency-increasing measures in existing large-scale (>10 MW) hydropower installations. Furthermore, it is envisioned that passage facilities and minimum flow should be established in 60 large hydropower stations with conditions favourable for fish passage and all smaller hydropower stations (< 10 MW) (HaV, 2019).

In addition, the NAP is meant to coordinate the permit review process at a national scale over the coming 20 years. It encourages modification of existing hydropower stations to increase their installed effect and production capacity, while also prioritizing river restoration. A private fund financed by major producers will cover most costs of these measures (HaV, 2019). However, by increasing the installed effect and production capacity of existing large-scale stations' hydropower, the rate and scale of change of river flow will also increase, potentially augmenting the ecological damage in the affected river basins (Bejarano et al., 2017).

Due to the recent energy price crisis, the process for the permit reviews has been paused for a year (Regeringskansliet, 2022). While energy companies welcome the decision with regards to the ongoing energy system challenges (Energiföretagen, 2022), environmental organizations focused on river habitats warn that such decisions are disrupting long-term anchoring processes, and not only risk the extinction of many fish species, but also high fines from the EU Commission for Sweden's failure to comply with the Water Directive (Älvräddarna, n.d.; Lexén et al., 2023).

There are thus important questions, trade-offs and hurdles that the implementation of the NAP will face, and new analytical tools will be needed for offering solutions that balance energy needs with biodiversity requirements.

5. Recommendations to improve hydropower planning

There is a need for more comprehensive systemic environmental assessments of water and energy infrastructures and their implications for riverine ecosystems in their specific locations, as these share the same water resources. Such assessments should:

- **enhance efficient and coherent planning** for dam operation, energy generation and industrial output

- **address synergies and trade-offs** between sustainability goals, environmental targets, economic policies and social development that may evolve based on various hydropower dam operation scenarios, hydroclimatic conditions, and socioeconomic development pathways.

The multifaceted challenges presented by climate change and the transition towards a fossil-free society are disrupting the traditional paradigm of hydropower as a clean, renewable and sustainable source of electricity. Northern Sweden is a perfect example where these issues have already come into play, but more regions around the world will face similar challenges. Policymakers should therefore recognize the need for a comprehensive approach that balances environmental protection with renewable energy goals.

- **Policy recommendation**: Ensure the review process facilitated by the NAP is evidence-based. Better models and data need to show efficiency and effectiveness beyond electricity production to also include environmental and socioeconomic impacts in the context of hydroclimatic change. Outcomes should suggest actions that give more bang for the buck across all pillars of sustainability, including the places or interventions that would provide most gains and least impacts.

The shift towards utilizing wind power as baseload and hydropower as a flexibility source raises questions about the implications for water systems and biodiversity. Coordinating with industrial actors that are already established or planning to establish operations in northern Sweden is crucial to ensure a coherent plan for upgrading the electricity grid to meet the growing demand.

- **Policy recommendation**: Foster collaboration between local authorities, water authorities, transmission and distribution grid operators, hydropower operators, wind power developers, and other relevant stakeholders to develop coordinated strategies that optimize grid upgrades and renewable energy source utilization, considering the environmental impacts on water systems and biodiversity.

Previous research has shown that there is significant potential for efficiency improvements in hydropower operations and measures to promote biodiversity.

- **Policy recommendation**: Revise hydropower planning processes to include community involvement, incorporating social and environmental perspectives into decisionmaking. Ensure that the benefits and impacts of hydropower projects are shared equitably among affected communities, spread justly throughout the country, and account for intragenerational justice.

The increase in hydropeaking levels may pose challenges to maintaining the ecological status of rivers, which are rich in biodiversity and ecosystem services. The potential effects of hydropeaking require more detailed evaluation, particularly in Nordic rivers. Sustainable river management needs methodologies to quantify hydropeaking and its relationship with power market demands.

- **Policy recommendation**: Conduct thorough assessments to understand the ecological impacts of hydropeaking on rivers and develop operational practices that balance the needs of ecological conservation, economic development, and social impacts. This could include incorporating environmental flow requirements into hydropower operation scheduling, optimizing dam release patterns to minimize ecological disruptions, and exploring the potential for energy storage technologies to mitigate hydropeaking impacts.

Currently, there is a knowledge gap regarding the impacts of major changes in the energy industry on hydropower reservoir operation practices. A significant share of the data needed for such analyses is unfortunately not open access.

- **Policy recommendation**: Invest in research, data collection, and open data management to improve understanding of the effects of changing energy industry demand on hydropower reservoir operations. Develop methodologies to quantify and mitigate the impacts of hydropeaking on river ecosystems. Policymakers should promote the implementation of adaptive management strategies for river systems affected by hydropeaking. This involves agreeing on monitoring and assessment programs that enable continuous evaluation of ecological impacts, identification of potential mitigation measures, and adaptive implementation of management actions based on monitoring results. It is essential to ensure that monitoring programs are adequately funded and have a long-term perspective.

A broader dialogue with actors beyond the purely energy perspective of hydropower, incorporating diverse dimensions and viewpoints into decisionmaking processes is therefore necessary.

- **Policy recommendation**: Establish platforms for multi-stakeholder engagement, including representatives from environmental organizations, indigenous communities, residents, and relevant government agencies. Encourage open and transparent discussions to address the social, economic, and environmental aspects of hydropower development. Policymakers should encourage collaboration between environmental agencies and power market operators to develop mechanisms that consider ecological factors in power generation and distribution.

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