DOE-Norway White Paper

Effective Environmental Decision Tools for Hydropower Development

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1. Introduction

In February 2020, the United States Department of Energy (DOE) and Norway's Royal Ministry of Petroleum and Energy made a commitment to collaborate on hydropower research and development by signing an Annex to a previously signed Memorandum of Agreement (MOU). This MOU Annex brings together the DOE Water Power Technologies Office (WPTO) and the Norwegian Research Centre for Hydropower Technology (HydroCen) to plan and coordinate hydropower research and development (R&D) activities; develop, share, and implement results; increase understanding of hydropower's role in the future energy mix; and provide input to international discussions regarding hydropower. Hydropower faces similar challenges and opportunities in the United States and Norway, and both countries are committed to enabling hydropower to support their respective electricity systems. Collaborative R&D under this MOU Annex can be related to the following topics: Markets and Value, Hydropower plant Capabilities and Constraints, Monitoring and Control Technologies, Environmental Design Solutions, Environmental Impacts and Tradeoffs, Flexible Operations and Planning, and Technology Innovation.

Throughout 2021, the DOE WPTO Project “Environmental Decision Support (EDS): Science-Based Tools for Hydropower Stakeholder Collaboration” led by Oak Ridge National Laboratory (ORNL) leveraged the MOU and the experience of Norwegian hydropower researchers to better understand ways to create effective environmental decision support tools needed for sustainable hydropower development across the United States. Researchers from ORNL, DOE, SINTEF, and the Norwegian Institute for Nature Research (NINA) met virtually five times from January through December 2021 to (1) discuss recently developed environmental decision tools, (2) reach consensus regarding the motivation for creating these tools and define what constitutes an effective decision support tool for hydropower stakeholders, and (3) identify key barriers to using environmental decision tools during hydropower development. This White Paper summarizes the results of the group’s five discussions and provides suggestions for future research to improve the effectiveness and uptake of environmental decision tools.

2. Background

US hydropower provides nearly 7% of the nation’s electricity and supports approximately 87,000 domestic jobs in project development and deployment, manufacturing, and operations and maintenance (Uria-Martinez et al. 2018). There are roughly 80,000 dams in the United States, and 2,400 of these facilities produce power with a total current installed capacity of 80 GW (Uria-Martinez et al. 2018). More than 44% of the nation’s hydroelectric power is delivered by 133 federally owned hydropower facilities (Uria-Martinez et al. 2015). The approximately 2,000 non-federally owned hydropower facilities found across the US require a license from the Federal Energy Regulatory Commission (FERC). These FERC licenses typically last for 30-50 years, and environmental impacts of the hydropower facility are rigorously evaluated at the time of licensing or relicensing (Levine et al. 2021). A large proportion of the US hydropower fleet has aging infrastructure, and between 2007 and 2017, approximately $9 billion was spent to upgrade and refurbish turbines and generators (Uria-Martinez et al. 2018). Over the next decade, more than 350 hydropower plants are expected to be relicensed in the United States (Uria-Martinez et al. 2018).

Norway has seen extensive hydropower development over the last century, resulting in almost 1700 hydropower plants (https://publikasjoner.nve.no/faktaark/2020/faktaark2020_06.pdf) that currently produce more than 90 percent of Norway's power (https://www.nve.no/energi/energisystem/kraftproduksjon/). This hydropower development has negatively impacted biodiversity within rivers. However, Norway has strict licensing procedures for new development, and the terms of more than 400 older licenses are being reviewed to improve ecological conditions. In addition, about 30 percent of water courses in Norway are protected from hydropower development.

On a global level ,"hydropower is expected to remain the world's largest source of renewable electricity generation and play a critical role in decarbonizing the power system and improving system flexibility", according to IEA (https://www.iea.org/reports/hydropower-special-market-report). IEA concludes that "reaching net-zero emissions by 2050 worldwide calls for a huge increase in hydropower ambitions."

3. Reasons for Creating Environmental Decision Support Tools

Researchers create environmental decision tools to help authorities, stakeholders and the hydropower industry with planning new hydropower projects and revising existing hydropower plants. These tools build on knowledge gained through past projects so that adverse environmental impacts can be identified and then avoided, reduced, or mitigated. Ideally, environmental decision support tools can help multidisciplinary teams of hydropower authorities and stakeholders (such as those essential to evaluating environmental impacts and permitting hydropower dams) absorb vast amounts of information needed to improve the identification and assessment of possible solutions and mitigations, make site-specific recommendations, and reduce errors in project implementation. Decision tools can ultimately save time and cost by moving stakeholders towards goal-focused, viable outcomes by identifying risks, information gaps, and priorities early in the process. Furthermore, environmental decision support tools can help experts examine biases to provide greater confidence in recommendations, identify areas of scientific uncertainty, clarify tradeoffs, and identify barriers (e.g., cost) that might hinder the application of solutions with the greatest potential for environmental benefits. Therefore, increased implementation of environmental decision support tools as components of hydropower environmental review workflows has great potential to enhance outcomes, improve both accountability and consistency, and increase stakeholder knowledge and engagement. These tools may also help to avoid disruptions from late arriving special interest groups that can set back timelines.

3.1 Avoid adverse impacts

Clean water is essential to the health of the people, animals, and plants. When water quality is compromised, it puts people and the environment at risk. Storage of water in reservoirs can change physical, chemical, and biological properties of the water. The size of the dam, its location geographically, or its position in a river system all influence the way storage affects both water quality and water temperature. Thus, some management and mitigation options are similar or twofold. Hydropower dam operations can be tailored to reduce impacts to water quality and to improve downstream conditions through water releases. Environmental decision tools can be used to develop specific requirements for timing and volume of water releases to help meet these objectives.

Mitigations to meet national environmental standards (e.g., National Environmental Protection Act of 1969, the Federal Clean Water Act of 1972, and the Endangered Species Act of 1973 in the USA; the Watercourse Regulations act of 1917 (amended 2004), the Industrial Concessions Act of 1917 (amended 2017), and the Water Resources Act of 2000 in Norway) can contribute significant costs to hydropower siting, permitting, and operations. Mitigation costs are highly variable, but in the US these costs can sometimes make up 30% of the levelized cost of energy produced at federally owned and operated hydropower facilities (Oladosu et al. 2021). Hydropower development often has negative impacts on biodiversity, with consequent effects on species of concern (Zarfl et al., 2019). The impacts to aquatic species have the highest median values for both capital costs (about $50/kW) and annual O&M costs (about $4/kW) for US projects (Oladosu et al. 2021). Mitigation costs to offset impacts to European aquatic species can also be significant. Example costs for instream habitat adjustments, fish migration facilities and guidance structures and other measures taken at European projects are summarized at https://www.fithydro.wiki/index.php/Costs_of_solutions. Across both regions, cost-effective tools to identify the range and cost of options for mitigation—particularly for species—will assist hydropower owners and operators in meeting environmental permitting requirements.

Across the US, there are numerous unique biomes, and hydropower impacts hundreds of different aquatic and terrestrial species at various levels and scales. In some areas, a single project has the potential to impact dozens of species. For example, the Smoky Mountain project in the US states of Tennessee and North Carolina has 103 fish species in the watershed and 37 species that are listed as federally or state threatened or endangered, or otherwise identified as species of special concern within the project boundaries (Pracheil et al. 2019). While many of these species have individualized protection or mitigation plans, decision support tools can help to identify commonalities among these species such as life history traits, habitats, and prey so that species and habitat management plans and mitigations can be tailored to serve the largest number of species or for umbrella species for efficient resource use.

In Norway, hydropower has detrimentally affected Atlantic salmon stocks in about 20% of Norway's salmon rivers (Forseth et al. 2017) and has caused the loss of 19 of the circa 480 known Norwegian salmon populations (Johnsen et al. 2011). Hydropower has also negatively affected other Norwegian fish species, such as the critically endangered European eel, *Anguilla anguilla* (see Durif et al. 2008; Kroglund 2019). A range of other ecosystem effects have been noted, and hydropower may be a particular problem for many rare and endangered species of lichens, bryophytes, vascular plants, and beetles which are often found in the type of river gorges that are exploited for hydropower in Norway (Erikstad et al. 2020). Finally, hydropower has contributed to population decline in the threatened freshwater pearl mussel, *Margaritifera margaritifera* (Dolmen and Kleiven 2008).

3.2 Make progress toward cross-cutting goals

Increasingly, researchers are creating environmental decision tools to help hydropower projects provide multiple benefits by making progress toward societal goals such as the development of flexible low-carbon electricity, the preservation of clean water resources for multiple uses, and the augmentation of outdoor recreational opportunities. Several new and revised initiatives in the US and Europe are underway to reduce greenhouse gas (GHG) emissions, and hydropower will play an important role in meeting global decarbonization targets for energy production.

In the US, there are trends in both the private sector and government to develop and implement policies and programs to improve environmental performance and practices. A variety of voluntary sustainability certifications and programs that support or promote renewable energy, low impact development, and/or environmental goals are available to many US hydropower owner/operators. Programs vary in structure, but a typical framework includes offering certification at a cost, and upon completion of requirements, enabling participation in premium markets as an incentive. Companies, power marketing groups, hydropower owners, and others may also make choices to enable "green" (e.g., environmentally friendly, sustainable) portfolios or plants to satisfy stakeholders, shareholders, customers, or business model philosophy. Further investments in green tools and products to improve operations or reduce environmental impacts can also add green value to projects. The renewed US commitment to reduce national GHG emissions by 50% by 2030 under the international Paris Agreement will push US corporations and utilities to rapidly increase their use of renewable, non-fossil-based energy resources.

Ecotourism and water-based recreation provides a potential source of tourism income for many parts of the US, including regions that have experienced economic distress from the recent decline of fossil fuel production (e.g., Appalachia). Environmental decision tools will be important for helping local decision makers coordinate the volume and timing of river flow needed to provide sport uses like white water rafting, kayaking, and sport/recreational fishing in addition to meeting the traditional demands of hydroelectric power generation and flood mitigation.

In Europe, the 2000 Water Framework Directive (WFD; Directive 2000/60/EC) and the newly established EU Taxonomy for Sustainable Finance (EU Directive 2020/852) give targets and criteria for hydropower to meet sustainability standards. The EU Taxonomy focuses on screening criteria to assess climate change impacts such as GHG emissions, and ecological criteria such as "do no significant harm" to "sustainable use and protection of water and marine resources". These criteria are harmonized with the EU WFD. During relicensing and the implementation of the European WFD, it is expected that most Norwegian water bodies within the hydropower river system will obtain good ecological status or good ecological potential. This will require implementation of mitigation measures such as environmental flows, fish migration solutions and habitat enhancements. Environmental decision tools can help Norway formulate plans to meet these new requirements. The environmental design concept (Forseth and Harby 2014) is designed to find good solutions both for hydropower generation and the environment in regulated hydropower rivers. Specialized tools such as a hydropeaking tool (Bakken et al 2021) to assess impacts of rapid and frequent flow variations caused by hydropower may also assist these objectives.

In September 2021, the International Hydropower Association (IHA) launched the Hydropower Sustainability Council to oversee the implementation of a new Hydropower Sustainability (HS) Standard certification program that builds upon the Hydropower Sustainability Assessment Protocol (HSAP). HSAP is a comprehensive framework designed to assess the performance of hydropower projects across more than 20 sustainability topics, including siting and design, downstream flow regimes, biodiversity and invasive species, water quality, and financial viability. Since 2011, HSAP has been applied to 23 hydropower projects around the world. Under the HS Standard, HSAP will be combined with two complementary tools—the Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP) and the Hydropower Sustainability ESG Gap Analysis Tool (HESG)—to "provide a common language to allow governments, civil society, financial institutions, and the hydropower sector to discuss and evaluate sustainability issues" (https://www.hydrosustainability.org/hydropower-sustainability-tools). Meeting the HS Standard will require hydropower projects to estimate and manage their GHG emissions, analyze and manage the risks of climate change for the project, and define the project's role in climate change adaptation.

4. Examples of Environmental Decision Tools

This section contains brief descriptions of several environmental decision tools for hydropower development that have been recently created by the authors of this White Paper and/or their colleagues.

4.1. River Function Indicator Questionnaire

Most privately owned US hydropower facilities are required to obtain an operating license from FERC. This regulatory process typically takes 5-7 years and is unique among energy infrastructure in that it is heavily stakeholder driven (Aldrovandi et al. 2021). During the study negotiation phase of the licensing process, environmental and energy stakeholders, as well as regulators from tribal, state, and federal agencies, must all work together to determine what the proposed project's environmental impacts will be and whether any additional studies or mitigation will be required. Stakeholders have complained that this is one of the least satisfying and most challenging parts of the FERC licensing process as the diversity of priorities and perspectives among hydropower stakeholders often leads to communication breakdowns and delays (Levine et al. 2021).

Since 2016, ORNL has been supporting DOE WPTO in the development of a science-based Environmental Decision Support (EDS) Toolkit to improve stakeholder communication during the study negotiation phase of a FERC licensing process. The project team started by conducting a cross-disciplinary literature review of environmental metrics which integrated the viewpoints of multiple types of hydropower stakeholders and the scientific research community (Parish et al. 2019). The literature review was used to build a database of over 3100 environmental metrics organized into six categories important for understanding the environmental impacts of hydropower: Biology & Biota, Connectivity & Fragmentation, Geomorphology, Hydrology, Land Cover, Water Quality, and Water Quantity. The environmental metrics were then grouped into 42 river function indicators (RFIs) used to measure common characteristics of riverine ecosystems (Pracheil et al. 2019). Each RFI represents a group of environmental metrics used to determine whether an ecological function of the river could be impacted by a proposed hydropower project.

Working with a cross-section of representatives from industry, federal agencies, universities, and non-governmental organizations through a Mission Advisory Board and Science Advisory Board, ORNL created an online, interactive RFI Questionnaire tool to provide stakeholders with a systematic and transparent method for identifying and discussing which RFIs are likely to be impacted by a hydropower project and which RFIs require additional information and discussion. Stakeholders can voluntarily use results from this tool as a resource during the study plan development phase of a FERC licensing proceeding, but the RFI Questionnaire does not recommend specific study methodologies or suggest any specific protection, mitigation, or enhancement measures. Shared language is encouraged by a definitions lookup incorporated throughout the tool. In October/November 2021, the RFI Questionnaire was pilot tested by 5 stakeholders in New England and Kansas through retrospective application to 3 hydropower projects previously licensed by FERC. Their feedback was incorporated into RFI Questionnaire Version 5, which is now available at https://rfiq.ornl.gov and through DOE's HydroSource website, where it is linked to related datasets and publications to form the "EDS Toolkit". Future stakeholders will potentially find great use in this EDS Toolkit over the next decade as the number of hydropower facilities facing FERC relicensing is expected to double between 2020 and 2030.

4.2 The Handbook for Environmental Design in Regulated Rivers

The Handbook for Environmental Design in Regulated Rivers developed by Forseth and Harby (2014) of CEDREN Research Center (www.cedren.no) offers a framework for diagnosing and implementing design solutions for habitat and hydrological bottlenecks that control Norway's salmon populations. In this system, habitat bottlenecks depend on spawning habitat and shelter. Hydrological bottlenecks depend on (1) how water covered area changes with discharge, (2) hydrological alteration (i.e., how flow and water-covered area change seasonally and between years), (3) reach characteristics (which depend on gradient and mesohabitat class), and (4) water temperature. Design solutions are evaluated iteratively using sets of mitigation measures (a.k.a., "scenarios") to achieve an optimal outcome. The principles of this Handbook may also be used for other species and services, and even for other energy sources than hydropower. Currently, the concept is being developed and adapted to other fish species, invertebrates and biodiversity, activities such as kayaking, swimming and recreational fishing, and other services like flood control, drought management, irrigation, and flexible energy services within the HydroCen research center (www.hydrocen.no).

4.3 FITHydro Tools

The European Fish friendly Innovative Technologies for Hydropower (FIThydro) project has recently developed several useful online tools and models available at www.fithydro.eu, including the European Fish Hazard Index (EFHI) tool, the FIThydro Wiki, the FIThydro Decision Support System (DSS), and the FIThydro Hydropeaking Tool.

The European Fish Hazard Index (EFHI) tool developed by van Treeck et al (2021) assesses the hazard of hydropower plants on fish populations by considering location-specific characteristics such as plant design and operation, sensitivity of fish species, and environmental development targets for the river. The tool takes mitigation measures into account for the final classification, and it is intended as a screening tool for risk assessment of hydropower projects. The software may be downloaded directly from https://zenodo.org/record/4686531#.YeyXvP7MI2w .

The FIThydro Wiki (www.fithydro.wiki) gathers and systematizes outputs from the FIThydro project, including a description of existing and innovative solutions for environmental mitigation of hydropower and which methods, tools, and devices can be useful for their implementation. Each solution is classified according to various characteristics, such as the fish species it is aimed at, in what types of rivers it can be applied, and the technology readiness level. Hydropower impacts and potential mitigation methods are grouped into five categories: habitat, environmental flow, sediments, downstream fish migration, and upstream fish migration. The wiki also contains information about test cases in the project with links to relevant and applied solutions, methods, tools, and devices.

The FIThydro DSS (https://www.fithydro.eu/the-fithydro-decision-support-system/) is a tool for environmentally friendly hydropower decision making, that can be used for commissioning and operating hydropower plants, with a view to mitigation measures, and developing cost-efficient environmental solutions and strategies for avoiding fish damage and enhancing fish populations. The DSS web-tool is based on the project management approach and outlines the steps that should be undertaken for the initial screening of a project to appraise the impacts, risks and scope options for further diagnosis and mitigation. The process leads the decision maker through four key steps which act to characterize, risk-assess, and prioritize the scheme(s) together with the identification of the most appropriate and potentially cost-effective mitigation options addressing the hazards and impacts arising due to the nature and context of the specific scheme(s). The four key planning steps are:

- Step 1: Pre-screening characterization, hazard identification & risk assessment
- Step 2: Ecological status assessment and review of existing mitigation
- Step 3: Identification of appropriate mitigation measures and synergistic solutions
- Step 4: Risk-based decision of scheme plan, or, Scoping of detailed cost-efficient mitigation plan.

The decision process leads ultimately to a structured assessment of the acceptability of a proposed scheme or scoping the measures required for mitigating existing hydropower plants, with associated risks and uncertainty

The FIThydro Hydropeaking Tool is designed to assess the impacts of hydropeaking on fish populations in regulated rivers. It is available as an Excel file. The hydropeaking tool is based on a method for assessing impacts from hydropeaking developed for salmonids at SINTEF Energy as a part of the CEDREN EnviPeak project. In FIThydro, the Hydropeaking Tool has also been developed for Iberian barbel and grayling, in addition to salmonids. Factors, criteria, and thresholds that determine the assessment for these species have been modified based on available literature and expert knowledge. The impacts from hydropeaking are divided into two axes: direct effects from hydropeaking, and vulnerability of the fish population to the additional impact from hydropeaking. The effect axis characterizes the possible ecological impacts of peaking from how physical conditions such as flow, water level and water covered area change, given the hydropower system and river morphology. The vulnerability axis characterizes how vulnerable the system is to further influence from hydropeaking. Both axes may be evaluated separately, but a system to combine them and obtain an overall assessment of hydropeaking is also provided.

Knowledge created through the FIThydro project and the FIThydro Wiki have been used to select and discuss mitigation measures for 3 test cases – Guma (Spain) Anundsjö (Sweden), and Las Rives (France) - each case presenting different challenges and therefore different mitigation measures for upstream and downstream fish migration. The effectiveness of the measures was assessed through modelling techniques that provided physical factors used as indicators (e.g., water velocity, water depth, roughness), weighted using literature-based indicators for the suitability of upstream and downstream migration. Costs were calculated for a range of procedures including operational changes (e.g., shutting down the turbines), morphological modifications (e.g., digging terrain to increase the depth) and structural solutions (e.g., trash racks). The three test cases and their results were discussed with the partner and stakeholders involved, and necessary model modifications were applied; with the tool's use of a Bayesian Network, there is the option to change probability values, beliefs and weightings based on expert opinion (see Barton et al. 2020), enabling additional modification of models throughout the process. Despite showing the potential applicability of the method, an important challenge was identified with regard to quantifying the effectiveness of the measures, mainly due to the lack of supporting biological data.

4.4 Multicriteria Decision Support Tool

Barton et al. (2020) developed a multicriteria decision support tool, using the software HUGIN (Madsen et al., 2005), for assessing environmental flows (eflows) and habitat remediation. HUGIN has the advantage that it can be used to build Influence Diagrams, which are probabilistic networks that differ from Bayesian Networks (BN) because they include decision variables and utility functions specifying the preferences of the decision maker (Kjærulff and Madsen, 2007). Barton et al. (2020) constructed an Influence Diagram to support the most cost-effective scenario for a regulated river in Norway that was undergoing a re-licensing process. Scenarios included different minimum flow releases (including a reduction of energy production cost), the removal of small weirs (including a demolition cost) and adding gravel to create spawning habitat conditions (including materials and construction costs). Scenario effectiveness was then estimated with a salmon smolt production model. Costs and effectiveness were weighted to find the most cost-effective scenario including the social perception and preferences from stakeholders, considering aesthetics (from the removal of the weirs and different discharges), fishability and willingness to pay.

5. Effective Environmental Decision Tools

Effective environmental decision tools provide a lens of viewing a question, organizing information, and exploring decisions that matter in a structured and transparent manner. Environmental decision tools can vary widely across a continuum that includes raw data, checklists, models, techniques, visualizations, and organizational processes to support evaluations, narrow the field of choice, and/or provide transparency in sources of information and criteria utilized in reaching evidence-based recommendations (**Figure 1**). Not every type of tool is intended to be used by every type of hydropower stakeholder. While traditional tools that provide technical knowledge can lead to more informed decisions by scientists and engineers with deep subject matter expertise, participatory approaches and stakeholder involvement through the process can lead to effective models for long-term decision making involving multiple goals and disciplines (Falconi and Palmer 2017).

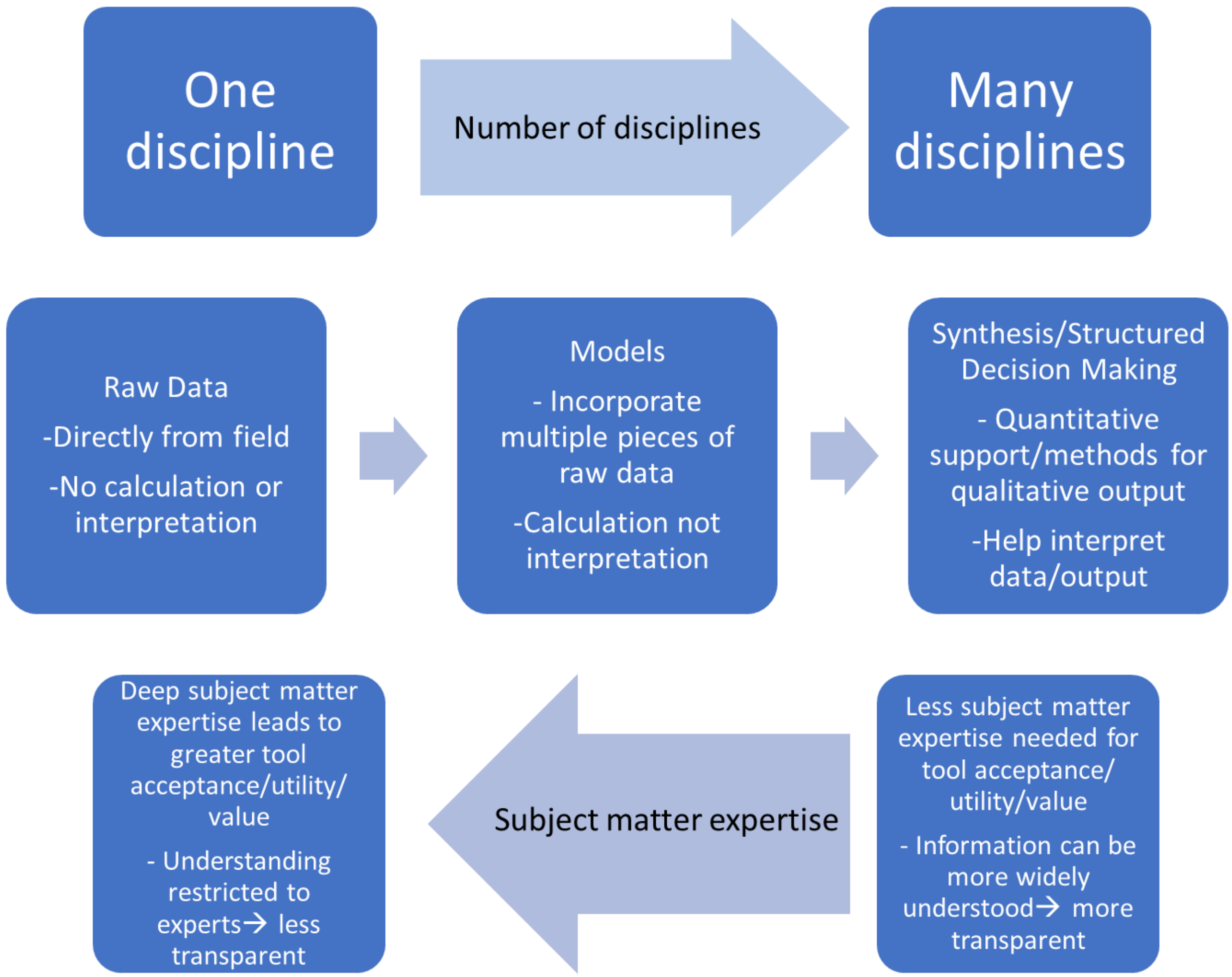

Figure 1. Environmental decision tool types vary along a continuum based on the number of disciplines involved and the degree of subject matter expertise needed for their interpretation.

Results from raw data and more technical tools will be more easily interpreted by scientists than other stakeholders. Due to the multidisciplinary nature of environmental hydropower impacts, multidisciplinary tools and therefore scientists with different expertise will also benefit from discussion and interpretation of the results, which are often complex. On the other hand, tools for policy and decision making can be found to be less data demanding and less complex but often can over- or underestimate positive and negative impacts.

Complicated assessments of localized and system-wide environmental impacts may require multiple routes of examination and inquiry to address. Moving from the traditional use of models with clearly defined outcomes or decisions to a more participatory approach involving multiple types of users and stakeholders requires a structured vocabulary and transparent, flexible tools. Environmental decision tools that cross disciplines are not intended to replace people or expertise; instead, they are meant to be part of a process that brings people to the table for discussion.

While some tools have relatively simple desktop user interfaces and provide instruction or training in forms ranging from documented user guides to full training programs (e.g., workshops, courses) there may still be the perception that users do not have sufficient training or expertise to properly use them. For complicated assessments that can be supported by decision support tools, the best practice is that all parties receive a group training prior to use. Hydropower environmental assessments will always involve multi-disciplinary groups that include subject matter experts in a variety of fields that provide information and interpretation that must be contextualized with social, economic, and other factors. Clarifying user requirements can increase confidence that tools are being appropriately applied and highlight where training would benefit applications to build trust in tool outputs.

The use of science-based environmental decision support tools is voluntary and supplemental to established hydropower regulatory and permitting processes. Therefore, successful implementation of these tools requires strategies to engage stakeholders with diverse priorities and areas of expertise to ensure tool acceptability and usability.

6. Barriers to Tool Uptake

Environmental decision tools play an important role in ensuring that comprehensive, consistent, and rigorous methods are utilized when examining evidence, and they provide meaningful opportunities for discussions on tool inputs and outputs to guide stakeholder processes. Despite this, there are several barriers to transferring environmental decision tools to the hydropower industry, and a variety of perceptions hinder acceptance of information provided by the tools and thus their adoption. For example, one barrier to uptake is the perception that a tool has been built to empower special interest groups to get what they want. Stakeholders may simply not like the tool's appearance, or they may be unfamiliar with its language. Stakeholders often do not understand what is "under the hood" of a tool, and they may have the bias that one tool is supposed to do everything and give "the answer". Decision support tools are intended to provide science-based information to stakeholders in a way that increases transparency. However, these tools may also highlight where information gaps exist in the science and where more research may be needed to reduce risks to the environment or species of concern prior to making a final management decision. As a result, identifying where more research is needed is another important outcome of such tools.

Norwegian researchers have found that tools may bias stakeholders. Empirical research and the practice of hydropower permitting has demonstrated the challenge of a range of decision-making processes due to limited data, knowledge, and conflicting criteria, and has highlighted the role bias may play in hydropower outcomes since many decisions in practice come down to expert opinion (Köhler et al. 2019) or negotiations. Further, decision makers do not always follow tools and may either adjust inputs or outputs to tools when moving towards recommendations (Käki et al 2019).

Furthermore, tools may be inaccurate or inadequate, and those using them may not have sufficient training and/or expertise. When transferring tools developed by scientific institutions to industry, concerns that the tools may provide inaccurate or inadequate information are often expressed. Early engagement with industry to define user needs and requirements can improve tool competency. Documentation of what tools do and do not do, along with instructions for appropriate use that clarifies when and how to modify tool inputs and outputs adds validity. While no one tool can do every task, tools built with sound methods and accurate data can be highly informative. Through the wider use of tools, their merits and limitations can be evaluated and (if needed) refined as new datasets and information become available.

7. Suggestions for Future Research

With increased data availability, rapidly changing power systems with increasing needs to integrate intermittent renewables for decarbonization, and unprecedented ecosystem stressors, now is the time for developing and using environmental decision tools. To improve the effectiveness of environmental decision tools and increase their adoption, we think that it would help to explore the following research questions:

- How should input be collected and captured from stakeholder groups with different goals (e.g., recreational use of rivers versus maximizing energy production)?
- What are the best methods for combining environmental, social, and economic priorities and tools for holistic decision-making?
- How should risk be assigned, weighted, and prioritized for different scenarios and outcomes (e.g., post-tool use or as a part of the tool)?
- What is the right balance between generalized information (“grand lists”) versus site-specific information?
- What are the most effective ways to clarify biases and uncertainties prior to tool use and/or during the interpretation of tool output?
- How can stakeholders (decision makers) be motivated to use environmental decision tools? (e.g., through governance, technology transfer or incentives?)
- How can outcomes of tool use be evaluated to improve tools and validate efficacy?

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