# Energy Flexibility-Environmental Outcomes Tradeoffs Workshop Report and Research Roadmap

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***HydroWIRES***

The U.S. electricity system is changing rapidly with the large-scale addition of variable renewables, and the flexible capabilities of hydropower (including pumped storage hydropower) make it well-positioned to aid in integrating these variable resources while supporting grid reliability and resilience. Recognizing these challenges and opportunities, WPTO has launched a new initiative known as HydroWIRES: Water Innovation for a Resilient Electricity System. HydroWIRES is principally focused on understanding and supporting the changing role of hydropower in the evolving U.S. electricity system. Through the HydroWIRES initiative, WPTO seeks to understand and drive utilization of the full potential of hydropower resources to contribute to electricity system reliability and resilience, now and into the future.

HydroWIRES is distinguished in its close engagement with the DOE National Laboratories. Five National Laboratories—Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the DOE portfolio that add significant value to the HydroWIRES initiative.

HydroWIRES operates in conjunction with the Grid Modernization Initiative, which focuses on the development of new architectural concepts, tools, and technologies that measure, analyze, predict, protect, and control the grid of the future, and on enabling the institutional conditions that allow for quicker development and widespread adoption of these tools and technologies.

***Connections with the HydroWIRES Roadmap***

This report on Energy Flexibility-Environmental Outcomes Tradeoffs Workshop Report and Research Roadmap focuses primarily on addressing HydroWIRES Objective 3.3: Optimizing Hydropower Operations. It is informed by previous work on HydroWIRES Topic A: Energy-Environment Tradeoffs and results from it will feed into current work on HydroWIRES Topic 2: Energy Flexibility-Environment Tradeoff Tool as well as future work on energy-environment tradeoffs. Other relevant DOE efforts include the Environmental Flow Determination Project (ORNL), Environmental Metrics for Hydropower and Environmental Decision Support projects (ORNL), and Environmental Mitigation Database project (ORNL) as these projects created a taxonomic framework for environmental outcomes and provide connections between the environmental impacts of hydropower and their mitigations.

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# Abstract

The U.S. Department of Energy (DOE) and Norway's Royal Ministry of Petroleum and Energy signed an Annex to a previously signed memorandum of understanding (MOU) in February 2020 to collaborate on hydropower research and development (R&D). This MOU Annex has brought together the DOE's Office of Energy Efficiency and Renewable Energy Water Power Technology Office and the Norwegian Research Center for Hydropower Technology (HydroCen) to plan and coordinate hydropower R&D activities to increase our understanding of hydropower's role in the future energy grid and how to minimize and mitigate the subsequent environmental impacts. As part of this MOU Annex, hydropower researchers from the U.S. and Norway have come together to conduct collaborative research on hydropower markets and value, hydropower plant capabilities and constraints, monitoring and control technologies, environmental design solutions, environmental impacts and tradeoffs, flexible operation and planning, and technology innovations. This report presents background information on hydropower environmental regulation in the U.S. and Norway and summarizes content and conclusions from this series of two, three-hour workshops on hydropower generation flexibility and environmental outcomes, that included structured discussions used to identify research priorities and collaborative research opportunities.

# Acronyms and Abbreviations

| | |
|---|---|
| DOE | United States Department of Energy |
| eFlow | Environmental flow requirement |
| EU | European Union |
| FERC | United States Federal Energy Regulatory Commission |
| MOU | Memorandum of Understanding |
| MW | Megawatts |
| NEA | Norwegian Energy Agency |
| NEPA | National Environmental Policy Act |
| NTNU | Norwegian University of Science and Technology |
| NVE | Norwegian Resources and Energy Directorate |
| PCM | Production cost model |
| R&D | Research and development |
| TWh | Terawatt hours |

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# 1.0 Introduction

Hydropower is predicted to play a major role in electric grid decarbonization due to its ability to provide flexible generation services that can be ramped up or down very quickly with short notice. However, this flexibility comes at a cost to the environment that includes stranding fish, dewatering nests of fish and other aquatic life, flooding nests of shore birds and other terrestrial organisms that live near the water's edge, and potentially reduced boating access and safety. On the other hand, environmental flow (eFlow) requirements such as minimum flows and ramp rate restrictions and reservoir operational requirements designed to protect or improve environmental outcomes may come at a cost to flexible hydropower operations. These constraints not only have the potential to impact revenue, but reliability of the grid itself.

Assessing these trade-offs requires a robust understanding of what is being traded-off from both the energy and environmental sides which can hamper eFlow negotiations during a Federal Energy Regulatory Commission (FERC) relicensing or other hydropower environmental proceeding. These negotiations can be particularly challenging for many reasons. For example, sector specific technical terminology/jargon may not be accessible to stakeholders from other sectors. As well, there may be a science limitation where there is a lack of deep understanding or knowledge gaps about the complexities and nuances between flows and some environmental outcomes. Moreover, in cases where the scientific linkages and terminology aren't clear, there can be distrust among stakeholders that can hamper eFlow negotiations and create further communication difficulties (Levine et al. 2021).

While the need for the flexible services from hydropower due to integration of other renewables into the electric grid may be new for the US, this is not universally the case for all countries. Norway is one country that began integrating hydropower generation long ago and now have more than 90% of their electric generation and all their flexibility coming from hydropower. Norway produces approximately 87 TWh of storage hydropower, more than 50 % of all in Europe (IHA, 2020) thus, Norwegian scientists have experience creating and examining the science needed to make energy-environment trade-off assessments. As part of the US-Norway Hydropower Research Memorandum of Understanding, the US Department of Energy funded HydroWIRES Environment-Flexibility Tradeoff project team partnered with Norwegian researchers at the Norwegian University of Science and Technology (NTNU) and SINTEF Energy Research that have an extensive research record of looking at the energy flexibility-environment trade-offs in hydropower systems.

As part of this collaboration, we held two workshops to discuss knowledge gaps and research priorities for energy flexibility-environment tradeoffs. These workshops provided context on the US and Norwegian energy systems, environmental regulations, and approaches for finding potential energy-environment win-wins. We also worked with workshop participants to define and prioritize research objectives energy researchers, environmental researchers, and energy and environmental researchers to work on together. This report provides a summary of these workshops including the lists of research priorities as part of a roadmap for further collaborations.

## 1.1 US Hydropower Environmental Regulation

Most privately owned hydropower facilities in the US are required to obtain a 30-50-year term license from the FERC that conducts, administers, and coordinates various parts of the environmental review process (Figure 1). The hydropower regulatory process has several codified steps centered on environmental regulation, at least some of which involve agencies other than FERC and direct interaction with stakeholders. Some of these steps and agencies include the Biological Assessment, which is often conducted by the license applicant on behalf of FERC[1], the National Environmental Policy Act (NEPA) document issued by FERC, the Clean Water Act Section 401 Certification[2], which is reviewed and issued by the tribal or state water quality regulatory agency where the project is located, and the Biological Opinion[3], which is issued by one of the federal fish and wildlife regulatory agencies when there are federally threatened or endangered species present.

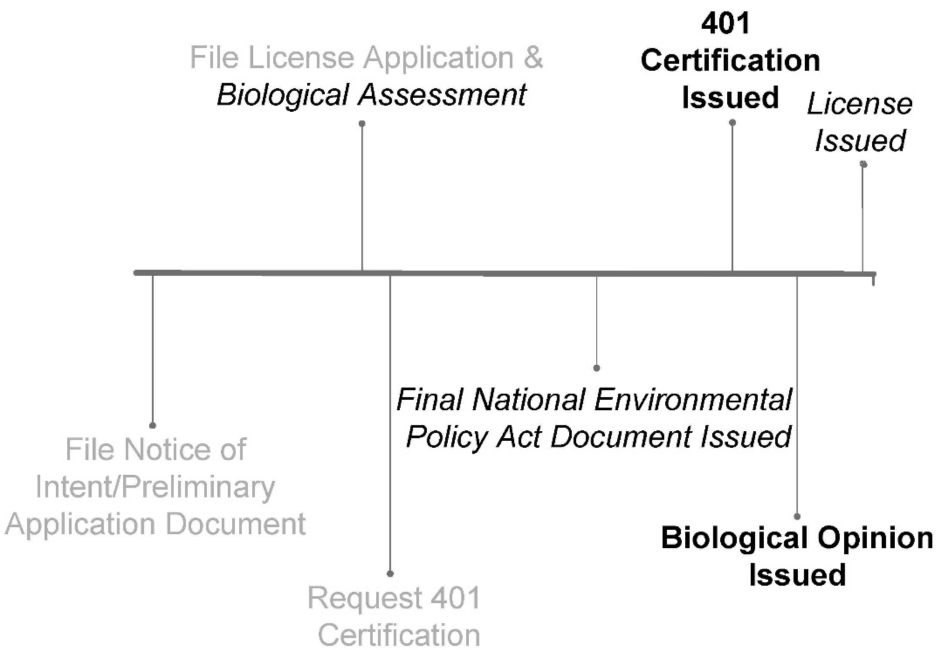


Figure 1. Some steps in the US FERC licensing process that involve environmental review. Steps are steps taken by the following entities: license applicant (gray text), FERC (black italics text), and other agencies (black bold text) which includes tribal and state water quality regulatory authority for the Clean Water Act Section 401 Certification, and the US Fish and Wildlife Service and/or the National Marine Fisheries Service for issuing the Biological Opinion.

[1] 18 CFR §380.13 Allows FERC to designate the license applicant as the non-Federal representative for informal consultation with the US Fish and Wildlife Service or the National Marine Fisheries Service on potential impacts to and mitigations for project impacted endangered species as part of Endangered Species Act compliance.

[2] §401 of the Clean Water Act requires the license applicant must obtain certification from the tribal or state water quality regulators that project discharges are consistent with the Clean Water Act and complies with applicable water quality standards.

[3] §7 of the Endangered Species Act describes that in cases where endangered species may be affected by project operations or maintenance, the US Fish and Wildlife Service and/or National Marine Fisheries Service must issue a document (called the Biological Opinion) stating, in the opinion of the agency, whether or not the hydropower project is likely to jeopardize the continued existence of federally threatened or endangered species or destroy or adversely modify their critical habitat.

## 1.2 Norway Hydropower Environmental Regulation

The development of hydropower in Norway has prioritized public ownership and control, through state, county, and municipal authorities. In 1909, the Norwegian Parliament introduced a licensing system that ensured national control over hydropower resources and provided a structure for management. A government agency (now the Norwegian Resources and Energy Directorate, NVE) was set-up in 1921 with the responsibility for regulating hydropower licenses. This has developed into a body that has scientific, advisory, and regulatory authority for all of Norway's water resources. Most water-related environmental regulations are managed by the NVE, but some regulations are also managed by the Norwegian Energy Agency (NEA) and County Governors.

The main goals of Norwegian legislation on hydropower have been to ensure that there is effective management of resources, that different interests are considered, and that projects are subject to government control. Licenses, required by this legislation and administered through the NVE, give permission to develop and run hydropower facilities. Licenses include general terms and conditions that allowing the imposition of environmental regulations to avoid or minimize negative effects of hydropower. The main legislation pertinent to Norwegian environmental hydropower regulation are the Waterfall Acquisition Act (1917), the Watercourse Regulation Act (1917), the Water Resources Act (2000), the Planning and Building Act (1965-2009), and the EU Water Framework Directive (2006) see Alfredsen et al. 2022).

**Waterfall Acquisition Act.** The Waterfall Acquisition Act ensures that hydropower developers have ownership rights. As such, licenses are only issued to public bodies (county authorities, municipalities, state-owned enterprises) or private companies where there is a minimum of two-thirds of voting and capital interests held by public bodies. Licenses impose conditions on the fees charged and obligations on the sale of power to the municipalities.

**Watercourse Regulation Act.** The Watercourse Regulation Act governs licenses for regulated flow in rivers, and transfer of water between river systems. Licenses include rules for the range of permitted water levels in reservoirs, and the minimum permitted flow and volume of water released at different times of the year.

**Water Resources Act.** The Water Resources Act may be involved in licensing of small-scale hydropower projects.

**Planning and Building Act.** The Planning and Building Act may be involved in environmental impact assessments of hydropower projects.

**Water Framework Directive[4].** The EU's Water Framework Directive, adopted by Norway in 2006, has the commitment to achieving "good chemical and ecological status" in all the more than 30 000 water bodies. Most of the hydropower impacted lakes and rivers are designated as heavily modified water bodies, where good ecological potential should be reached by relevant mitigation measures (see the European mitigation library linked to EU COM, 2020). This requires the establishment of a river basin management plan with program of measures, which should be prepared, implemented, and then reviewed every 6 years. Licensing balances power production and environmental costs based on this directive.

[4] Guide - Water Framework Directive - Environment - European Commission (europa.eu)

### 1.2.1 Status of hydropeaking mitigation

Ecological impacts from hydropeaking are mainly an issue from storage hydropower plants with tailraces into rivers. However, a huge part of the approximately 19,000 MW of hydropower produced in Norway have tailraces that empty into reservoirs or lakes of fjords, both of which are water bodies that can dampen the waves of peaked releases (Halleraker et al, 2022). For approximately 800 out of nearly 1,700 hydropower facilities in Norway, the tailrace empties into riverine reaches, although many of these are small scale hydropower facilities are diversion, run-of-river facilities with little to no storage.

Integration of modern environmental regulation of hydropeaking plants and corresponding mitigation measures varies. Revision of hydropower license terms can be done after 30 years, and theoretically updated every sixth year in line with the EU Water Framework Directive. So far, relatively few of the more than 400 licenses have gone through revision. Relevant hydropeaking mitigation measures were summarized by Halleraker et al. (2022) and include:

- Operational ramping restrictions to avoid severe stranding of biota is quite common, although the wording is vague and does not include ramping thresholds for most of the approximately 350 hydropower licenses with such regulations.
- Baseflow requirements are also common in regulated rivers downstream of hydropower facilities, but in general, the level of baseflow required seems to be relatively higher in Norwegian National Salmon Rivers compared to inland rivers.
- Bypass-valves have been installed in approximately 110 mainly small-scale hydropower facilities with licenses issued after 2008 to ensure baseflow requirements are met in cases of accidental or emergency shutdown of hydropower turbine flow.
- Other relevant, constructed hydropeaking measures such as retention basins that can help maintain hydropower flexibility while avoiding or limiting environmental impacts, have so far not been included in the revision of license terms in Norway, although this measure type is common in the European Alps.

### 1.2.2 Sustainable hydropower

EUs Taxonomy of Sustainable Finance requires that economic activities labeled as sustainable must meet certain standards. This EU regulation was adopted by a new law in Norway in December 2021. The Taxonomy requires meeting both parts of the definition of sustainability which includes 1. contribute to at least one of the six environmental objectives listed in the Taxonomy, and 2. to do no harm to any of the other six objectives, while respecting basic human rights and labor standards. The six environmental objectives listed in the Taxonomy include 1. Climate change mitigation, 2. Climate change adaptation, 3. Sustainable use and protection of water and marine resources, 4. Transition to a circular economy, 5. Pollution prevention and control, 6. Protection and restoration of biodiversity and ecosystems. While the precise standards for meeting these objectives are being determined by each country, sustainable hydropower in Norway must also include ecologically efficient mitigation of hydropeaking as a requirement (if relevant) in the criteria to report hydroelectricity as sustainable.

# 2.0 Knowledge Gaps and Research Priorities

This series of two virtual workshops relied on workshop participants to identify knowledge gaps and research priorities. The first workshop focused on knowledge gaps in hydropeaking and identified knowledge gaps across the power system outcome to ecological outcome spectrum (Appendix A). Knowledge gaps in this workshop were identified by participants through raising their virtual hand or submitting questions and comments in the meeting chat. The second workshop utilized a facilitation team and XLeap software to guide the discussion and resulted in listing and prioritization of key research challenges (Appendix B). Below we present a summary of these discussions.

## 2.1 Knowledge gaps in hydropeaking research

In the US, hydropeaking is likely to become more common with increased reliance on solar and wind and the need for hydropower to quickly ramp up and down (Somani et al. 2021). Hydropower in Norway makes up approximately 95% of all electricity generation and requires storing water in reservoirs for future electricity generation. Storing water for future generation leads to a disruption in the seasonal, and in many cases, daily flow patterns as water is stored for times of year (winter) and day with higher electricity demands leading to widespread hydropeaking activities and needs to mitigate the environmental impacts of hydropeaking.

There is an existing and growing body of work on the environmental impacts of hydropeaking although many important issues remain unresolved. To help identify these knowledge gaps, participants in the first workshop were asked to contribute and discuss the most pressing issues for hydropeaking research to address. Below, we summarize hydropeaking research knowledge gaps listed in this discussion.

- What is the range of fish mortality rates caused by hydropeaking?
    - What factors are associated with fish escaping (and living) versus become stranded (and dying)?
    - What are the impacts of chronic short-term flow fluctuations downstream of hydropower facilities? Is there some sort of cumulative impact of these short-term alterations?
        - What effects do these flows have on individual organisms over months? Seasons? Years?
        - If there are impacts, do they lead to population-level consequences?
        - Gaining an understanding of impacts of sub-daily flow may require new ecological/environmental paradigms because of temporal scale mismatch between current paradigms like the natural flow regime that use average daily discharge as the base metric.
- How often do critical power events occur at the same time as critical life history events?
    - Create phenology of organisms in the context of power system events
        - Do system blackouts or failures of other generation sources coincide more frequently with some critical life history event than others? For example, do fish migrations or spawning more frequently occur during situations where flexibility is needed to avoid outages or reduced quality of power supply
            i. Can improvements in energy demand forecasting help with mitigating environmental/ecological impacts?
                1. Merging energy and ecological information to understand when flexibility is needed versus when it is available. Peaking data should be obtained from markets and not producers because it is more transparent.

2. How is forecasting carried out across power systems and how is power versus ancillary services valued?

ii. Cross-disciplinary learning is needed for identifying win-wins (e.g., ecologists gain some understanding about electricity generation, markets, etc./electricity sector gain some understanding of ecology and environmental processes)

iii. How can climate projections be incorporated into environmental flow requirements including water quantity and timing, with an eye towards flexibility?

1. One problem is that power producers/planners don't regularly have climate data and are using historic data for planning
2. What is intersection between hydropower-environment-climate change? Is this space fully defined?

Could we include a point on the above list about new types of sensors and monitoring? And how to incorporate data from these new sources into hydropower scheduling? I think most regulation requirements on eflows, ramping etc. are set to be on the safer side. This may reduce flexibility and grid support more than necessary. New monitoring or sensor technologies that provide real-time measurements of rivers and reservoirs can be utilized for management of hydropower operations, allowing for flexible operations while ensuring that environmental and ecological requirements are met.

## 2.2 Research Priorities

Assessing energy-environment tradeoffs and finding win-wins requires research collaboration between environmental and power system researchers although there are also important research questions that each field needs to address independently. The second workshop asked participants to self-identify as belonging to the energy sector, environmental sector, or "other" sector and then asked to provide a list of research priorities for energy researchers, environmental researchers, and collaborative research for energy and environmental researchers. Research priorities provided by workshop participants were grouped by common themes to prevent priorities from appearing multiple times. Each workshop participant was then asked to select one of these research priorities as their top priority. The number of times a priority was selected by participants as the top research priority was then used to rank priorities. Research priorities are shown in the table below in descending rank order for each sector (i.e., energy, environment, energy and environment) based on the number of top priority selections each priority received.

Table 1. Research priorities by sector (i.e., energy, environment, energy and environment collaboration) identified by workshop participants. Participants were then asked to identify the most important research priority in each sector from the below sector priorities. The number of top priority selections in each sector were then summed and used to rank priorities in descending order.

| Sector | Research Priority | # Top Priority Selections |
|---|---|---|
| Energy | | |
| | Better understanding of evolving demands on hydro operations to integrate wind and solar | 10 |
| | Characterize national, regional, and local aspects to power system balancing | 5 |
| | Catalog range of tools used to make power system and flow decisions used by industry | 1 |

| | | |
|---|---|---|
| | Define flexibility and different types of flexibility in the power system | 1 |
| Environment | | |
| | Develop standard metrics that will allow for generalization of hydropeaking across rivers and allows for spatial and temporal considerations | 8 |
| | Quantify how realistic or useful are biological models for understanding effects of hydropower on a broad scale | 7 |
| | Characterize considerations for multispecies management in hydropower systems | 5 |
| | Characterize effects of ramping rates on environmental outcomes including recreation and ecological components of the ecosystem | 1 |
| | Characterize and compare efficacy of various fish passage methods | 1 |
| Energy & Environment | | |
| | Characterize implications of climate change on operational flexibility and energy-environment balance | 7 |
| | Determine best mitigations for hydropeaking that allow for balance of environmental needs and operational flexibility | 4 |
| | Create common metrics that could be useful for both environment and power sector | 4 |
| | Characterize considerations that should be included in energy-environment trade-offs | 4 |
| | Improve quantification of economic value for understanding energy-environment trade-offs | 2 |

After research priorities were ranked, participants were then asked to add items to lists of information and tools required to address the above research priorities. Participants were allowed to add information and tools to any priorities they wanted irrespective of sector of priority/participant. Information provided by participants is summarized in the table below and is attributed to sector of the contributing participant. Participants did not add information or tools to all research priorities.

Table 2. Workshop participant generated table of information and tools needed to address research priorities by sector. The sector of the attendee(s) contributing the information and tools are provided.

| Research Priorities | Information and Tools Needed | Contributing Sector(s) |
|---|---|---|
| Energy | | |
| Better understanding of evolving demands on hydro operations to integrate wind and solar | | |
| | Improved data accessibility and resource, generation, and demand forecasting for energy and ancillary services | Energy, Other |
| | Improved production cost modeling that can account for different time resolutions and marginal prices of different of generation sources | Energy |
| | Understanding reserve needs given overall balancing and need for reserves and not just markets (i.e., Security of Supply perspective) | Energy |

| | | |
|---|---|---|
| | Need and alternative sources for energy and ancillary service flexibility across time scales | Other |
| | Water-based computation of opportunity costs for lost energy due to hydro providing regulation and reserves | Other |
| | Improved understanding of how power markets will develop | Energy |
| Characterize national, regional, and local aspects to power system balancing | | |
| | Determine the level and relevance of details needed at various temporal and spatial scales including energy-environment tradeoffs | Energy |
| | Understand bottlenecks in power infrastructure to determine best locations of reservoirs and hydropower plants | Energy, Other |
| | Improved data accessibility that supports realistic representation of reservoir operations in large-scale modeling | Other |
| | Improved production cost and other models that can understand the system at various temporal and spatial scales | Energy |
| | Improved linkages between production cost models, reservoir models, and resource uncertainty | Other |
| Develop standard metrics that will allow for generalization of hydropeaking across rivers and allows for spatial and temporal considerations | | |
| | *Information and tools on this research topic are combined with the metrics topic in the collaborative research priorities section* | |
| Environment | | |
| Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | | |
| | Species/life stage specific information on stranding mortality from dewatering and speed of movement out of dewatered areas during down-ramping | Environment |
| | Improved species/life stage coverage of bioenergetics parameters | Environment |
| | Empirical data for model validation and parameterization | Environment |
| | Improved taxonomic coverage of empirical studies of population effects | Environment |
| | Improved accessibility for pre-impoundment historic data | Other |
| | Hydropower environmental impact decision support tools | Other |

| | | |
|---|---|---|
| Characterize considerations for multispecies management in hydropower systems | | |
| | Increased species coverage of documented impacts of hydropower operations including impacts on fish and other aquatic species and riparian flora and fauna | Environment |
| | Standardized list of multiple stressor measurements for determining multispecies impacts including gas supersaturation, temperature, predation, invasive species, upstream sedimentation, downstream sediment erosion | Environment |
| Energy & Environment | | |
| Characterize implications of climate change on operational flexibility and energy-environment balance | | |
| | Climate-related data for hydropower impacted species including phenology, critical thermal minimum/maximum temperatures, current and projected water temperature, and temporal and spatial water availability | Environment |
| | Current and projected generation under different renewable energy penetration and climate scenarios | Energy, Environment |
| | Interactions between reservoir operations and mitigating or exacerbating climate change | Other |
| Determine best mitigations for hydropeaking that allow for balance of environmental and operational needs | | |
| | Catalog needs for hydropower flexibility, ways in which hydropower can provide flexibility, and associations between types of flexibility and environmental impacts | Energy, Other |
| | Simple, efficient, and informative software that can provide power system modeling (e.g., large-scale storage, balancing ancillary services) and reservoir/environmental models that power producers and stakeholders can use | Other |
| | Improved availability and species coverage of life history data | Environment |
| | Decision support tools for assessing biodiversity and ecosystem vulnerability to hydropeaking such as the FIThydro hydropeaking tool | Other |
| Create common metrics that could be useful for both environment and power sector | | |
| | Consensus definitions of flexibility, categories of flexibility, classification of operational paradigms and hydropower resource types and how those link to power system services as well as standardized environmental profiles so plants can be characterized as providing a certain category of environmental outcomes. | Energy |

| | | |
|---|---|---|
| | Increase accessibility of hydropower plant flexibility parameters (e.g., waterway time constant, inertia parameters) to quantify short-term flexibility | Other |
| | Glossary/catalog of terms for describing energy flexibility and environment tradeoffs | Environment |
| | Define and characterize overlap of critical periods for energy flexibility and environment (e.g., season, time of day, week, month) | Energy |
| | Metrics that characterize operations, environmental impacts, and environmental characteristics that impact flexibility and operational restrictions | Environment |
| Characterize considerations that should be included in energy-environment trade-offs | | |
| | More accessible and higher resolution climate predictions including temperature, hydrology, spatial and temporal patterns of predicted future reservoir inflows | Other, Energy |
| | Energy production and environmental restoration/protection goals for river system | Environment |

When taken together, Tables 1 and 2 provide the foundation for a roadmap for environment-flexibility research needs. Many of the themes of these research priorities can be grouped into a few categories: 1. Understanding the future of hydropower in the grid, 2. Characterizing resources, operations, or infrastructure, and 3. Finding ways of generalizing hydropower facilities by their characteristics to allow for increased transferability of information among facilities, power markets, and spatial and temporal scales.

The future of hydropower in the grid was a common theme among research priorities in the energy sector and for collaborations between the energy and environment sectors. Research priorities in these sectors both point to the need to gain an understanding of how changes in power markets and generation mixes in the future may change the role of hydropower. Of particular interest seems to be how solar and wind integration will change the role of hydropower in the grid.

In preparing to create an energy system that is robust to climate change and extreme natural events, characterization of the current state of infrastructure, operations, mitigations, etc. provides a useful baseline for understanding what tools are available for climate adaptation. Research priorities across the energy and environment sectors described the need for resource assessments. These research priorities described the need to characterize national, regional, and local aspects to power system balancing, and implications of climate change on operational flexibility and energy-environment balance.

Hydropower is often said to be unique and site specific, but many of the research priorities listed by workshop participants were geared towards generalizing operations and impacts. For example, the second highest energy sector priority was to characterize national, regional, and local aspects to power system balancing. The top three environment research priorities provide a way of generalizing environmental characteristics or impacts in a hydropower system including development of standard metrics for generalizing hydropeaking across systems and scales, quantifying the generalizability of biological models, and defining considerations for management of multiple species. For collaborative research between the energy and environment sectors, creation of common metrics for energy and environment sectors and considerations for energy-environment tradeoffs were listed in the top four priorities.

Hydropeaking was specifically discussed in the first workshop because of its central importance to understanding environmental effects of hydropower. The importance of gaining a better understanding of hydropeaking effects as a research priority was further explicitly stated in three of the priorities defined in the second workshop and was implied in additional research priorities. Research priorities mentioning "flexibility", or "ramping rates" may have some hydropeaking component as well.

Workshop participants from across sectors named the need for new or more accessible data to address the research priorities named in Table 1 and was the top (or tied for the top) category of information and tools needed to address research priorities for all sectors or combinations of sectors. In fact, the need for new or more accessible data was the most common response for information or tools needed to address research priorities, more common than all the other categories of information and tools combined. New and more accessible data collected to address research priorities in Table 1 could be used to inform and potentially improve energy and environmental outcomes.

Participants that self-identified as being from the energy sector or other said that new models, especially production cost models (PCMs), were needed to address research priorities. Specifically mentioned were the need for PCMs that can account for differences in temporal and spatial resolutions and marginal prices across generation sources and improved linkages between PCMs, reservoir models, and resource uncertainty. Participants that self-identified as being from the environment sector did not list new models among the information and tools needed to address research priorities although model validation was listed as a need.

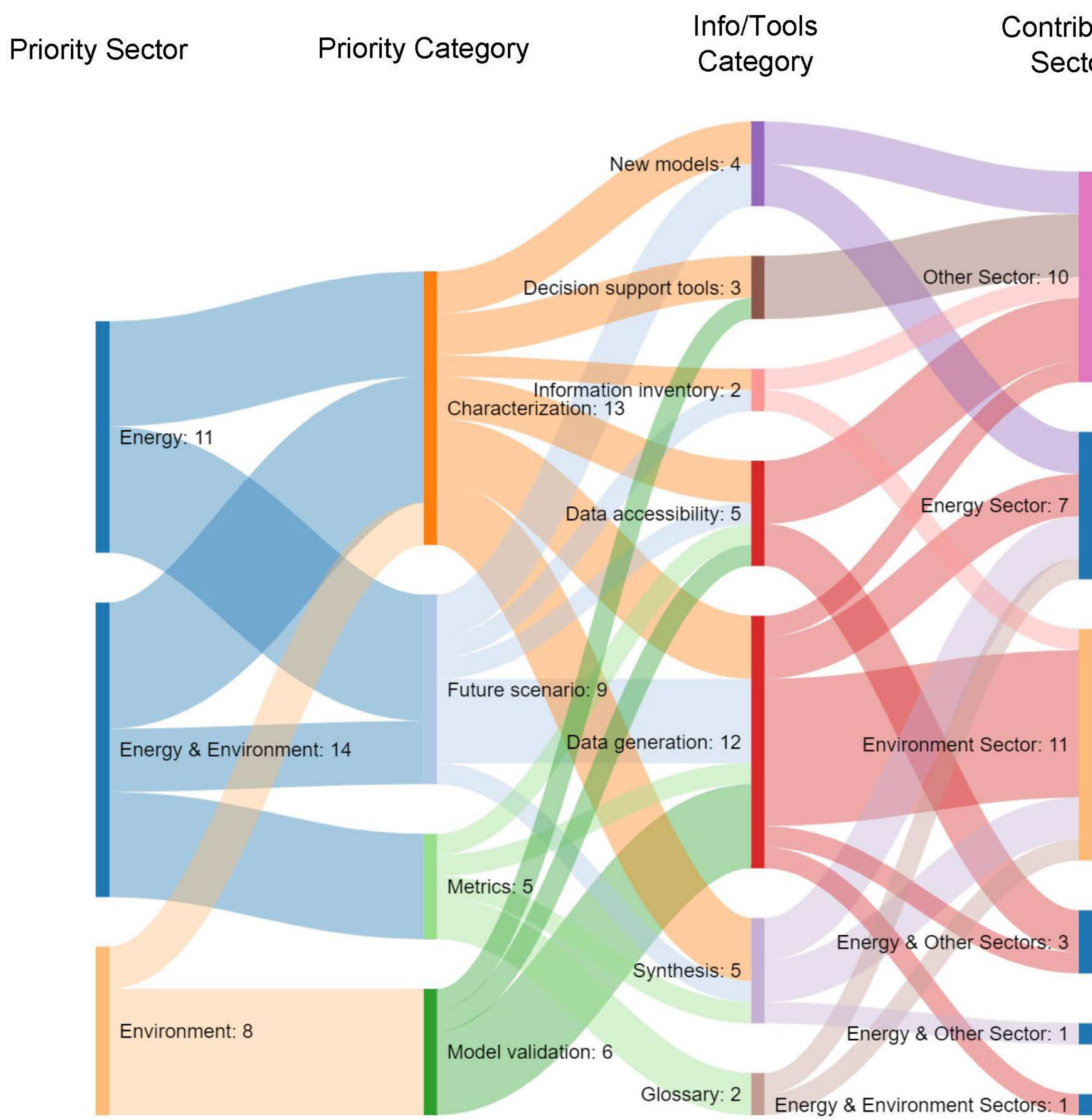


Figure 2. Sankey diagram showing connections between the sector the research priority listed in Table 1 applies to, the category of research priority, the category of the information and tools from Table 2 needed to address the research priorities, and the sector(s) of the workshop participant(s) who contributed the information on the category of the information and tools needed to address research priorities. Designations for research priorities provided in Appendix C.

## 2.3 Research Roadmap

In a perfect world, foundational and basic research would both be prioritized for funding because they are both critical to advancing the state of science and technology. This is not always the case because foundational and basic research may be time intensive, requiring laboratory or field experiments that may last months of years. In this section, we have split research priorities listed by workshop participants into two categories: critical foundational research and quick-wins. The critical foundational research may require making observations on multiple species over long time periods or special laboratory equipment to make bioenergetic or biomechanical measurements. In the energy sector, critical foundational research may require collecting new data on power markets, projected generation trends, and climate forecasts. Critical foundational research is highly impactful, and this information may be useful across sectors for understanding energy flexibility-environment tradeoffs. However, critical foundational research can be highly resource intensive, and it may not be feasible to address several research priorities in this area. Research identified under the quick-wins heading are research priorities identified by workshop participants that can address important, yet specific, research needs by applying, recomputing, or altering existing information, techniques, or models. Quick win research can lead to impactful science within 1-3 years.

### 2.3.1 Quick-Win Research

- Create common metrics and consensus definitions of terminology that entwine energy and environment concepts that can be useful across energy and environment sectors. Research fitting this description could include defining metrics for and definitions and categories of flexibility, generalization of hydropeaking metrics and calculations that accounts for spatial and temporal elements of flow fluctuations, cataloging needs for hydropower flexibility, the ways that hydropower can provide flexibility, define and characterize overlap of critical periods for energy flexibility and environment (e.g., season, time of day, week, month), and associations between types of flexibility and environmental impacts.
- Characterize power system balancing at local to national scales to better inform production cost and other models.
- Increase accessibility of future climate and hydrologic scenarios to allow for more widespread use of models describing future generation needs and sources.
- Improved accessibility of pre-impoundment and other historic environmental data.
- Conduct analyses that simulate operational and flow mitigation scenarios and evaluate both power system and environmental outcomes at the grid-scale. For example, are there meaningful feedbacks for grid reliability if several plants within a power market area have ramp rate restrictions under current and future levels of solar and wind generation?
- Creation of simple, efficient, and informative software and decision support tools (like SINTEF's virtual hydropower lab web interface software that can schedule short-term hydropower operations scheduling) that can help users conduct power system modeling (e.g., large-scale storage, balancing ancillary services), reservoir modeling, determine environmental impacts, and/or simulate tradeoffs between or among these components.

### 2.3.2 Critical Foundational Research

- Increased availability and species coverage of basic biological information was by far the most listed information/tool for addressing research priorities. Basic information on hydropower-impacted species such as spawning time and habitat, time and distance of migration, migration and spawning cues, thermal tolerance, and relationships between environmental conditions and energy expenditure does not exist for many species of hydropower importance. This information is foundational for addressing both environment and energy sector research priorities including those related to assessment of environmental impacts based on future scenarios, metric development, and model validation. This research is needed to address second and third top environmental research priorities, and second and fourth top research priorities for energy and environment collaborative research priorities.
- Research listed in Knowledge Gaps in Hydropeaking Research listed above.

- Improve PCMs so they enable understanding the power system at a variety of temporal and spatial scales and improves linkages between PCM outputs, reservoir models, resource uncertainty, and marginal prices of different generation sources. This research is needed to address top two research priorities for energy researchers, and top research priority for energy and environment collaborative research priorities.
- Improved understanding of current and future trends in power markets for creating more realistic future scenarios. This research is needed to address top two research priorities for energy researchers, and top research priority for energy and environment collaborative research priorities.
- Increased accessibility of hydropower plant generation data and flexibility parameters (e.g., waterway time constant, inertia parameters) to that can be used to characterize short-term flexibility as a resource.

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## 3.1 APPENDICES

APPENDIX A: Workshop notes from Workshop 1.
APPENDIX B: Xleap report from Workshop 2.
APPENDIX C: Categorization of research priorities and information/tools into categories used in Sankey diagram.

# Appendix A

# Workshop 1 Notes

## Environmental Flexibility Workshop

14 December 2020

Workshop on tradeoffs between hydropower flexibility and environmental outcomes

- This will be the first in a two-workshop series on this topic for US and Norwegian researchers resulting from the hydropower MOU signed in February 2020
- Workshop 1 will focus on defining collaborative goals, research gaps, grand challenges
- Workshop 2 (Q2 FY21) will focus on refining goals and challenges defined in Workshop 1
    - Product of these workshops will be a roadmap/report on the future of flexibility-environment tradeoffs in hydropower

### Workshop 1 Agenda

- Introductions and agenda (10 minutes)
    - Sam Bockenhauer, Dana McCoskey
- Background/context US and Norway (45 minutes)
    - Regulatory and Power System Context
        - U.S. Hydropower Regulatory Process. Brenda Pracheil (Oak Ridge National Laboratory)
        - The U.S. Power system. Vishvas Chalishazar (Pacific Northwest National Laboratory)
        - The Nordic power system, the importance/role of hydropower, market and regulations. Linn Emelie Schäffer (NTNU)
    - Environmental context (45 minutes)
        - U.S. Hydropower environmental flow mitigations and flexibility. Brenda Pracheil
        - Environmental regulations with a focus on flexibility. Survey of hydropeaking operations. Jo Halleraker (NTNU)
        - Challenges and tools for environmental impacts from flexible operations. Atle Harby (SINTEF), Line Sundt-Hansen (NINA)
        - HyPeak network, Lennart Schönfelder (SINTEF). Ideas for a European hydropeaking study, Mauro Carollo (SINTEF) 5 min
- Break (10 minutes)
- Structured discussion of group goals and grand challenges (60 minutes)
- Next steps and Workshop 2 (10 minutes)

## Knowledge Gaps in Hydropeaking

1. Mortality rates
    a. When do fish escape versus become stranded?
2. Chronic impacts of short-term flow fluctuations on fish and aquatic biota
    a. What effects do short-term flow fluctuations downstream of hydropower facilities have on individual aquatic organisms over months? Seasons? Years?
    b. If there are impacts, do they lead to population-level consequences?
    c. Gaining this understanding may require new ecological/environmental paradigms.
3. How often do critical power events occur at the same time as critical life history events?
    a. Create phenology of organisms in the context of power system events
4. Can improvements in energy demand forecasting help with mitigating environmental/ecological impacts?
    a. Merging energy and ecological information to understand when flexibility is needed versus when it is available
    b. How is forecasting carried out across power systems and how is power versus ancillary services valued?
5. Cross-disciplinary learning is needed for identifying win-wins (e.g., ecologists learning how the grid works, electrical engineers learn about ecology)
6. How can climate projections be incorporated into environmental flow requirements including water quantity and timing, with an eye towards flexibility?
    a. One problem is that power producers/planners don't regularly have climate data and are using historic data for planning
    b. What is intersection between hydropower-environment-climate change? Is this space fully defined?

## Organizers*/Presenters:

1. Brenda Pracheil* (Oak Ridge National Laboratory; ORNL)
2. Atle Harby* (NTNU)
3. Linn Emelie Schäffer* (NTNU)
4. Sam Bockenhauer (DOE)
5. Dana McCoskey (US Department of Energy; DOE)
6. Vishvas Chalishazar (Pacific Northwest National Laboratory; PNNL)
7. Jo Halleraker (NTNU)
8. Line Sundt-Hansen (NINA)
9. Lennart Schönfelder (SINTEF)
10. Mauro Carolli (SINTEF)

# Appendix B

# Workshop 2 XLeap Report

## Environmental Outcome - Hydropower Flexibility Workshop

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| | |
|---|---|
| **Date** | May 3, 2021 |
| **Host** | Kate Shattuck |

## Contents

1 Brainstorm: Research Questions........................................................................................ B.1
2 DeepDive: Information & Tools Needed for Research Questions................................................. B.4

## 1 Research Questions

**Brainstorm question or instruction:**
Research Questions
What research questions do we need to ask to help set the stage for future directions? (Think it terms of priorities for power researchers, priorities for environmental researchers, and priorities that will require both power and environmental people to work together).

**Sticky points:**

- 🟡 Most Important - Power (One point per participant)
- 🟤 Most Important - Environmental (One point per participant)
- 🔴 Most Important - Both (One point per participant)

**Unsorted (0)**

**1. Priorities for Power Researchers (5)**

🟡(10) **7. Evolving demands on hydropower operations to integrate wind and solar. (Power Sector)**

- Merged items
- Within a short 5-year period, California's net demand went from a standard demand curve to a "duck curve" (looks more to me like a camel, btw). It appears that more of the Western US is following this trend. We should research how added non-dispatchable renewable generators will change net demand and model ways in which hydropower facilities can be more flexible and assist in meeting the new net demand. (#28 | Other)
- Flexibility of operating hydropower in high renewable integrated grid (#31 | Power Sector)
- Flexibility in a system dominated by variation of wind and solar (#41 | Other)

🟡(1) **17. Understanding the range of tools that are used in making flow and power system decisions used by industry as they relate to hydropower operations (e.g. I appreciate that Brenda's case study used the actual operations model that the utility uses). (Power Sector)**

**36. hydropower plant generation for ancillary services market energy markets (Power Sector)**

🟡(1) **50. define flexibility, and different types of flexibility in the power system (Power Sector)**

- Merged items
- hydropower machine related issues for quick ramping for either direction up and down during consecutive time period (#47 | Power Sector)

🟡(5) **20. power system balancing has national, regional and local aspects needed to be considered - in addition to the environmental and energy perspectives (Power Sector)**

- Merged items
- Power system balancing does not only requires TSO services, significant share of balancing is currently provided by spot sales. S&B view is not sufficient. (#43 | Power Sector)

**2. Priorities for Environmental Researchers (5)**

🟤(8) 🔴(1) **52. What kinds of metrics can be developed that will allow for generalization of hydropeaking across rivers that allow for spatial and temporal and spatial considerations (Environmental Sector)**

- Merged items
- There is a need to develop standardized environmental metrics for 'hydrofribilation' (love this term) that can be generalized across rivers. (#5 | Environmental Sector)

(7) **51. How realistic or useful are biological models and tools for understanding hydropower effects on a broad-scale (Environmental Sector)**

- Merged items
- biological models validation (#4 | Environmental Sector)
  - I would find a comparison of the agent-based modeling approach vs. the statistical fish models useful to understand the strengths/weaknesses of both (#2 | Other)
  - applicability of Norwegian tools (e.g. agent-based salmon modeling) for US systems and licensing process, and vice versa (#21 | Power Sector)

(5) **53. How and what kinds of considerations do we need to manage for multiple species, including non-fish species, in one hydropower system? (Environmental Sector)**

- Merged items
- Managing for multiple species in the same system (#8 | Environmental Sector)
  - focus on other species than fish (#12 | Environmental Sector)
  - Effect of small scale frequent fluctuations on fish and other species (#13 | Environmental Sector)
    - effects of subdaily flows on fish (#1 | Environmental Sector)
      - On all fish species? (#37 | Other)
    - Better parameterization of how fish respond to hydraulics during hydropeaking etc. Ideally studies done under controlled conditions (#24 | Environmental Sector)
  - we need to adress both up (flushing) and downramping (stranding) effects and mitigation for more species than salmonids (#22 | Environmental Sector)
  - Studies on hydropeaking mortality, relating mortality to duration of dewatering (#32 | Environmental Sector)
  - Understand the ecological role served by inhabiting floodplain versus the danger of hydropeaking, trade-offs. (#35 | Environmental Sector)

(1) **54. What are the effects of ramping on recreational use including fishing, boating, nature-watching, etc.? (Environmental Sector)**

- Merged items
- Effect of small and large scale ramping on recreational use (fishing, kayaking, ,,,,) (#16 | Environmental Sector)
  - Nature is also nature experience (#14 | Power Sector)
  - impact of ramping and peaking of hydropower plant operation to the nonpower impacts (#25 | Power Sector)
  - Effects of hydropeaking (and reservoirs fluctuaction) on other ecosystem services than habitat suitability for fish (#30 | Environmental Sector)

(1) **55. How effective are fish passage methods for moving fish around dams? (Environmental Sector)**

- Merged items
- Effectiveness of fish passage methods around large dams (e.g., trucking, Whoosh!) (#40 | Environmental Sector)
  - Are technical solutions for fish migration past a dam something that is interesting? (#45 | Environmental Sector)

**3. Priorities that require both Power & Environmental Researchers to work together (5)**

(7) **59. What are the implications of climate change on flexibility and energy-environment balance? (Environmental Sector)**

- Merged items
- climate change alter inflow patterns, these need to be considered as well (#33 | Power Sector)

🔴(4) **56. What are best mitigations for hydropeaking that allow for balance of environmental needs and operational flexibility (Environmental Sector)**

- Merged items
- question: is as close to natural always the best for the environment? Or can we also talk about positive impact of HP regulation? (#3 | Power Sector)
- Why aren't small retention pools more common for mitigating hydropeaking effects? They sound like a simple and efficient solution to me (#6 | Environmental Sector)
- The EU project HydroFlex is looking into a technical solution for active mitigation of discharge fluctuations due to hydropeaking operations. Very interested in working with the environmental sector to find good case studies for mapping the benefits that can be achieved! (#18 | Environmental Sector)
- Consider the potentially positive benefits of reservoir operations for climate mitigation vs negative impacts with respect to environmental impact (#39 | Other)
- Options for supplying environmental flows with power-producing technologies (#44 | Other)
- Guidance for ramping rates (#49 | Environmental Sector)

🔴(4) **57. What are common metrics that could be useful for both the environmental and power sector? (Environmental Sector)**

- Merged items
- Analysis of the the metrics of flexibility from individual hydro power plants - in order to see the trade-offs between hydropeaking and environmental influences in indivudal cases (#23 | Other)
- Do we have a common understanding of what is high low, moderate and no hydropeaking/subdaily flow operation? Need to standardaise the terms? (#38 | Environmental Sector)
- We should make distinctions between hydropower units that are "hydropeakers" and those that are "load followers" in order to determine the differences in downstream environmental impacts. For example, if hydropeaking has adverse impacts to fish, but load-following units less so, then some "peakers" could be reoperated as "load-followers". (#46 | Other)

🔴(4) **61. What considerations should be included in energy-environment trade-offs? (Environmental Sector)**

- Merged items
- Hydropower availability for power grid considering nonpower constraints in multiple time resolutions ((seasonal, daily, hourly) (#9 | Power Sector)
  - There is a "balance" between the needs for flexible operation of the energy system and environmental impacts of such operation. How can we value each side of this "balance", or "calculate" the right balance? (#10 | Other)
  - How much hydro power flexibility is needed? and how much of it is or should be restricted by environmental factors (#11 | Power Sector)
- hydropeaking/short term flex vs long-term reservoir managment/flex! (#15 | Power Sector)
- What are the most important factors to consider for basin/watershed planning and impact evaluations to optimize outcomes for energy and the environment? (#19 | Environmental Sector)
- The effect of ramping during winter (#26 | Environmental Sector)

- How do we consider the tradeoff of the impacts of longer-range storage needs/benefits that hydropower can provide with the associated environmental impact? (#27 | Other)
- Effect of ramping flow on sediments, water temperature, ice formation, water quality and other physical variables other than discharge (#34 | Environmental Sector)
- How do we make energy-environment trade-offs that are both informative yet generalizable? (#60 | Environmental Sector)
  - Ways to avoid complex hydrodynamic modeling, possibly development of surrogate models by post-processing simulated data. (#29 | Environmental Sector)

(2) **58. How can we more completely quantify economic value for understanding energy-environment tradeoffs? (Environmental Sector)**

- Merged items
- improved quantification of benefits (jobs, macroeconomics, equity) associated with environmental and flexibilty outcomes (#42 | Power Sector)
- Some recent economic studies have shown that hydropower has "non-use" economic value. More studies should be done on this subject. (#48 | Other)

## 2 Information & Tools Needed for Research Questions

**Question or instruction for the Deep-dive:**
Information & Tools Needed for Research Questions
Enter each box below - What information and tools are needed to address these research questions?

**Evolving demands on hydropower operations to integrate wind and solar.**

- Merged items
- Within a short 5-year period, California's net demand went from a standard demand curve to a "duck curve" (looks more to me like a camel, btw). It appears that more of the Western US is following this trend. We should research how added non-dispatchable renewable generators will change net demand and model ways in which hydropower facilities can be more flexible and assist in meeting the new net demand. (#1)
- Flexibility of operating hydropower in high renewable integrated grid (#2)
- Flexibility in a system dominated by variation of wind and solar (#3)
- Comments
- INFORMATION - What information is needed to address this research question?
  - Better meterological data is needed for future scenarios. (#37 | Power Sector)
  - Better demand forecast, better forecast in general for all resources as well. (#38 | Power Sector)
  - What will be the daily pattern for net demand with increased penetration of non-dispatchable renewable generation? (#46 | Power Sector)
  - Power system is not only about TSO markets, it is about the overall balancing and need for reserves. Better understanding of reserve needs in a Security of Supply perspective. (#47 | Power Sector)
  - Readily accessible datasets for end users to evaluate impacts on their system (#48 | Other)
  - Better demand forecast for both energy and ancillary services. (#51 | Other)
  - Alternatives for flexibility - costs, applications, markets... (#53 | Other)
  - Modeling of utility's resource stack and how hydropower can be dispatched to assist utilities in meeting a net demand created by the addition of renewable generation (#62 | Power Sector)

- The issue with hydropower is that you have to keep water in the river channel, so there needs to be water passed through the facility during times of overgeneration. Would this water be bypassed? In our case we must pass it through the turbines and thus electricity is generated. Another issue becomes downstream recreation, this is specifically important if there is economy or large development downstream. We can't simply drop to minimum flow mid-day otherwise it becomes a public safety issue, and furthermore, if it effects the economy of the communities that rely on the recreation and tourism the river brings, they go directly to their elected officials, who then write letters to our senior leaders. (#117 | Other)

- Water based computation of opportunity costs for lost energy due to a hydroplant's providing regulation and reserves (#64 | Other)
- Better understanding of the need for flexibility across different time scales, and the impact on variable renewables (VRE) on the energy system (#74 | Other)
- Interaction with other flexibility providers (#111 | Power Sector)
- Better understanding of how the markets will develop! (#112 | Power Sector)
- Geographical coupling, how much flexibility does this really give us? (#114 | Power Sector)

· TOOLS - What tools are needed to address this research question?

- Better wind and solar models, detailed dynamic models for the same, Non-blackbox wind and solar models for electromagnetic transient stability analysis. (#52 | Power Sector)
- production cost model which can understand power system in different time resolutions of hydropower, solar, wind generation and marginal prices of the system (#61 | Power Sector)
- support for equipment maintenance to handle more regular turbine ramping and response to the grid not experienced historically. (#104 | Other)
- Currently, a water-based model to co-optimize energy, regulation, and reserves is under development as a DOE HYDROWIRES project. (#120 | Other)

**power system balancing has national, regional and local aspects needed to be considered - in addition to the environmental and energy perspectives**

· Merged items

· Power system balancing does not only requires TSO services, significant share of balancing is currently provided by spot sales. S&B view is not sufficient. (#4)

· Comments

· INFORMATION - What information is needed to address this research question?

- What level of detail do we need at different "scales", i.e. different planning horizons and different spatial scopes? Is the required level of detail increasing at all levels? Or is it just a change in the type of details we need to include? How can we pin point what are important details and not. (#41 | Power Sector)
  - And considering environmental aspects versus flexibility, what questions should be addressed at the different levels? (#55 | Power Sector)
- Bottleneck studies, power flow restrictions, (#59 | Power Sector)
- Bottlenecks i power infrastructure: technical solutions og better location of reservoirs and HPP? (#77 | Other)
- Datasets to support realistic representation of reservoir operations in large-scale modeling (#84 | Other)

· TOOLS - What tools are needed to address this research question?

- production cost models which can understand the system in national, regional, local aspects in different level of details (#49 | Power Sector)
- Good practice/methods on how to use models with different strengths combined (i.e. different planning horizons and scope) (#66 | Power Sector)
- Better linkage with production cost models, reservoir models, and uncertainty in flows/associated datasets to support (#68 | Other)
  - Agreed, just what I was thinking as well! (#76 | Power Sector)

**How realistic or useful are biological models and tools for understanding hydropower effects on a broad-scale**

· Merged items

· biological models validation (#6)

- I would find a comparison of the agent-based modeling approach vs. the statistical fish models useful to understand the strengths/weaknesses of both (#5)
- applicability of Norwegian tools (e.g. agent-based salmon modeling) for US systems and licensing process, and vice versa (#7)

· Comments

· INFORMATION - What information is needed to address this research question?

- To assess hydropeaking effects, information is needed on (1) stranding mortality as a function of the duration of dewatering and (2) the speed of displacement of fish away from dewatered areas during downramping. This needs to be broken down according to fish species and life-stage. (#39 | Environmental Sector)
- Bioenergetics data (#45 | Environmental Sector)
- Collection of field data about how good are our modelling simulations (#56 | Environmental Sector)
- More experimental studies on population effects for non-salmonids (#78 | Environmental Sector)
  - more studies on other organisms than fish (#113 | Environmental Sector)
- Historic data for original status (naturelike) - vs todays situation (#115 | Other)

· TOOLS - What tools are needed to address this research question?

- validation data (#79 | Environmental Sector)
- improve and develope more generic pressure-impact tools like the ones developed by BOKU in Austria for other riverine species. (#90 | Environmental Sector)
- Tools that help us understand the difference between natural variation and natural impacts on one side and the effects of hydropower and hydropower operations on the other side (#91 | Other)
- Field studies under semi-controlled conditions and controlled studies lab studies can be used to parameterize models (#100 | Environmental Sector)

**How and what kinds of considerations do we need to manage for multiple species, including non-fish species, in one hydropower system?**

· Merged items

· Managing for multiple species in the same system (#9)

- focus on other species than fish (#10)
- Effect of small scale frequent fluctuations on fish and other species (#11)
  - effects of subdaily flows on fish (#8)
    - On all fish species? (#16)

- Better parameterization of how fish respond to hydraulics during hydropeaking etc. Ideally studies done under controlled conditions (#13)
- we need to adress both up (flushing) and downramping (stranding) effects and mitigation for more species than salmonids (#12)
- Studies on hydropeaking mortality, relating mortality to duration of dewatering (#14)
- Understand the ecological role served by inhabiting floodplain versus the danger of hydropeaking, trade-offs. (#15)

· Comments

· INFORMATION - What information is needed to address this research question?

- How sensitive is each species to an operational change? Also, are there critical thresholds where sensitivity increases? (#44 | Environmental Sector)
- More empirical studies on flow ramping and biodiversity (for non-salmonids) like riparian flora and fauna. (#69 | Environmental Sector)
- Are there indicator or umbrella species/groups that can reduce complexity of multi-species management? (#73 | Environmental Sector)
- Habitat studies should include more ecological factors (e.g. predation, food availability, shelters and refugia) (#89 | Environmental Sector)

· TOOLS - What tools are needed to address this research question?

- Metrics that quantify value of each and tools that optimize subject to these (#75 | Environmental Sector)
- Multipressures must be adressed in multispecies - multistresors impacts downstream HP facilities, a need to also include; 1) Supersaturation, 2) Temperature issues, 3) Predation (more likely when fisk and biota needs to esape during ramping), 4) Sedimentation degradation (damming effect upstream) (#109 | Environmental Sector)

**What are best mitigations for hydropeaking that allow for balance of environmental needs and operational flexibility**

· Merged items

· question: is as close to natural always the best for the environment? Or can we also talk about positive impact of HP regulation? (#17)

· Why aren't small retention pools more common for mitigating hydropeaking effects? They sound like a simple and efficient solution to me (#18)

· The EU project HydroFlex is looking into a technical solution for active mitigation of discharge fluctuations due to hydropeaking operations. Very interested in working with the environmental sector to find good case studies for mapping the benefits that can be achieved! (#19)

· Consider the potentially positive benefits of reservoir operations for climate mitigation vs negative impacts with respect to environmental impact (#20)

· Options for supplying environmental flows with power-producing technologies (#21)

· Guidance for ramping rates (#22)

· Comments

· INFORMATION - What information is needed to address this research question?

- 1) Flow ramping data with relevant time resolution (e.g. turbine flow every hour), 2) HP caharacteristics , 3) If flow ramping in rivers; a typology relevant to assess ecological risk from hydropeaking (#43 | Environmental Sector)
- Needs for flexibility as well as information about the characteristics of the environment downstream the powerplant (#50 | Other)

- A methodology for getting a hydrograph for the HP outlet which represent discharge that is acceptable for the river ecology, as a target for hydropower ramp rates (#71 | Environmental Sector)
- A better understanding of the environmental impacts across a variety of hydropower types (i.e. hydropower facilities differ significantly in how they are operated) (#87 | Power Sector)
- ramping restriction is dependent on minimum flow in river, as well as on other mitigating measures as weirs and river-in-river aspects and so on. (#106 | Power Sector)

· TOOLS - What tools are needed to address this research question?

- Efficient tools that can bring the modeling of power systems (e.g., both large-scale storage & balancing needs and ancillary service needs) to the level that can be assessed without massive compute resources so reservoir/environmental models can work more directly with this (#40 | Other)
- FIThydro Hydropeaking Tool (#57 | Other)
- Longitudional flow ramping data downstream HP outlets, and bioidiversity assemblages potentially impacted + basic info about ecological sensitivty (to rank the most critical ecological periods) related to flushing and/or stranding. (#58 | Environmental Sector)
- understanding power system requirement energy, ancillary services, environmental emission reduction by less variable renewable curtailment, production cost models are helpful (#108 | Power Sector)
- National mitigation strategies, aiming at ensuring flexible hydropower production that are ecologically sustianable. E.g. may be needed to redesign turbines to maximize hydropeaking in old HP schemes with minor or no impacts in rivers! (#119 | Environmental Sector)

**What are common metrics that could be useful for both the environmental and power sector?**

· Merged items
· Analysis of the the metrics of flexibility from individual hydro power plants - in order to see the trade-offs between hydropeaking and environmental influences in indivudal cases (#23)
· Do we have a common understanding of what is high low, moderate and no hydropeaking/subdaily flow operation? Need to standardaise the terms? (#24)
· We should make distinctions between hydropower units that are "hydropeakers" and those that are "load followers" in order to determine the differences in downstream environmental impacts. For example, if hydropeaking has adverse impacts to fish, but load-following units less so, then some "peakers" could be reoperated as "load-followers". (#25)

· Comments

· INFORMATION - What information is needed to address this research question?

- categories of flexibility that can be standardized across the operations of different plants; classification of operational paradigms and hydropower resource types, and how those link to power system services (work with EPRI underway in this). Then, perhaps link these operational paradigms to a more standardized set of environmental profiles, so that each plant can be described as providing a certain category of power system services as well as having a certain category of environmental outcomes. (#92 | Power Sector)
- The combined hydro/environmental community needs to develop a glossary of terms and their consensus definitions. (#93 | Other)
- Flexibility parameters of hydro power plants are generally not easily available, ie waterway time constant, inertia parameters, etc. Making this information available will make it easier to quantify short-term flexibility in specific cases. (#94 | Other)
- catalog of terms (#96 | Environmental Sector)

- What define critical periods for the environment and flexibility? Do they overlap? Is it given by season, time of the month/week/day, or is it given by temperature/inflow/other weather related aspects. 2. AND what is flexibility? Too wide of a term... ;) (#98 | Power Sector)
- Good definitions for cross-sector collaboration (#101 | Other)

· TOOLS - What tools are needed to address this research question?

- I'm not sure addressing this research question will require tools so much as it will require thought (#88 | Environmental Sector)
- Tools could be just explanation of the different metrics, like a dictionary (#103 | Other)
- Consistent use of terminology. Clear and easily available definitions within a field would be a starting point before we try to coordinate between fields! (#105 | Power Sector)
- Transparent optimalisation tools (models) adressing the peak demand in each region (pr hour/min) vs the flow ramping intensity that is likely to have high-moderate-low ecological impact. May be R&D also on more flexible environemtal operational restrictions (dependent on wet, dry years etc) (#118 | Environmental Sector)

**What are the implications of climate change on flexibility and energy-environment balance?**

· Merged items
· climate change alter inflow patterns, these need to be considered as well (#26)
· Comments

· INFORMATION - What information is needed to address this research question?

- A database of aquatic phenology to evaluate shifts in life history timing (#42 | Environmental Sector)
- Temperature, temperature, temperature - include this in design of reservoir operation and design of ecological constraints to protect biota. (#54 | Environmental Sector)
- Data on min and max temperature tolerance for aquatic species (#63 | Environmental Sector)
- Data that can enable forecasting of range shifts in aquatic species (#70 | Environmental Sector)
- Data to enable consideration of changes in human population centers, energy efficiency, generation sources, and interactions between environmental requirements and hydropower generation (#81 | Environmental Sector)
- Water availability variation, temperature which impact for power generation and demand (#82 | Power Sector)
- Inflow pattern will change with climate change. Both amount, location and timing of inflow. Has consequences both for environmental and power production / water handling aspects. (#97 | Power Sector)
- Recognize reservoirs have the ability to mitigate climate change (shift timing of flows, e.g., with shifts in snowmelt) as well as make impacts worse. How to evaluate this? What is the target with respect to flow regimes? (#116 | Other)

· TOOLS - What tools are needed to address this research question?

- Regional-scale models of thermal effects of reservoirs now and in future (#65 | Environmental Sector)
- Integration of non-stationary processes in the planning and operations with measures of acceptable risk (i.e. is <100% reliability acceptable? do we have tools to assess this?) (#67 | Other)
- Models of hydropeaking effects on downstream thermal regimes, and research to extend these to avoid being site-specific. (#80 | Environmental Sector)

- power system models which can understand power demand, power generation capabilities in different climate scenarios (#86 | Power Sector)

**What considerations should be included in energy-environment trade-offs?**

- Merged items
- Hydropower availability for power grid considering nonpower constraints in multiple time resolutions ((seasonal, daily, hourly) (#27)
  - There is a "balance" between the needs for flexible operation of the energy system and environmental impacts of such operation. How can we value each side of this "balance", or "calculate" the right balance? (#28)
  - How much hydro power flexibility is needed? and how much of it is or should be restricted by environmental factors (#29)
- hydropeaking/short term flex vs long-term reservoir managment/flex! (#30)
- What are the most important factors to consider for basin/watershed planning and impact evaluations to optimize outcomes for energy and the environment? (#31)
- The effect of ramping during winter (#32)
- How do we consider the tradeoff of the impacts of longer-range storage needs/benefits that hydropower can provide with the associated environmental impact? (#33)
- Effect of ramping flow on sediments, water temperature, ice formation, water quality and other physical variables other than discharge (#35)
- How do we make energy-environment trade-offs that are both informative yet generalizable? (#36)
  - Ways to avoid complex hydrodynamic modeling, possibly development of surrogate models by post-processing simulated data. (#34)
- Comments
- INFORMATION - What information is needed to address this research question?
  - Better climate predictions. Larger reservoirs/consentration of reservoirs? (#60 | Other)
  - Value of nature differ, energy AND flexibility, flood damping, power price impact, (#72 | Power Sector)
  - Environment to be nature+ climate change. Need for new knowledge of climate impacting inflows pattern: where, how much and when details is required (#83 | Power Sector)
  - Goals for river system in terms of power and environmental restoration/protection. (#85 | Environmental Sector)
  - Recognition that species or environmental factors may change regardless of hydropower operations. Simply due to water temperature, a species may become more limited (or increased), and the hydro goals should adapt. (#95 | Other)
  - Is there a way to quantify the value of a particular species or "environment service"? (#107 | Environmental Sector)
  - Identifying - for each river system - what environmental variables are important (#110 | Power Sector)
- TOOLS - What tools are needed to address this research question?
  - water releases from dams and economic value hydropower for energy and ancillary services of the system, variable renewable curtailment reduction, production cost models help (#99 | Power Sector)
  - Models that incorporate multiple objective functions (e.g. environmental and power value) (#102 | Power Sector)

# Appendix C

## Categorization of XLeap responses used in Figure 2

| Sector of Topic | Research Priorities | Information and Tools Needed | Priority Category | Info and Tools Category | Contributing Sector(s) |
|---|---|---|---|---|---|
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Improved data accessibility and resource, generation, and demand forecasting for energy and ancillary services | Future Scenario | Data Accessibility | Energy, Other |
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Improved production cost modeling that can account for different time resolutions and marginal prices of different of generation sources | Future Scenario | New Models | Energy |
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Understanding reserve needs given overall balancing and need for reserves and not just markets (i.e., Security of Supply perspective) | Future Scenario | Data generation | Energy |
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Need and alternative sources for energy and ancillary service flexibility across time scales | Future Scenario | Information Inventory | Other |
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Water-based computation of opportunity costs for lost energy due to hydro providing regulation and reserves | Future Scenario | New Models | Other |
| Energy | Better understanding of evolving demands on hydro operations to integrate wind and solar | Improved understanding of how power markets will develop | Future Scenario | Synthesis | Energy |

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|---|---|---|---|---|---|
| Energy | Characterize national, regional, and local aspects to power system balancing | Determine the level and relevance of details needed at various temporal and spatial scales including energy-environment tradeoffs | Characterization | Synthesis | Energy |
| Energy | Characterize national, regional, and local aspects to power system balancing | Understand bottlenecks in power infrastructure to determine best locations of reservoirs and hydropower plants | Characterization | Data generation | Energy, Other |
| Energy | Characterize national, regional, and local aspects to power system balancing | Improved data accessibility that supports realistic representation of reservoir operations in large-scale modeling | Characterization | Data Accessibility | Other |
| Energy | Characterize national, regional, and local aspects to power system balancing | Improved production cost and other models that can understand the system at various temporal and spatial scales | Characterization | New Models | Energy |
| Energy | Characterize national, regional, and local aspects to power system balancing | Improved linkages between production cost models, reservoir models, and resource uncertainty | Characterization | New Models | Other |
| Energy | Develop standard metrics that will allow for generalization of hydropeaking across rivers and allows for spatial and temporal considerations | *Information and tools on this research topic are combined with the metrics topic in the collaborative research priorities section* | | | |

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|---|---|---|---|---|---|
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Species/life stage specific information on stranding mortality from dewatering and speed of movement out of dewatered areas during down-ramping | Model Validation | Data generation | Environment |
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Improved species/life stage coverage of bioenergetics parameters | Model Validation | Data generation | Environment |
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Empirical data for model validation and parameterization | Model Validation | Data generation | Environment |
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Improved taxonomic coverage of empirical studies of population effects | Model Validation | Data generation | Environment |
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Improved accessibility for pre-impoundment historic data | Model Validation | Data Accessibility | Other |
| Environment | Quantify realism/utility of biological models for understanding effects of hydropower on a broad scale | Hydropower environmental impact decision support tools | Model Validation | Decision Support Tools | Other |

| | | | | | |
|---|---|---|---|---|---|
| Environment | Characterize considerations for multispecies management in hydropower systems | Increased species coverage of documented impacts of hydropower operations including impacts on fish and other aquatic species and riparian flora and fauna | Characterization | Data generation | Environment |
| Environment | Characterize considerations for multispecies management in hydropower systems | Standardized list of multiple stressor measurements for determining multispecies impacts including gas supersaturation, temperature, predation, invasive species, upstream sedimentation, downstream sediment erosion | Characterization | Synthesis | Environment |
| Both | Characterize implications of climate change on operational flexibility and energy-environment balance | Climate-related data for hydropower impacted species including phenology, critical thermal minimum/maximum temperatures, current and projected water temperature, and temporal and spatial water availability | Future Scenario | Data generation | Environment |
| Both | Characterize implications of climate change on operational flexibility and energy-environment balance | Current and projected generation under different renewable energy penetration and climate scenarios | Future Scenario | Data generation | Energy, Environment |

| | | | | | |
|---|---|---|---|---|---|
| Both | Characterize implications of climate change on operational flexibility and energy-environment balance | Interactions between reservoir operations and mitigating or exacerbating climate change | Future Scenario | Data generation | Other |
| Both | Determine best mitigations for hydropeaking that allow for balance of environmental and operational needs | Catalog needs for hydropower flexibility, ways in which hydropower can provide flexibility, and associations between types of flexibility and environmental impacts | Characterization | Synthesis | Energy, Other |
| Both | Determine best mitigations for hydropeaking that allow for balance of environmental and operational needs | Simple, efficient, and informative software that can provide power system modeling (e.g., large-scale storage, balancing ancillary services) and reservoir or environmental models that power producers and stakeholders can use | Characterization | Decision Support Tools | Other |
| Both | Determine best mitigations for hydropeaking that allow for balance of environmental and operational needs | Improved availability and species coverage of life history data | Characterization | Data generation | Environment |
| Both | Determine best mitigations for hydropeaking that allow for balance of environmental and operational needs | Decision support tools for assessing biodiversity and ecosystem vulnerability to hydropeaking such as the FIThydro hydropeaking tool | Characterization | Decision Support Tools | Other |

| | | | | | |
|---|---|---|---|---|---|
| Both | Create common metrics that could be useful for both environment and power sector | Consensus definitions of flexibility, categories of flexibility, classification of operational paradigms and hydropower resource types and how those link to power system services as well as standardized environmental profiles so plants can be characterized as providing a certain category of environmental outcomes. | Metrics | Glossary | Energy |
| Both | Create common metrics that could be useful for both environment and power sector | Increase accessibility of hydropower plant flexibility parameters (e.g., waterway time constant, inertia parameters) to quantify short-term flexibility | Metrics | Data accessibility | Other |
| Both | Create common metrics that could be useful for both environment and power sector | Glossary/catalog of terms for describing energy flexibility and environment tradeoffs | Metrics | Glossary | Environment |
| Both | Create common metrics that could be useful for both environment and power sector | Define and characterize overlap of critical periods for energy flexibility and environment (e.g., season, time of day, week, month) | Metrics | Data generation | Energy |
| Both | Create common metrics that could be useful for both environment and power sector | Metrics that characterize operations, environmental impacts, and environmental characteristics that impact flexibility and operational restrictions | Metrics | Synthesis | Environment |

| | | | | | |
|---|---|---|---|---|---|
| Both | Characterize considerations that should be included in energy-environment trade-offs | More accessible and higher resolution climate predictions including temperature, hydrology, spatial and temporal patterns of predicted future reservoir inflows | Characterization | Data accessibility | Other, Energy |
| Both | Characterize considerations that should be included in energy-environment trade-offs | Energy production and environmental restoration/protection goals for river system | Characterization | Information Inventory | Environment |

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