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RESEARCH ARTICLE

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Rivers under pressure: Interdisciplinary feasibility analysis of sustainable hydropower

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Abstract

Global biodiversity loss is most severe in freshwaters, particularly in river ecosystems. Hydropower is one of the main culprits. While being promoted as a carbon free source of renewable energy, hydropower disrupts the flow, habitats, and biota of rivers. Environmental policies and programs seek to mitigate the damage hydropower causes. Any policy action aiming at making the utilization of our rivers more sustainable must be ecologically, economically, and legally feasible. We show that the interdisciplinary feasibility of mitigation measures divides existing facilities into three categories (i) large facilities in which biodiversity mitigation measures are needed but electricity generation and balancing the electricity grid should remain as their main focus, (ii) small facilities in which dam removal and full scale river restoration measures can be taken by assisting the facilities to seize operations, preferably just before their next big investments, and (iii) medium facilities where benefits and trade-offs associated with alternative paths should be analyzed case-by-case to determine the most feasible path forward. Policy action is feasible in all three categories but in different ways: requiring fish passes in the case of large facilities, helping remove dams and restoring the rivers in the case of small facilities, and focusing cost–benefit analysis efforts on the non-trivial group of the medium sized facilities.

KEYWORDS
dam removal, hydropower, mitigation hierarchy, river biodiversity

1 | INTRODUCTION

Sustainable hydropower is elusive. In 2019, hydropower provided 4250 TWh or 17% of the global electricity demand (International Energy Agency, IEA, 2020a). Hydropower is the largest source of renewable energy with further growth expected to meet the greenhouse gas reduction targets of the Paris Agreement (International Energy Agency, IEA, 2020b). Hydropower also continues to be one of the most inexpensive sources of electricity (IRENA, 2021).

However, hydropower is detrimental to biodiversity. Lakes, reservoirs, and rivers cover only about 2% of Earth's surface but host approximately 10% of all known animal species (Reid et al., 2019). Globally, freshwater ecosystems are the most threatened environments with serious declines in the number of species, populations, and biodiversity (Higgins et al., 2021). Within freshwater ecosystems, river biodiversity has been hit particularly hard (Tockner et al., 2011; Vörösmarty et al., 2010).

Mirroring the elusive nature of hydropower's sustainability, public policies governing it are ambiguous. The tradeoff is clear in Europe, which strives for progressive sustainability policies in all dimensions of the United Nations 2030 Agenda. EU's climate policy promotes renewables but the EU Biodiversity Strategy for 2030 (COM[2020] 380 final) and the EU Water Framework Directive (2000/60/EC, art. 4) aim at preventing further deterioration and at promoting the restoration of freshwater biodiversity. As a concrete target, the biodiversity strategy calls for restoration of 25,000 km of free flowing rivers (COM[2020] 380 final).

In addition to the tedious tradeoffs and conflicting policy goals, societal decision-making is faced with a mature hydropower industry structure. In the 21st century, the rate of introducing new hydropower generation capacity in Europe has slowed down as over 50% of the hydropower potential is already exploited (International Energy Agency, IEA, 2018; IPCC, 2012). Strikingly, dams built for hydropower, irrigation, and flood control generate about 1.2 million disruptions on river continuity, translating to on average 0.74 barriers for each river kilometer in Europe (Belletti et al., 2020). The challenge for societal decision-making is that hydropower facilities are long-lived and often built under very different socio-economic reality from today's world. Decision-makers perceived non-market values less important than energy supply during the era of rebuilding Europe after the WWII, when most of the hydropower dams were built (Moran et al., 2018). The societal setting, however, has changed considerably since then. Valuation of the environment has increased with the standard of living, and technological development has made solar and wind the most competitive sources of energy in many regions (IRENA, 2021).

The changed societal setting around hydropower has prompted societies to promote the sustainability of existing hydropower operations. An obvious question is: How to best reconcile hydropower and environment to meet the current societal needs? However, with the stark multidimensional constraints, perhaps a more plausible question would be: What changes are possible in the first place, and what is the best choice, acknowledging the constraints. These constraints need to be overcome even if there were a strong political will for a change. The local geographical, climatic, and other ecosystem characteristics determine the ecological needs for and the impact of mitigation measures. The set of economically feasible measures in turn is affected by the age, size, and other characteristics of any hydropower facility. Moreover, hydropower facilities may enjoy ongoing financial support making the existing industry structure even more protected (Bundesnetzagentur, 2021). Finally, even though influenced by international legal framework, it is the contemporary national law, which renders mitigation measures and/or dam removals legally feasible or infeasible. It also impacts the economic feasibility by, for instance imposing protections on hydropower investments and requirements for compensations of economic losses (Soininen et al. 2018).

This article analyses the feasible options to improve the sustainability of existing hydropower operations from ecological, economic, and legal perspectives. Our approach starts by sketching the ecological, economic, and legal boundaries for re-evaluating existing hydropower operations, that is, by defining what is possible in any particular case. We use Finnish hydropower industry as a case study to ground our analysis. Finland is a fitting case study country as it has a rather typical history beginning with industrialization, increased need for electricity driven by energy security issues during WWII and economic growth after the war. At the same time, we recognize that Finland typically hosts single-purpose dams while globally multi-purpose dams for power generation, irrigation, and flood management are more common. Despite this difference, we maintain that Finland provides a solid case study for the article.

The rest of the article is organized as follows. In Section 2, we discuss the theoretical and methodological framework for the interdisciplinary analysis. In Section 3, we analyze the ecological aspects of hydropower and the most common methods to mitigate adverse impacts. In Section 4, we discuss the market- and firm-level economics of hydropower. In Section 5, we present our case study context, the Finnish hydropower industry, and the legal factors that push for a change and those resisting it. In Section 6, we synthesize our analysis and provide a feasibility taxonomy for re-evaluating existing hydropower facilities in different size categories. We also discuss the policy implications of our findings. The last Section concludes the article.

2 | THEORETICAL AND METHODOLOGICAL FRAMEWORK

The scientific analysis of river biodiversity and economic activities can be approached from two different, often complementary perspectives. One alternative is to look at rivers at a systemic level to map the current status of biodiversity, recognize the most significant pressures, and suggest ways forward from a bird's eye perspective (e.g., analogically to Elmqvist et al., 2019 in an urban context). A key shortcoming in such analyses is that they do not typically include the legal, economic, political, or other limitations the actors operating and making decisions in the system are facing even though such limitations are mentioned and discussed when reflecting the implications of such analysis to reality. A second alternative is to focus on the feasibility of implementing the global and EU biodiversity goals from the perspective of actors on the ground, mainly public authorities and hydropower operators (analogically to Patterson et al., 2021 in an urban context). In essence, the feasibility perspective seeks to make visible the detailed challenges and opportunities in implementing the biodiversity goals.

Our interdisciplinary approach considers the short- and long-term drivers of the hydropower industry. We address ecological feasibility by using an ecosystem approach in combination with defined ecological mitigation measures (Arlidge et al., 2018; Link, 2010; Link et al., 2008; McLeod & Leslie, 2009). The economic analysis of feasibility comprises – as in, for instance Borenstein (2012) – both public and private economics of hydropower including externalities. The legal feasibility is based on doctrinal analysis of the law (Hutchinson & Duncan, 2012).

Methodologically, the article is based on interdisciplinary co-production of knowledge (e.g., Norström et al., 2020). Co-production operates both between scientific disciplines as well as between science and societal decision-makers (Mauser et al., 2013). The article is produced by the SusHydro consortium funded by the Academy of Finland. The consortium consists of experts from three disciplines: ecology, economics, and law. The disciplinary knowledge is a synthesis of existing literature and the expertise of the consortium members. Beyond the consortium (transdisciplinary co-production), the consortium members have in the past 5 years actively participated in several policy processes discussing the future of hydropower.[1] The views of earlier workshops and other events, discussions and email exchanges with the Finnish ministry officials, permit and planning authorities, NGOs and the hydropower industry have steered us toward the analysis of feasibility in general, and helped us outline the key challenges and feasible ways forward for the future of hydropower.

3 | ECOLOGICAL CONTEXT—EXTERNALITIES OF HYDROPOWER

3.1 | The ecological impacts of hydropower

The robustness of our global life support system hinges on biodiversity (Chapin Iii et al., 2000; Díaz et al., 2006). The ecological and social resilience provided by the diversity of genes, species and ecosystems becomes particularly valuable as climate change causes abrupt and unpredictable changes to living conditions across the globe (Dawson et al., 2011). Hydropower affects the flow, habitats, and biota of rivers (Kuriqi et al., 2021). Damming makes a naturally flowing river (lotic) ecosystems resemble a chain of pools more typical for lake (lentic) ecosystems (Ellis & Jones, 2013). Hydropower changes the natural variability of the river flow for which the local ecosystem has been adapted over the course of several millennia (Poff et al., 1997). Altering natural river flow changes the discharge and water velocity patterns (Anderson et al., 2015). At the extreme, hydropeaking (i.e., intensive short-term regulation) strands small fish and dries up shores and suitable habitats (Batalla et al., 2021; Smokorowski, 2022).

Hydropower dams fragment habitat by breaking the river continuum (Grill et al., 2019). Stream biota depends on the river flow. Downstream drifting invertebrates serve as feed for various species and nutrients are utilized by primary producers (Allan & Castillo, 2007). Fragmentation hinders migration between different habitats needed by many species during their life cycle. Suitable habitats may also be changed from a stream habitat to a lentic environment (Wang et al., 2020).

By inhibiting migration, hydropower has contributed to the collapse of valuable trout and salmon stocks (e.g., Bradford, 2022; Gibeau et al., 2017). Dams prevent upstream and downstream migration as turbines cause injuries to and mortality of fish. However, the effects on river biota are more profound (Bowes et al., 2020; Jones, 2013; Nilsson & Berggren, 2000). With the loss of longitudinal connectivity, the behavior and physiological alteration of aquatic species changes from stream-adapted to local populations. If natural stream habitat upstream is available, stream-adapted populations can sometimes persist and become secluded. However, lentic species become prevalent.

3.2 | Measures to mitigate ecological impacts

Measures to mitigate the ecological impacts of hydropower should help reconnect the disrupted river flow, restore habitats and revive biota (Schramm et al., 2016; Yu & Xu, 2016). According to the established principles the environmental impacts should be (1) avoided, (2) minimized, (3) remediated, and if the first three options are not feasible, (4) offset (Arlidge et al., 2018). Offsetting that is, compensating the harm by restoring habitats elsewhere, has not been studied extensively nor conducted in practice in the hydropower sector, even though guidance material exists (IHA, 2021; TBC, 2016). Therefore, we exclude offsetting from our discussion.

With existing hydropower operations, avoiding the ecological impact of power generation is no longer an option. Minimizing the negative impact on migratory fish includes measures such as fish stockings and building of fish passes. A fish pass can be seen merely as a fish migration route (technical fishway), or it can also provide mitigation habitat (natural bypass). Stockings have often turned out to be unsuccessful or even harmful (Agostinho et al., 2010; Pompeu et al., 2012; Winemiller et al., 2016). For sustaining the resilience of river ecosystems minimizing the impacts should preferably be based on maintaining an environmental flow close to the natural flow of the particular river (Arthington et al., 2018; Yu & Xu, 2016).

The most effective remediation measure is obviously dam removal which usually enables ecosystems to recover fully (O'Connor et al., 2015). Brown et al. (2013) demonstrate the poor total efficiency of sequential fish passages and provide strong arguments for dam removals. Restoring disturbed parts of the river can be a viable alternative, if done in close proximity to non-degraded habitats, so that organisms can colonize restored habitats (Scruton et al., 2005). Additionally, river fragmentation should be mitigated by fishways or bypasses.

3.3 | Impacts, mitigation measures and the size of the river

The ecological impacts of hydropower generation are different in large and small rivers (Poff & Hart, 2002; Wang et al., 2020). Large rivers and, consequently, large hydropower facilities (without reservoir capacity) are often situated in lowland areas. Typically, the mainstem of a large river has little habitats suitable for lotic species even in a pristine state. Natural-like bypass is an efficient option to allow for fish migration and to generate stream-type ecosystems (Clarke, 2016; Jormola et al., 2016; Scruton et al., 2005). However, ecosystem functions such as organic matter transport or habitat needs of certain migratory species (e.g., Atlantic salmon, Salmo salar) are associated with high discharge rates. These effects may thus not be attained with a typical small bypass structure.

Small hydropower operations are often constructed in high elevation areas and/or regions characterized by fragile river ecosystem where fluvial processes play an important role (Huđek et al., 2020). Small streams provide habitats for spawning fish which could be made accessible with bypasses. However, small streams are prone to hydropeaking periods. Therefore, environmental flow schemes should be used to complement the bypasses. This could require allowing for a full discharge via bypass. This would, however, be detrimental to electricity generation. Hence, dam removal is the most effective measure for small streams.

3.4 | Economic value of negative externalities produced by hydropower operations

Hydropower influences the provision and quality of a complex set of aquatic and terrestrial ecosystem services. In economic terms, the ecological impacts of hydropower are externalities—unintended effects of production affecting the wellbeing of others (Baumol et al., 1988). In the absence of price signals or regulation, markets overproduce negative externalities and underproduce positive externalities. Policies are needed to correct market failures. To design such policies, we need monetary estimates of externalities' welfare effects (Dasgupta, 2021; Gómez-Baggethun et al., 2010; Krutilla, 1967).

Hydropower externalities affect both use- and non-use values. Use-values arise from direct (e.g., fishing) or indirect (e.g., landscape values) utilization of ecosystem services. Non-use values encompass existence values, altruistic values for current and future generations and option values for later use of river ecosystem services (Rogers et al., 2019). Use-values can be economically valued through e.g., property market values (e.g., Lewis et al., 2008; Provencher et al., 2008) and outdoor recreation values (e.g. Håkansson, 2009; Laitila & Paulrud, 2008; Lienhoop & Ansmann, 2011).

Focusing on use-values limits beneficiaries to those with access to river ecosystem services. Recognizing passive, or non-use values expands the affected human population to a less spatially defined entity.

Environmental valuation literature suggests that hydropower externalities have a sizeable impact on non-use values (Håkansson, 2009; Mattmann et al., 2016; Tabi & Wüstenhagen, 2017). Including non-use values in cost–benefit comparisons of relatively large hydropower facilities in Lower Snake and Elwha[2] rivers (USA) made dam removal an economically best choice (Loomis, 2006). Riepe et al. (2019) finds large benefits for hydropower policies promoting biodiversity and abiotic services supporting recreation alongside hydropower production in France, Germany, Norway, and Sweden. Use-values alone can also justify changes in river management and restoration. Changes in water level and flow management in constructed rivers can induce considerable recreation benefits (Kotchen et al., 2006; Lienhoop & Ansmann, 2011). However, free-flowing rivers provide higher recreational benefits and property values than their dammed counterparts (Getzner, 2015; Provencher et al., 2008).

Scientific knowledge and people's preferences may change radically during the lifespan of a hydropower facility. Hence, it may be welfare improving and socially desirable to build a facility at one point in time and to demolish it at another. The Gold Ray Dam in Oregon, for instance, was both built and decommissioned using US Federal stimulus money (Duffield, 2011). Anticipating such changes, already Krutilla (1967) argued for retaining a wide variety of ecosystem services as a precaution.

The disturbed flows of riverine ecosystem services affect our wellbeing both directly and indirectly, and we can, to some extent, put economic value on them. We also understand that these values are dynamic and that recreation values alone represent a small part of the total economic value of river ecosystem services.

4 | ECONOMIC CONTEXT—HYDROPOWER AS AN INDUSTRY AND AS A BUSINESS

4.1 | Electricity markets and the value of electricity

The market economic value of hydropower stems from two sources. First, it creates profits for producers and surplus for consumers. Second, its production is flexible and can thus be adjusted to balance the short-run variation in demand and the supply of other sources of electricity. In an electricity market, the market prices are set so that the short-term supply and demand are in balance. Short-term prices shape the future expectations and influence the long-term supply by providing incentives to invest in new capacity or to close existing facilities. The value of hydropower in the market is thus determined by the current and expected future market prices of electricity.

The total supply of electricity is generated with a combination of technologies, each with different production costs. At any point in time, the market price is determined by the technology with the highest marginal costs. If the production with low-cost technologies, such as hydropower, decreases, electricity needs to be generated with some other technology that will have higher costs. This will increase the cost of generation. Demand is typically inelastic, i.e., the consumption of electricity does not depend on the price of electricity. Inelastic demand also means that supply shocks have a strong effect on market price. In the long-term, higher prices will create an incentive for new generation investments or demand reductions (e.g., Joskow, 2012).

4.2 | Value of flexibility

Electricity markets balance supply and demand at all times, i.e., on a daily basis, every hour, every minute and so on. There are separate markets and hence market prices for adjustments in supply. Generally, prices are higher for short interval adjustments. The fastest adjustments need to be delivered in less than a second. Ability to regulate power generation with reservoirs separates hydropower from other renewable energy sources. The going argument from the energy industry has been that hydropower has no substitutes. Such reasoning is countered by the increasing shares of intermittent renewables in regions with no or limited hydro resources, such as California, Spain, or Texas. A plethora of technology choices are available now or in the near future that will enable high levels of intermittent renewables (Lund et al., 2015).

There is a widespread belief that the economic value of flexible technologies in the electricity markets is going to increase with the introduction of intermittent renewables (see e.g., Heal, 2016; Ambec & Crampes, 2019 for a discussion). This has been a particularly strong argument for maintaining and increasing the hydropower capacity.[3] However, the absolute value of flexibility may in fact decline as the energy transition progresses (Liski & Vehviläinen, 2020). Expected profits in adjustment markets incentivize investments in storage and adjustment technology. Increasing adjustment supply decreases prices in adjustment markets and reduces the profits for all suppliers. The ongoing increase of intermittent renewable energy sources does thus not necessarily increase the value of flexibility hydropower is providing.

Run-of-the-river type of hydropower facilities do not provide flexibility benefits as they lack the reservoirs to control water flows. Rather, the provision of power is uncontrollable and intermittent, akin to wind or solar power. The output of such facilities also tends to be small. Therefore, they have no significant impact on electricity markets in terms of the energy they provide or their adjustability.

4.3 | Market structure

Large electricity suppliers have a strategic incentive to use their generation portfolio to manipulate price levels to their advantage (e.g., Bushnell et al., 2008; Kauppi & Liski, 2008). If the entry of low-cost renewables pushes the price levels down, the incumbents can respond by reducing capacity that leads to price recovery for their other assets (Liski & Vehviläinen, 2018). However, because of the increasing regulatory oversight, the firms are becoming more constrained in their ability to manipulate prices directly.[4] Instead, firms may choose to close capacity to achieve higher prices for the remaining output. This incentive may thus work in favor of river restorations.

In contrast, smaller firms are price takers in electricity markets. If the sole stake in the market outcomes for an owner depends on one small installation, then the private value of the firm is based on given market prices and output.[5]

4.4 | Long-term supply of small hydropower facilities

There are several constraints to the choice of short-run production level. The existing production capital is fixed; the water table of the reservoir is typically regulated; certain amount of water has to run through fish passes; run-of-the-river facilities are run according to the natural discharge of the river, and so on. The long-run economic analyses on small-scale hydropower typically concern optimal investment decisions, with *net present value* (NPV, see Equation 1) as one of the key indicators (see, e.g., Kaldellis et al., 2005, Montanari, 2003).

In the real option approach by Bøckman et al. (2008), the plant first defines the type of optimal investment after which it determines a threshold electricity price that triggers the investment. Under this framework, we could think of a small-scale hydropower plant facing massive investments, such as fish ladders, as being put back on square one: does it pay off to invest to continue? If the price threshold raises high enough this will be the case. The lucrative subsidies for small-scale hydropower plants in Germany (Bundesnetzagentur, 2021) can perhaps be seen as ways to avoid the politically sensitive and regulatorily complex closures of small-scale hydropower.

Another way is to consider the long-term profitability as a constraint for the facility. To stay in business, a firm's average long-run production costs must be lower than the average price of the output (Varian, 1993). If the long-term profits fall below zero, for instance due to fish passage investments, the only economically feasible solution would be to quit power generation at the most convenient moment.

Long-run profitability is a business economic constraint. In the same manner, we can define a constraint for the social profitability: the stream of economic net profits must outweigh the economic damages from the externalities. For instance, a facility might remain slightly profitable in the long run, even after installing and operating a fish passage. Its long-term social profitability, however, might turn negative because a fish passage mitigates – even at its best – only part of the environmental damage the facility generates.

This can be expressed using the NPV that is, the present value of estimated future economic net benefits of an investment or of an entire facility. The future revenues and costs are discounted to their present value and summed up to form the NPV (Brealey et al., 2012). For socio-economic NPV (NPV_S), the costs also include the monetized value of externalities. Mathematically, NPV_S is defined as:

$$NPV_S = \sum_{t=0}^{t=T} \beta^t \pi_t - \sum_{t=0}^{t=T} \beta^t D_t = \sum_{t=0}^{t=T} \beta^t (\pi_t - D_t), \quad (1)$$

where π_t refers to net profits on period t, $\beta = \frac{1}{1+r}$ is the discount factor derived from the discount rate r and D_t is the monetized value of the negative externalities on period t. If $D_t = 0$ for all t, there are either no externalities or we are ignoring them. If $T = \infty$, the time horizon is infinite.

In the long run, the facility chooses the investment path that yields the highest NPV, without considering the externalities. If there are no future paths for which NPV >0, the facility should not be in the business. If there are no investment paths for which NPV_S >0, the society would rationally want to drive the facility out of business.

This long run constraint limits the mitigation alternatives that are economically or socio-economically feasible. For certain types of facilities, there might be no options to comply with environmental regulation and to stay in business. Closing down the facility, removing the dam and restoring the river might be the economically least costly that is, the best, option. Such retirement options might be the best choices either from purely business economic perspective, or when considering the economic damage of externalities as discussed in the previous chapter. It is obvious that there are more facilities that run out of *socio-economically feasible* solutions than ones that run out of business economically feasible options.

5 | LEGAL CONTEXT OF SUSTAINABLE HYDROPOWER

As an industry and market, hydropower is strongly regulated. Every facility is embedded in a rigid and complex regulatory framework. Today, the legal and policy landscapes for hydropower are shifting. In the EU, the Water Framework Directive and the EU Biodiversity Strategy seek to improve river biodiversity. The shift in aspirations does not, however, translate to more sustainable hydropower generation without considering the legal challenges and opportunities specific to every legal system and to every hydropower operation with its particular ecological, economic, and legal setting. We will focus on Finnish hydropower regulation.

Our key point in this section is that despite political will and policy aspirations to rebalance the tradeoffs between the economic and climate benefits of hydropower on the one hand, and biodiversity harm of damming rivers on the other, results have been slim so far (Section 5.2). We maintain that the legal system regulating hydropower, in this case the EU and Finnish legal systems, are complex in the sense that they are not and cannot be controlled by any single actor (e.g., the EU Commission or national legislatures) (Ruhl et al., 2021). This is due to legal (often constitutional) barriers slowing down or even preventing the legislature from re-evaluating existing water laws protecting hydropower operations (e.g., the right to property and the protection of legitimate expectations, see Section 5.3). These constitutional requirements considerably limit the scope and pace of change of hydropower policies, despite political will for such change.

5.1 | Development of hydropower regulation in Finland

Before the 1930s, the Water Rights Act (31/1902) prohibited the blocking of rivers' navigable fairways for the passage of fish. This hindered hydropower construction and protected fisheries in Finland. As the demand for electricity increased, so did the political pressure to pass legislation deviating from its strict rules (Myllyntaus, 2002). The 1930s recession and the World War II led to the introduction of ad hoc legislation that established far-reaching exemptions to the 1902 act (Pokka, 1991). Between 1934 and 1941, the Finnish Parliament passed four acts (62/1934; 134/1939; 383/ 1940; 196/1941) that lowered the legal criteria for permits to hydropower operations. The ban on blocking a river's navigable fairway was replaced by a weighing norm requiring merely that the benefits of a project must outweigh the harms produced (Legislative proposal 99/1938; Löyttyjärvi, 2013).

According to the ad hoc legislation, hydropower facilities still required a permit. The law also required hydropower-related harms to fisheries to be mitigated, minimized, and compensated (Hepola, 2007). The main measures for minimizing the harm were fishways, and stocking rivers and lakes with farmed fish (Hepola, 2007; Löyttyjärvi, 2013; Soininen et al., 2018). In practice, hydropower permits were almost always granted to all projects applying one. Furthermore, many of the permit obligations were never enforced by the state agencies (Hepola, 2007).

Despite being founded on ad hoc legislation, the issued hydropower permits were granted permanence by the Finnish water legislation. The currently in force 2011 Water Act (587/2011) and its predecessors (1961 Water Act 264/1961; 1902 Water Rights Act) are based on a strict ex ante ideology: once a hydropower operation is granted a permit, it cannot be revoked or greatly adjusted (Belinskij & Soininen, 2017; Soininen et al., 2018). The permits granted to hydropower operations are considered to reflect the private ownership of the rivers (Belinskij & Soininen, 2017; Hepola, 2005, 2007; Soininen et al., 2018). The current Water Act allows, however, some revisions to permit conditions, especially fisheries conditions, under certain circumstances (Chap. 3, secs. 20–21).

5.2 | Legal drivers for greening hydropower

Legal drivers for greening hydropower can be found both in EU and Finnish law. At the EU level, the Water Framework Directive (2000/60/EC), Environmental Liability Directive (2004/35/EC) and Regulation (EU) 2020/852 on Sustainable Investment (Taxonomy Regulation) all support sustainable hydropower generation. Also, the EU Biodiversity Strategy (COM[2020] 380 final) seeks to establish legally binding objectives on aquatic biodiversity. In Finland, the constitutional Right to the Environment as well as a shift to more environmentally oriented interpretation of the Water Act are pointing in the same direction.

5.2.1 | EU-level drivers

In the context of the Water Framework Directive (WFD), the European Commission has repeatedly recommended Finland to review existing hydropower permits to achieve the environmental objectives of the Directive. The Commission emphasizes ecological flows, fishways and other impact mitigation measures (SWD(2019) 46 final, 22, 140; SWD(2015) 50 final, 108–109). According to WFD, water bodies should achieve good water status or, if heavily modified, good ecological potential (art. 4(1)). WFD requires Member States to periodically review water impoundment permits and update them, if necessary (art. 11 [3 and 5]). Changes to the water flow and hydro morphology are one of the main factors preventing the achievement of the environmental objectives of WFD (COM(2015) 120 final, 8, 12; CIS Guidance Document No. 31, 2015).

The Environmental Liability Directive (ELD) establishes a framework for environmental liability based on the polluter-pays principle. The Directive requires the operator to take necessary measures to prevent and remedy environmental damages and cover their costs (arts. 5–9). Accordingly, water damage is defined as any damage with significant adverse effects on the status of a water body as defined in WFD. The Court of Justice of the European Union (CJEU) stated in the Folk-ruling (C-529/15) that ELD applies to all environmental damages that have occurred after 30 April 2007 even though a facility causing the damages would have been authorized in accordance with existing laws and put into operation before that date. The case dealt with fish mortality caused by a hydropower operation (Judgment paras 23, 33).

The Taxonomy Regulation is 'a key milestone in defining legally sustainable activities' and it applies to EU and Member States measures concerning the environmental sustainability of the financial markets (Gortsos, 2020, 33). The Regulation establishes the degree to which an investment is environmentally sustainable (art. 1). Accordingly, an economic activity is environmentally sustainable if it contributes substantially to one or more of the environmental objectives of the Regulation and does not significantly harm any of them (art. 3). The environmental objectives include hydropower-related objectives of climate change mitigation, sustainable use and protection of water and marine resources and protection and restoration of biodiversity and ecosystems (art. 9). The Commission Delegated Regulation (COM [2021] 2800 final) sets technical screening criteria for hydropower. It stipulates that hydropower generation does not significantly harm water resources when, for example, all technically feasible and ecologically relevant mitigation measures have been taken in accordance with the WFD. The Regulation promotes ensuring conditions as close as possible to undisturbed river continuity with fish passes, with turbines safe for downstream migrating fish and with minimum ecological and sediment flows.

Until the 2000s, the constitutionally protected private ownership of the river flows was considered to prevent any major changes to existing hydropower permits in Finland without full compensation to the hydropower operator (Constitutional Committee PeVL 18/1982 vp and 8/1986 vp). In 1995, however, Finland enacted the constitutional right to a healthy environment (Constitution of Finland, 731/1999, sec 20) that has increasingly affected the interpretation of the right to property and its previous dominance in the Finnish constitutional law (Länsineva, 2002, 43–46).

At present, the right to property must be thoroughly balanced with the right to a healthy environment (see e.g. Constitutional Committee PeVL 10/2014, 2013, 55/2018, 2018, 69/2018, 2018 vp). The Constitutional Committee has pointed out that its previous standpoint on the full compensation of hydropower when conserving rivers predated the enactment of the right to a healthy environment (PeVL 61/2010, 2009 vp). Thus, the right to property is not as significant a hindrance for greening hydropower as it once was and the right to a healthy environment may become a driver for change in this regard.

5.2.2 | Drivers in the Finnish water law

Concerning the existing hydropower permits, the revision of fisheries-related permit conditions is gathering legal momentum in Finland. The Water Act stipulates that fisheries conditions in permits can be amended if there is a public interest in reviving migratory fish stocks (Chap. 19, Sec. 10), a change in the social-ecological circumstances (Chap. 3, Sec. 22) and the amendments do not cause disproportionate costs for the hydropower operator (Chap. 3, Sec. 14; Chap. 2, Sec. 7) (Soininen et al., 2018, 5). While many individual hydropower permits have been amended (e.g., Supreme Administrative Court cases KHO 20014:98 and 29 January 2013, case 356), in 2017, the supervisory authority applied for the revision of fisheries conditions in two large rivers, Kemi and Ii, including eight and five hydropower plants respectively (Lapin, 2017a; 2017b). The process is still ongoing in the time of writing and will potentially provide a legal path for the future permit revisions.

5.3 | Legal hindrances of greening hydropower

Despite the strong EU push to green hydropower generation and review existing hydropower permits, the Finnish Water Act still maintains that as the main rule, once granted permits enjoy permanence. The review of permit conditions or issuance of new conditions is limited and cannot significantly reduce the benefit gained from the project. The applicant of review must also pay compensation for the permit holder in cases other than minor loss of benefit (Chapter 3, section 21). The fisheries conditions in permits can be amended more freely if the socio-ecological circumstances have changed (Chapter 3, Section 22) but entirely new fisheries conditions cannot be easily added in existing permits (Supreme Administrative Court 4 April 2013, case 1160;Belinskij & Soininen, 2017; Soininen et al., 2018). Moreover, a hydropower permit cannot be entirely revoked against the consent of a permit holder (Belinskij & Soininen, 2017; Soininen et al., 2018), unless a river restoration project competing with the hydropower generation expropriates a hydropower operation and is granted a permit. A permit for a restoration project can be granted if the benefits of the project outweigh its harms and the losses to hydropower operators must be fully compensated (Chapter 3, Section 4; Chapter 13, Section 11; Soininen, 2016). To our knowledge, no such restoration projects have been initiated in Finland so far.

A key hindrance for reviewing hydropower permits is that hydropower is considered private property protected by the constitution, as discussed above. In essence, changing permit obligations, adding new obligations, or in revoking a hydropower permit as part of broader river restoration project, the permit authority must consider whether the changes to the existing permit constitute expropriation of property for which full compensation is due to the hydropower operator. A further complication is that there are no clear legal criteria for establishing what full compensation means. Some guidance may be sought in the Water Act, which stipulates that in permitting a new project, the benefits of the project are evaluated to be 20 times the value of annual hydropower generation (chapter 8, section 2). This rule does not, however, directly apply to evaluating the value of existing hydropower operations that may have been in operation for several decades at the time when their review is taken up. A further consideration in evaluating the value of hydropower is that under the standard compensation rules of the Finnish Water Act, compensations for hydropower are to be valued at 1.5 times of their actual value (chapter 13, section 11).

All in all, these legal details on the permanence of permits, difficulty in changing and adding new permit obligations, and hydropower as private property constitute feasibility challenges to greening hydropower generation and reviewing existing permits. That is, despite a strong EU and, to some extent, national push for transition.

6 | RESULTS—TOWARD SUSTAINABLE HYDROPOWER

The complex ecological, economic, and legal aspects of hydropower have a common thread: The size of the river and therefore the size of the facility is decisive in determining the ecological, economic, and legal feasibility of a measures to promote river biodiversity. This together with the relatively small set of mitigation alternatives (basically fish passages, stockings, environmental flows, dam removals, and river restorations) allows us to synthesize the analysis and provide clear classifications and recommendations that apply generally to the hydropower industry. In the following, we pinpoint the feasible ways forward for large, small, and medium sized facilities. Finally, we take a look at the Finnish hydropower sector to see real life implications of our suggested changes.

6.1 | Large facilities

Proposition 1. *In large rivers, the ecological damage caused by hydropower can be relatively well mitigated with environmental flows and fish passes. The actions are costly even though the decrease in supply and the ensuing increase in electricity prices partly compensates the losses for hydropower firms with market power. Relatively weak legal drivers and strong barriers to enforce mitigation efforts easily result in lengthy stalemates. It is unlikely that the largest hydropower facilities would be taken out of production because they are economically significant and legally protected.*

The habitats of large rivers could be improved by securing the connectivity with natural fish passages with a steady water flow. For migratory fish, there should also be guidance systems to help the smolts survive their downstream journey from the spawning areas. Ecologically, dam removals and river restorations would also be feasible, although not simple. River ecosystem tends to bounce back swiftly (Brenkman et al., 2019). However, there are issues related to large dam removals that require attention such as sedimentation of estuaries and losing the habitats of reservoirs themselves (Foley et al., 2017).

Fish passages are costly to build, and they reduce electricity generation and thereby the revenues. For facilities with a significant share in electricity markets, however, fish passages also increase revenues. For instance, Kemijoki River generates about 35% of Finland's hydropower. None of the facilities have fish passages. In its response to requirements to build such, the largest of the firms (Kemijoki Oy, about 90% of the river capacity) estimated that the sum of non-discounted investment costs and revenue losses would be 554 million euro for the next 25 years. However, due to concentrated ownership and the fact that a decrease in electricity supply would impact the market price, the revenues of the firm from the existing power generation are estimated to *increase* by a total of 106 million euro over the 25-year period (Vehviläinen, 2021). This significantly increases the economic feasibility of fish passages for the owners of large facilities. In addition, it can be argued that for strategic reasons the firms have over-estimated the constructions costs of the passages.

Economically, removing large dams would require replacing massive amounts of electricity supply, and the adjustment capacity in particular. Infrastructure, housing, and recreational activities might also have been adapted to water tables of the reservoir, generating economic and social costs were the reservoirs lost.

From the legal point of view, the key question is what kind of permit revisions can be required from the large facilities. In Finland, the Water Act supports the mitigation of fisheries harms to a certain extent and, according to the Constitutional Committee, environmental mitigation measures do not easily breach the right to property of large firms (PeVL 55/2018 vp). Nevertheless, the revision processes are burdensome and characterized by strong lobbying. The above-referred Kemijoki River permit revision process began in 2017 but is still on-going. Substantial revisions to environmental permit conditions other than those related to fisheries are virtually impossible due to the requirements to compensate the losses and not to significantly reduce the benefits of hydropower to the operator (Water Act, chapter 3, section 21).

EU law exerts significant pressure to revise hydropower permits in Finland to achieve the environmental objectives of the Water Framework Directive. The Taxonomy Regulation may increase the interest rates of loans for the large hydropower facilities ignoring these objectives and the Environmental Liability Directive requires the large facilities to prevent and remedy environmental damages. However, WFD also includes a possibility to name water bodies as heavily modified due to hydro morphological alterations related to hydropower generation. The understanding of the Finnish Government is that 5%–10% of loss in hydropower generation is significant and thus an absolute limit to the economic impacts of environmental measures in heavily modified water bodies (SWD (2019) 46 final, 105–106).

Neither EU nor Finnish law puts pressure on removing the large hydropower facilities. In reality, the only option for this scenario to be realized would be that a public authority would lead a river restoration project which would expropriate one or more facilities. The significant economic losses to owners of large facilities should be fully compensated.

6.2 | Small facilities

Proposition 2. *For small facilities, the option feasible from ecological, economic, and legal perspectives is often to find a voluntary way of ending production, removing the dam and restoring the river.*

The relative ecological impacts of small, run-of-river hydropower facilities may be disproportionally high compared to larger hydropower plants relying on reservoirs (Kelly-Richards et al., 2017). Small rivers tend to have small flows with relatively large hydrological variations. Reviving the river ecosystems weakened by small facilities requires restoring river connectivity and hydrological variability. This can be achieved either by removing the dam and restoring the rapid or by building natural fish passages with environmental flow schemes.

There are two cases when removing the facility and restoring the river is the only economically feasible option even if we consider merely the private profits. First, the upcoming business-related investment itself, for instance turbine renewal, might be too expensive to be covered by the facility's future revenue stream; or the economic environment might have otherwise changed.[6] Second, investment costs and revenue cuts due to new, revised or enforced permit requirements might be too high to be covered by future revenues.

An important economic and ecological complication is the joint effect of multiple facilities located by a single river. Consider a river with three small hydropower facilities. Analyzed individually, it might be socio-economically feasible to reconcile hydropower and river ecology with, for instance, fish passages. The benefits of removing an individual dam (conversely, the negative externalities of having it in place) are too small to make the social NPV negative. However, if all three would be considered simultaneously, it might be that the only feasible option was the removal of all facilities. Opening the entire migration routes would generate a discontinuous jump in the benefit of removing the dams.

Legally, removing a hydropower facility basically calls for compensating its value for its owners. A low value thus makes the removal projects easier to carry out. In addition, the water permits needed for the permanent structures of the restored river may be less complicated as the small run-of-river facilities do not typically regulate the water tables of significant lakes or reservoirs. One legal obstacle with small facilities, however, is that the disproportionate costs from revising a permit or changing permit conditions create constitutional difficulties. It is not trivial that the environmental authority cannot impose environmental requirements if their implementation makes the initial economic activity unprofitable. This underlines the importance of voluntary negotiations in dam removal and river restoration processes.

6.3 | Medium sized facilities

Proposition 3. *For medium sized facilities, joint feasibility does not single out the most feasible mitigation measure unless the socio-economic NPV is negative. Research efforts on defining and monetizing hydropower externalities should prioritize these rivers. Also, if there is a known alternative economic option utilizing a free river with an unambiguously higher private NPV, the removal option would be the best – if not the only feasible.*

Economic and welfare economic characteristics are decisive for this group. Ecological characteristics are shared with the previous group of small facilities. Legal context has features of both small and large, depending on the case.

Economically, medium sized facilities remain profitable even after implementing and fulfilling the environmental permit requirements. Continuing to generate electricity with fish passages and environmental flows is thus a feasible option. However, there are two cases that add dam removal into the set of jointly feasible options. First, it might be that there is an alternative market value – or the value for the local community via variety of businesses – that is greater than that of hydropower. In such a case, both options are feasible, and the choice boils down to finding the sales price satisfactory for both parties.

Second, there are still negative externalities associated with hydropower with fish passages and environmental flows. Monetizing these externalities might yield a negative social NPV for the reconciled electricity generation. That is, dam removal might be the only socio-economically feasible option. To calculate the social NPV, we would need ecological analyses of the development of river ecosystems under alternative scenarios, and the economic values related to these scenarios. These should include both market and non-market values.

One legal complication arises as facilities and their ecological impact grow larger. Namely, the preparatory work such as environmental impact assessment for dam removal and river restoration gets heavier with the scope of the environmental changes. Also, possessing the new water permit covering the permanent river structures might be a heavy duty making it more difficult to identify the legal entity holding the permit in the future. All this may in reality be too much even for many private operators looking for an exit from hydropower generation.

Corollary. *Feasibility analysis of mitigation options can divide the hydropower industry into three groups 1) Large facilities which should construct fish passes, 2) Small facilities which are economically unable to reconcile river ecosystems and business and should therefore be assisted to retirement at the least cost point in their investment cycle, and 3) Medium sized facilities for which thorough ecological-economic analysis is needed to determine the feasible and optimal choices.*

6.4 | Example—Finnish hydropower industry

Finland has 3200 MW of hydropower capacity, supplying some 15% of total annual electricity consumption and 4% of energy consumption. There are 219 business-oriented production units in Finland. Figure 1 shows their size distribution.

Vertical lines in Figure 1 denote the thresholds of 1 and 20 MW.

Considering small hydropower operations, by the time of writing this article, there were 19 facilities (out of the total of 89) under 1 MW that were in some part of dam removal negotiations. In addition, there were processes involving significant improvements in sustainability at larger facilities. Table 1 lists some of the cases for which the processes have been made public.

The nature-like mitigation habitat besides the largest facility in Finland, Imatrankoski, exemplifies the technical possibilities for habitat

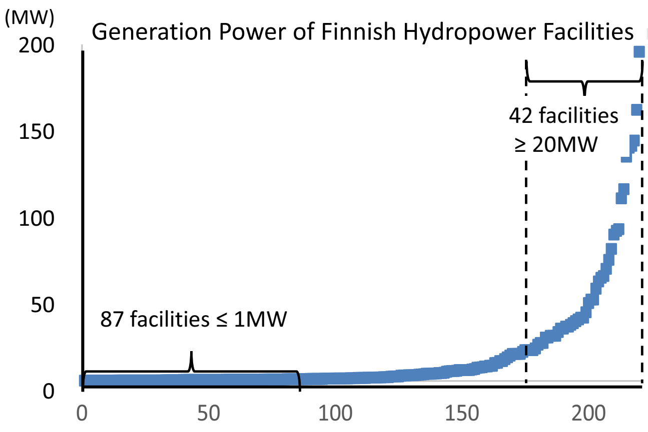

FIGURE 1 Generation power of Finnish hydropower facilities from smallest to largest.

TABLE 1 Selected river connectivity improvement and restoration cases for various size classes.

Class	Case	Key viewpoints
Large	Kemijoki river (7350 km, 1206 MW)	Responsible of roughly one third of the hydropower in Finland Ongoing contested legal process to enforce build fish passages Salmon catch was historically 350,000 kg per year, now the population is extinct
	Imatra nature-like mitigation stream	The biggest hydropower operation in Finland Mitigation habitat not as a part of environmental obligations Brown trout density better than in the natural streams Stream ecosystem in good status after 3 years
Medium	Kuusinki river	Natural, high value brown trout population Tourism and fishing
	Tainio river	High potential for brown trout, some remaining natural populations Lengthy legal process to implement environmental regulations with a 10-year forced closure due to lack of fish ladders
	Varkaus	Possible habitat for critically endangered lake salmon and endangered brown trout populations Voluntary 10% ecological flow implemented
Small	Louhikoski	Possible habitat for endangered brown trout populations Hydropower operator voluntary resignation and dam removal Free flowing river length 120 km

restoration in the context of large hydropower operations (Jormola et al., 2016).[7] The most important river in terms of electricity generation, Kemijoki, on the other hand, exemplifies the lobbying power and inertia of the large facilities: only one of the 21 facilities has a fish passage and there is a currently ongoing administrative process concerning the building of fish passages in and changing the permit conditions of the Kemijoki hydropower facilities. With high likelihood, the process will end in court as the economic and environmental interests at play are significant.

The medium sized facilities are exemplified first by the removal process of Myllykoski facility (1.4 MW) in the river Kuusinki. The initiative to purchase the facility and to restore the river came from local stakeholders who saw the economic potential of the free river higher than the net present value of electricity generation.[8] The river is in Kuusamo, an area with a viable nature tourism industry. Second, the three facilities of the river Hiitola are to be removed by the year 2023. The total power of these sequential facilities is 1.8 MW. Third, the Finnish Government funded Nousu-program brought a solution to a long stalemate by the 0.6 MW facility in river Tainio, sold to a third party for demolition in late 2021.

Part of the removal processes in Finland meet our criteria of small facilities. The initiative to remove the Louhikoski facility in Northern Karelia, for instance, came from the owner, Pohjois-Karjalan Sähkö. One reason for removing the 0.5 MW facility was business economic.[9] Required investments and the anticipated fish passage requirements made the removal a preferrable option. The governmental Nousu-program facilitated the process by providing funding for the restoration and by assisting in the permitting process.

The initiatives and programs to transition the Finnish hydropower industry to better match the current ecological, economic, and legal setting are new. There are no comprehensive data on the economic conditions of the facilities nor on the ecological benefits that their removal and river restoration would bring about. That is, we cannot pinpoint to which category each facility would belong, nor whether it should preferrable be removed. However, we may illustrate how a hypothetical large-scale removal scenario would look like geographically and in terms of electricity generation.

Figure 2 shows two maps of the rivers and watersheds of Finland. The map on the left identifies locations of all existing hydropower facilities. The one on the right illustrates what would happen if we kept only those facilities located in the rivers with large hydropower plants to begin with and restored all other rivers.

In the right panel of Figure 2, the white color indicates non-constructed watersheds. The dark gray denotes the watersheds that would be free of hydropower were the facilities from all except six largest rivers removed. The light gray indicates the watersheds that would remain constructed. The total hydropower lost with such a removal would be 121 MW or 3.8% of the generation capacity in Finland (422 GWh of the mean annual generation volume, or 3.2%).

As we can see, size is decisive. On the one hand, the size distribution is skewed so that there are many small facilities whose total contribution to electricity supply is minor. On the other hand, they cover

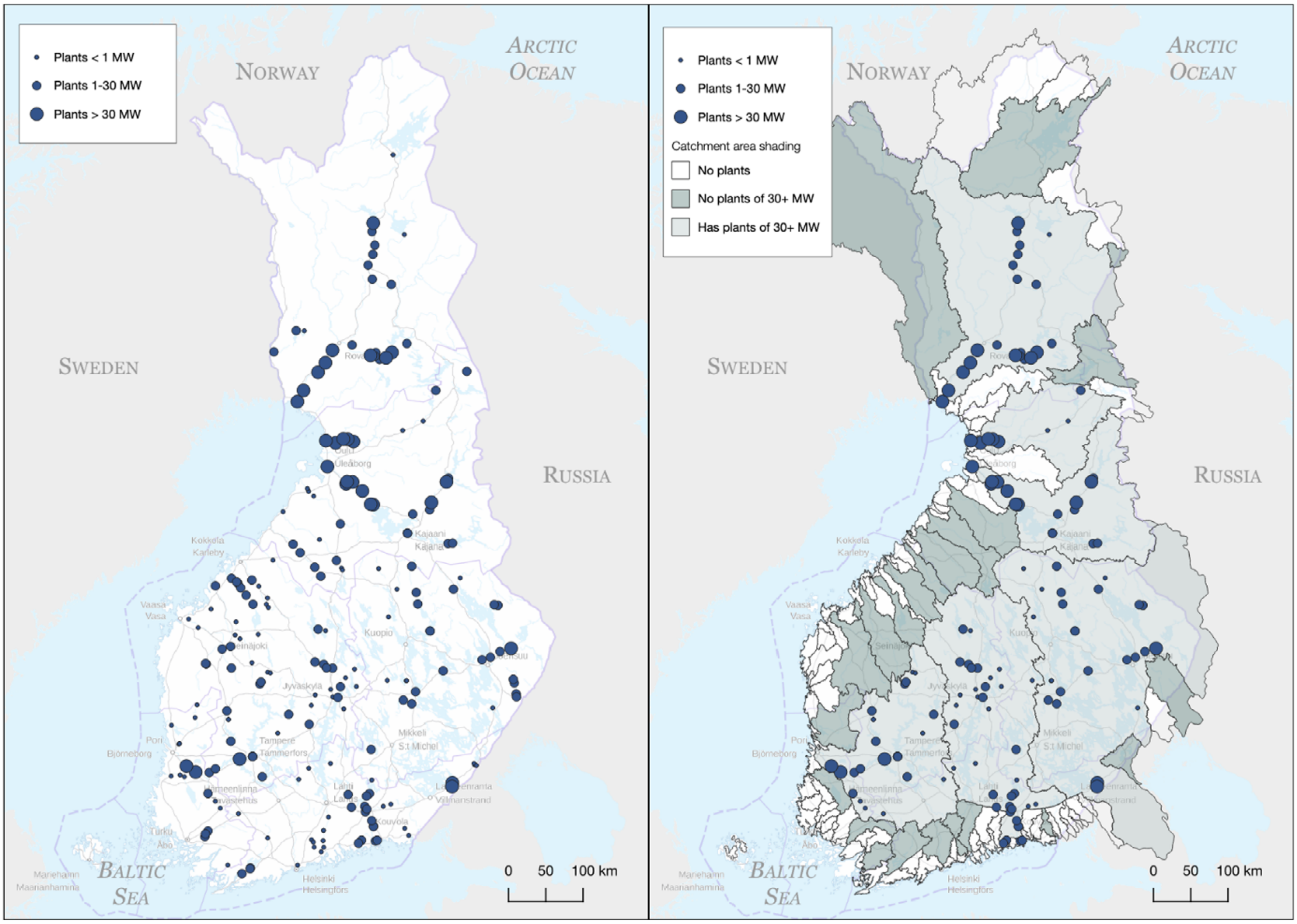

FIGURE 2 Constructed rivers and watersheds in hydropower production in Finland.

substantial geographical areas and their total contribution to river ecology is thus substantial.

7 | CONCLUSIONS

Hydropower is a major source of renewable energy on the one hand and a key driver in the deterioration of freshwater ecosystems on the other. The basic options for mitigating its ecological damages are construction of fish passages, managing the environmental flow, and dam removals and river restorations. To find the right option, we must identify the ecological, economic, and legal feasibility of the available mitigation measures for individual facilities. We did this by shedding light on the inherent heterogeneity of hydropower industry. In particular, we identified the economically unsustainable combination of generating electricity in small hydropower facilities and protecting river biodiversity. There is a serious need to consider the removal of small sized facilities while, at the same time, we must continue finding efficient measures to make large facilities more sustainable. For medium sized facilities, case-specific research efforts are needed to find a feasible solution.

The need to cut down greenhouse gas emissions is one of the key arguments for hydropower. However, it is important to understand that climate change is only one of the pressing global crises. Biodiversity loss is posing an immediate threat on the ecosystem services our livelihoods rely on. Therefore, actions aimed at mitigating climate change should be ecologically feasible.

Economic feasibility is driven by business economic considerations on one side, welfare economic on the other. The life cycle of a hydropower facility is long, and hydropower is vital for the current electricity market design. Large facilities are important suppliers of electricity and in balancing the short and longer-term supply and demand. For large facilities the fish passages are costly to construct and operate, but economically feasible. For smaller facilities, the relative additional costs of fish passages and environmental flow schemes may be too high to enable profitable power generation in the long run. Such facilities should preferrable be assisted to retirement according to their investment schedule. For medium sized facilities, feasibility hinges on the welfare provided by the alternative utilization schemes of the river. Considering the economic value of environmental externalities might render some facilities out of feasible (welfare) economic options that include power generation.

Efforts to analyze costs and benefits of mitigation measures should be focused on the group of medium sized hydropower facilities. Particularly the non-market benefits of alternative uses for rivers may be large. Because such analyses are costly and case specific, they should be targeted to cases where they support decision making. This is particularly important because of the long life cycle of facilities. The window of opportunity for reconsidering the way we utilize rivers opens rarely, not even every decade. Missing the right moment because of lacking decision support information might mean that the river is allocated for a use that is generating lower welfare than its alternative.

Hydropower industry has traditionally been strongly protected by law. Therefore, the current industry structure may seem permanent. Nevertheless, the legal landscapes are changing, and the troubled coexistence of hydropower and river biodiversity has gained attention and prompted requirements for remediating actions. EU has ambitious water quality, biodiversity, and green funding targets, while at the national level the right to a healthy environment has begun to balance the strong constitutional protection of hydropower in Finland.

To conclude, there was a time when no hydropower had been constructed and there will be a time when all hydropower will be removed—either by humans or by nature. While the extremes are trivial, the intermittent states are not. Hydropower is an important, adjustable source of renewable energy but it is also detrimental for river biodiversity, an essential component of Earth's life support systems. Protecting biodiversity becomes more crucial as our climate is getting more unpredictable. To make it possible for the emerging political will to make hydropower more sustainable, the alternatives need to satisfy the necessary conditions of ecological, economic, and legal feasibility.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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ENDNOTES

[1] For instance, participating in the development of Finnish water law to meet the EU water and biodiversity requirements and providing economic advice in several dam removal negotiations between the governmental Nousu-program and small hydropower facilities.

[2] Elwha and Glines Canyon dams were removed during the period of 2011 and 2014 (https://www.nps.gov/olym/learn/nature/elwha-ecosystem-restoration.htm)

[3] E.g. Finnish Energy Industry, "Hydro power is a prerequisite for other renewable electricity generation" (in Finnish), Press release, 7 Feb 2019.

[4] For example, the Spanish competition regulator fined Iberdola, one of the large utilities, in 2015 for manipulating their hydropower bids in the Spanish electricity market (https://www.cnmc.es/node/271406).

[5] Sometimes the private use of electricity from installations may be of more value if the owner is able to circumvent the need to pay grid fees and taxes through own generation.

[6] Subsidies for small scale hydropower existed in Finland until the end of 2011 and still do, for instance, in Germany (Bundesnetzagentur, 2021).

[7] https://yle.fi/uutiset/3-10578998 (in Finnish)

[8] https://kuusinkijoki.fi/en/

[9] https://yle.fi/uutiset/3-11539201 (in Finnish)

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