Improving Hydropower Representation in Power System Models

Report Summary of PNNL-NREL Technical Workshop Held March 6-7, 2019 in Salt Lake City, UT

November 2020

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HydroWIRES

In April 2019, WPTO launched the HydroWIRES Initiative[1] to understand, enable, and improve hydropower and pumped storage hydropower's (PSH's) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system. The unique characteristics of hydropower, including PSH, make it well suited to provide a range of storage, generation flexibility, and other grid services to support the cost-effective integration of variable renewable resources.

The U.S. electricity system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. While increasing deployment of variable renewables such as wind and solar have enabled low-cost, clean energy in many U.S. regions, it has also created a need for resources that can store energy or quickly change their operations to ensure a reliable and resilient grid. Hydropower (including PSH) is not only a supplier of bulk, low-cost, renewable energy but also a source of large-scale flexibility and a force multiplier for other renewable power generation sources. Realizing this potential requires innovation in several areas: understanding value drivers for hydropower under evolving system conditions, describing flexible capabilities and associated tradeoffs associated with hydropower meeting system needs, optimizing hydropower operations and planning, and developing innovative technologies that enable hydropower to operate more flexibly.

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 HydroWIRES portfolio as well as broader DOE and National Laboratory efforts such as the Grid Modernization Initiative.

Research efforts under the HydroWIRES Initiative are designed to benefit hydropower owners and operators, independent system operators, regional transmission organizations, regulators, original equipment manufacturers, and environmental organizations by developing data, analysis, models, and technology research and development that can improve their capabilities and inform their decisions.

More information about HydroWIRES is available at https://energy.gov/hydrowires.

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[1] Hydropower and Water Innovation for a Resilient Electricity System ("HydroWIRES")

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November 2020

Executive Summary

In March 2019, Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL) held a US Department of Energy (DOE)-sponsored workshop with the goal of understanding research needs to improve the representation of hydropower in electric power system models. The motivation for bridging the gap between power system and water management models is to support capturing the full range of complex hydropower operations and enabling hydropower to further support grid reliability and receive effective compensation.

The workshop brought together 40 diverse experts from 25 organizations to address critical challenges associated with modeling hydropower systems in the power grid. Leading international experts in power grid modeling, hydropower modeling, reservoir operations, as well as representatives of hydropower system operators, grid managers, national laboratories, US DOE, and other federal agencies were brought together to discuss how hydropower modeling could be improved to better represent its dynamic role in a changing grid. An overview of the workshop is provided in Section 2.

The goals of the workshop were to:

1. **Understand the current state of representation of hydropower in power system models**, including challenges of effective characterization of hydropower assets and seams (spatial, temporal, units, computational complexity) between electricity dispatch and water management models.
2. **Discuss the perceived negative consequences of model limitations** in terms of unused flexibility and non-monetized services as well as how improved representation could enhance operations, increase economic opportunities, and provide informed investment strategies.
3. **Identify and prioritize research and modeling activities** to improve the representation of hydropower services in power system models.

Workshop participants discussed the nuances and different types of hydropower models at different scales, and highlighted research gaps and areas of improvement for these models (Table 1). A general consensus emerged from the group regarding the need for differentiated approaches to hydropower modeling at different scales, improvements in the organization of publicly available data, improved approaches for validation and characterizing uncertainty, new modeling frameworks that can address multiple competing objectives, and increased collaboration and interaction among the hydropower and power grid modeling communities. These themes are discussed in detail in Section 3.

Identified next steps include cataloguing and characterizing study objectives that rely on hydropower representation; more thoroughly reviewing how hydropower is currently represented within bulk power system models and related applications; assessing publicly available data associated with calibration and validation of bulk power system models; and further developing partnership and collaborative activities to address ongoing and also future representation challenges associated with the contribution of hydropower to the future grid. These potential activities are captured in Section 4.

In addition to this report, all presentations and materials for the workshop are available online[1]: https://www.pnnl.gov/events/hydropower-modeling-workshop

[1] Until 2024. Available upon request to the authors at all times.

Table 1: Summarized characteristics of hydropower representations and associated research gaps by application. Table 3 provides more details.

	Grid and System-Scale Reliability and Resources Adequacies (Mid to Long Term)	Utility Scale (Short to Mid Term)	Grid and System-Scale Short Term Planning	UCED Model Developers
Priorities	• Consistent hydropower representation across the domain • Representative operations and hydropower flexibility	• Compliance with river regulatory requirements • Maximized hydropower revenues • Compatibility with system-scale market models	• Speed of information • Accurate representation of firm hydropower flexibility	• Customization to Complex Systems
Research Gaps	• Data to support parameterization and/or exogenous hydropower datasets • More accurate representation of hydropower flexibility • Data for validation	• Coupling approaches with system-scale market models • Marketization of hydropower flexibility contributions • Region-specific representations	• Data to support parameterization • Forecast accuracy	• Data to support parameterization and/or exogenous hydropower datasets • Multi-market modelling resulting in product prices

Acronyms and Abbreviations

DOE	Department of Energy
HTC	hydro-thermal coordination
NREL	National Renewable Energy Laboratory
PCM	production cost model
PLF	proportional load following
PNNL	Pacific Northwest National Laboratory
UCED	unit commitment economic dispatch
WECC	Western Electricity Coordinating Council
WPTO	Water Power Technologies Office

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1.0 Introduction: The Gap between Power and Water Management Models for Hydropower Resources

Electric power system modeling is an essential component of power system operations and planning decisions, which also informs policy, market, consumer and industry strategies. Power systems have become more complex over the decades, with more diversity in generation technologies and changing load patterns. Each generation technology has different inherent characteristics which defines how efficient or cost-effective that generation technology is at providing energy or ancillary services (e.g., generation or a type of reserve). With the emergence of new generating technologies (especially variable renewable resources), the power system requires increasing amounts of available flexibility from existing technologies in order to balance adequate supply and maintain grid reliability with security constraints such as contingency and regulation reserves (DeCesaro et al., 2009). Demand side management, storage technologies as well as hydropower provide those balancing and reserve services.

Over the same decades, there have been significant changes in hydropower operations. These changes are the result of accommodating increased competition in water uses, environmental requirements, and associated river regulation as well as from providing complementary power services required to allow higher penetration of variable renewables. Yet the representation of hydropower in power system models has not evolved at the same speed to capture the range and availability of responding hydropower resources. Many optimization and/or rule-based water management models already exist to support decision making in multi-objective water management across a range of stakeholders and river systems. The representation of hydropower plants and reservoirs in models is typically physics or process-based with an explicit representation of river routing, reservoir storage variations, downstream constraints and coordination between reservoir operations (HydroLogics Inc., 2009; Labadie, 2011; Zagona et al., 2001). Production cost models, or unit commitment and economic dispatch models, typically use exogenous information about monthly hydropower potential and then dispatch as driven either by the local electricity demand (proportional load following) or the regional market (hydro-thermal coordination) with a range of conceptual parameterizations (Dennis et al., 2011). When available, the hourly hydropower generation output from the multi-objective water management model is used as input to the production cost model and considered as fixed dispatch (Ibanez et al., 2014).

There is a growing common understanding that the current representation of hydropower in grid models is inadequate, that there are fundamental differences in the ways hydropower is represented between grid models and water management models, and that there is a lack of insight and exchange across models and modeling purposes (Voisin et al., 2017) (Figure 1). These gaps ultimately result in a sub-optimal dispatch, which limits hydropower's economic opportunity as well as system performance across economic and environmental parameters.

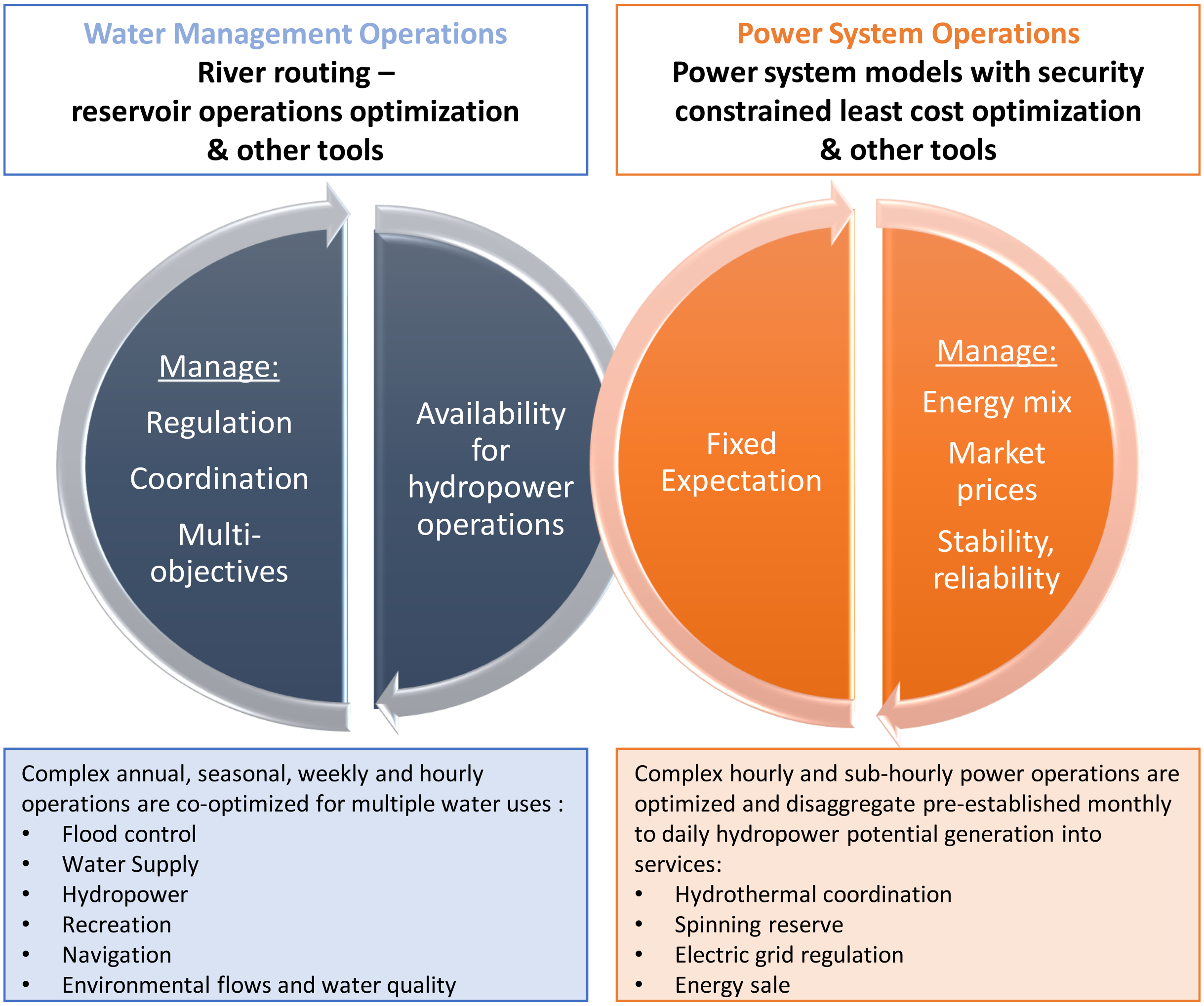

Figure 1. Hydropower is typically part of two systems: water management (left) and power systems (right) with fundamental differences in representation of hydropower associated with contrasting modeling objectives. The lack of information exchange and the inconsistency in the modeling representations might lead to sub-optimal use of hydropower in both systems.

2.0 Workshop Overview

To consider these hydropower modeling challenges, Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL) held a workshop at the Western Electricity Coordinating Council (WECC) in Salt Lake City, Utah, over March 6-7, 2019. This workshop brought together water managers, power system engineers, and planners to address key pressing questions, including how hydropower and associated hydro-thermal coordination is currently represented in power system models. Key questions were which day-ahead to long-term planning questions that cannot be addressed with the current modeling representations, modeling gaps in hydropower valuation, and the most impactful and urgent data, computation, or modeling needs to improve representation of hydropower in power systems models.

Forty diverse experts from 25 organizations attended the workshop. (See Appendix C for a full participant list.) For the first time, leading international experts in power grid modeling, hydropower modeling, reservoir operations, as well as representatives from hydropower system operators, grid managers, national laboratories, US DOE, and other federal agencies came together to specifically address how hydropower modeling could be improved to better represent its dynamic role in a changing grid. Workshop participants discussed the nuances and different types of hydropower models at different scales, and highlighted research gaps and areas of improvement for these models.

The scope of the workshop covered perceived as well as actual modeling gaps in power system model representations of hydropower from both research and operational perspectives. The workshop featured discussions of the most impactful direction for future research investments in collaboration with industry and government. The scope was intentionally limited to production cost models (PCM), which assess the operational generation and capacity services provided by hydropower, rather than grid capacity expansion models, which are used for long-term planning and focus on capacity and transmission constraints. PCMs are used by utilities for seasonal and real-time planning and scheduling. PCMs are also used by DOE laboratories and other research entities to evaluate the operational economic sustainability of expansion plans, impact from new technologies, new policy and environmental changes. As we better understand the contribution of hydropower to the grid using PCMs, we plan to explore similar questions in future workshops for capacity expansion and power flows, which rely on PCM hydropower scenarios.

The goals of the workshop were to:

- **Understand the current state of representation of hydropower in power system models**, including challenges of effective characterization of hydropower assets and seams (spatial, temporal, units, computational complexity) between electricity dispatch and water management models.
- **Discuss the perceived negative consequences of model limitations** in terms of unused flexibility and non-monetized services as well as how improved representation could enhance operations, increase economic opportunities, and inform investment strategies.
- **Identify and prioritize research and modeling activities** to improve the representation of hydropower services in power system models.

The organization of the two-day workshop was designed to encourage interaction and exchanges across stakeholder groups. (See Appendix B for the workshop agenda.) Specific activities included having four breakout groups of participants with diverse perspectives – water management or power system management, day ahead or/and long term planning, researchers and practitioners, and so on. Each group was challenged to reflect on overarching questions related to each workshop goal and then report findings to all participants by the end of the first day. (See Appendix D for Day 1 breakout session questions.) Outcomes from the Day 1 breakout groups were summarized into various themes and questions directed to panelists on the second day of the workshop. (See Appendix E for Day 1 Breakout Session Outcomes and Appendix F for Day 2 Panel Questions.) On Day 2, three sets of panel presentations and group discussions addressed critical modeling questions and needs. Plenum discussions was an integrated part of each panel session.

The participants converged on specific themes and areas of agreement. These major themes are discussed in the section below.

3.0 Workshop Outcomes and Emergent Themes

Across breakout sessions, individual presentations, and large group discussions, several themes emerged consistently and were areas of widespread agreement. These themes were relevant among all stakeholder groups represented and transcended specific discussion topic questions, represented below as they relate to a workshop goal:

1. **Current State of the Art: Diversity of Hydropower Systems and Models**

Hydropower objectives (and thus modeling needs) in power system models can be quite diverse, depending on the question (e.g., environmental change, integration of renewables, real time or day-ahead markets, resource adequacy), and specifically the time scale of interest (e.g., operations optimization vs. long-term investment planning). This also means that there are different needs and challenges for hydropower modeling. Improvements in hydropower modeling will have to address these unique and differentiated needs in order to provide relevant solutions.

2. **Model Limitations: Data Availability as a Barrier to Modeling**

Lack of publicly available hydropower-specific data hinders some (but not all) hydropower modeling activities in a power system perspective. In many cases, publicly available data could suffice, but this data is not universally accessible, organized, formatted, or readily usable.

3. **Model Limitations: Hydropower Models Lack Effective Validation and Uncertainty Characterization Methods**

There is a need for improvements in how we validate results and characterize uncertainty from hydropower models. There are no standards for evaluating the accuracy of models, or for attributing the origin of sources of error. This could be beneficial to develop as a way to benchmark improvements in hydropower modeling.

4. **Model Limitations: Traditional Hydropower Modeling Frameworks Might Not Represent Most Recent Dynamics**

Recognizing the complexity and difference in priorities of both hydropower systems and the power grid, new modeling frameworks are needed to capture this diversity. New modeling frameworks should be able to link the least-cost optimization decision-making of the power grid with the localized non-economic decision-making approaches of hydropower systems. These new frameworks could include linking existing models (water and power system models are optimized in silo and time series of hydropower and block cost are shared in a recursive manner), developing co-optimization couplers to connect existing models and substitute in-silo optimizations for water and energy, or creating entirely new models with endogenous and explicit representation of river operations in bulk power system models.

5. **Recommendations: Collaboration Across Sectors and Modeling Groups is Needed**

As the grid is changing, the role of hydropower is changing. Production cost models and their representation of hydropower flexibility, markets, and scale-specific optimization of hydropower operations are inadequate to effectively represent hydropower dynamics and capabilities. Further collaboration among energy system modelers and hydropower operators and modelers is needed to improve this representation.

These themes and their functional relation to each other are highlighted in Figure 2. Theme 1 which corresponds to the first objective of the workshop, presents the diversity of hydropower systems and associated representations. Themes 2-3 address the second objective of the workshop on understanding limitations and consequences of the different representations between power and water models. The availability of data (Theme 2), protocol for validation (Theme 3), and computational complexity for combining models (Theme 4) lead to the third objective of the workshop: recommendations and research priorities emerging from cross-disciplinary collaboration (Theme 5).

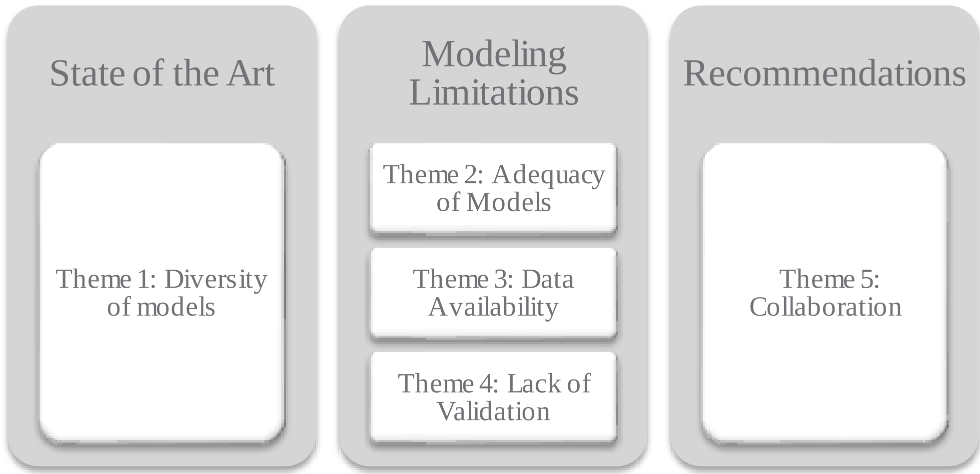

Figure 2. A conceptual diagram of the relationship between workshop themes and goals.

3.1 Theme 1: Diversity of Hydropower Systems and Models

River systems over the United States are highly regulated for a number of benefits, with over 90,000 dam structures. Only 2% (over 2,000) of those dams are used for hydropower. The vast majority (63%) of hydroelectric generation dams over the United States are operated as multi-purpose dams, most often water management is taking priority over hydropower operations(USACE, 2019). These other objectives include flood control, irrigation, recreation, fish and wildlife. Reservoir operations are unique to each dam, taking into consideration the different reservoir levels, reservoir sizes, storage to annual flow ratios, inter-annual variability and exogenous demands. Exogenous demands on a dam may include water storage for irrigation, recreation needs upriver or downriver, environmental flows, or flood control. Operation is also subject to change with changes in water availability, environmental regulation, and other governing attributes. For example, a shift in precipitation towards more rain than snow compared to previous years will move flows earlier in the spring, which may necessitate a change in operations compared to previous years (Brekke et al., 2009).

Depending on the complexity of the system and level of coordination with other dams, hydropower operators use reservoir operations models to address the multi-objective aspect of water management. There is a large diversity in those models (examples include RiverWare (Zagona et al., 2001), OASIS (HydroLogics Inc., 2009), MODSIM (Labadie, 2011), HYDSIM, HEC RESsim (USACE, 2003) which use water supply or hydropower as objective functions and other objectives as constraints. In addition, hydropower scheduling models can connect with those water management models and use information from power system models, typically locational marginal prices. Hydropower scheduling models differ from unit commitment in production cost model in that the hydropower units are optimized for the best combined use of water and revenues for the power plant. Those models are considered water models in this workshop and are either used in chain or are fully integrated in the reservoir operations models.

There is also a great deal of diversity in the power system modeling tools themselves and their representation of hydropower. Some production cost models use the system-scale security constrained least-cost production for objective function and will use hydropower for its no-fuel-cost characteristics.

Other production cost models have the dispatch optimization focused on resilience metrics and might use hydropower flexibility based on slightly different strategies. Computational time, especially for large domain models with high temporal and geographic resolution, is an important consideration. Greater complexity increases computation lag-time for model outputs, creating a tradeoff. Depending on the tolerance for model runtimes and precision, there may be an incentive to simplify the physical constraints on hydropower plants to generate quicker if slightly less precise results.

Several hydropower operators from different types of systems were present at the workshop, including Columbia Grid, Hydro Tasmania, Manitoba Hydro, PacifiCorp, Powerex, and the United States Army Corps of Engineers (USACE). Many discussed the uniqueness of their system. As an example, Manitoba Hydro sources their water from a large geographical area but the overall elevation drop is low, therefore all of their dams have low head but large discharges. They are also situated with a close connection with Midcontinent Independent System Operator (MISO) and export about 30% of total generation to MISO. In contrast, Hydro Tasmania has the capability and the terrain to build considerable new pumped storage hydropower facilities, but their limitation in local load and lack of connections to the mainland of Australia disincentivize making those investments. Many participants discussed their aging hydropower fleet and the benefits and constraints that must be balanced when looking at rehabilitating these plants. Many questions were posed, such as would Kaplan turbines, which are more flexible but less efficient, be worth the investment. Participants also discussed desires to and challenges with optimizing over a large fleet (e.g., 12,000 MW) and a large geographic area with a large amount of flexibility, including the ability to store water for multiple years.

Table 2 presents the range of water and electricity models that were discussed at the workshop to discuss the differences in assumptions and representations of hydropower, as used by the participants. Additional discussion focused on the value of hydropower services, other than generation, to the grid and how to capture/include that value in the modeling. It is expected that the value of energy generation will decrease in the future with additional renewables coming online while the value of flexibility and capacity will increase. This is a multi-scale problem, temporally, operationally and geographically, and decisions are made by entities interacting with each other – all of which adds complexity to the modeling effort.

In summary, understanding the current state of hydropower representation in power system models is not a straightforward exercise. While models are clear about which question they can help address, there seems to be a lack of clarity on which model is best to address customized questions with so many nuances in the optimization objectives, representation of hydropower, complexity of river system dynamics and availability of data, leading a number of entities to develop their own tailored models. The next themes address modeling limitations, which should guide future efforts for unlocking modeling efforts transferable across systems.

Table 2: Representative Models Discussed at the Workshop

	Water Model – Multi-Objective Optimization, Maximize Revenues	**Unit Commitment Economic Dispatch Model with Reservoirs – Maximize Revenues**	**Production Cost Model – Minimize System Cost and Meet Security Constraints**
Description	Explicit representation of reservoir operations as either rules curves or optimization for short to long term multi water uses. Exogenous information about locational marginal prices to guide the optimization. Water models simulate hourly to seasonal hydropower schedules that meet other water objectives (flood control, water supply, recreation, navigation, etc) throughout the river system and maximize power plant revenues.	Representation of generators, turbines, governors, plant topology (tunnels and penstocks) to optimize specific power plant revenues. Typically for short term applications (1-14 days), reservoir operations are explicitly represented albeit with limits and constraints coming from multi-objective and horizons water management requirements. Exogenous information about the inflow and reservoir levels are needed. UCED model simulate sub-hourly hydropower dispatch (minutes to seconds) and associated hydraulic operations that maximize power plant revenues.	Representation of generators and transmission operations to optimize least-cost production cost within security constraints. Exogenous information about hydropower capabilities (fixed hourly schedule, monthly potential, some cascading reservoir joint operations, etc). Production cost models simulate hourly hydropower dispatch that meet grid needs within parameterized constraints.
Models represented at the workshop	• RiverWare (CADSWES (Zagona et al., 2001))	• SHOP (SINTEF, https://www.sintef.no/en/software/shop/) • GTmax (Argonne National Laboratory, https://ceeesa.es.anl.gov/projects/Gtmax.html) with explicit representation of reservoirs • HERMES, SPLASH (Manitoba Hydro, http://www.pubmanitoba.ca/v1/exhibits/km-2.pdf) with explicit representation of reservoirs	• GridView (ABB, https://new.abb.com/enterprise-software/energy-portfolio-management/market-analysis/gridview) • PLEXOS (Energy Exemplar, https://energyexemplar.com/solutions/plexos/) • HiGRID (Eichman et al., 2013) • EMPS (SINTEF, https://www.sintef.no/en/software/emps-multi-area-power-market-simulator/) • PRODRISK (SINTEF, https://www.sintef.no/en/software/prodrisk/)

Hydropower Modeling Best Practices

Throughout the presentations and the discussion, participants highlighted good modeling practices that can be applied across all types of models. Such good modeling practices included:

- Developing clear research questions
- Choosing a model that has been designed to address selected research questions. In some cases this may require developing a new model.
- Using high quality input data will result in more accurate model outputs. Utilities that use proprietary data in their production cost models see more accurate results than when models are run with aggregations or generalized inputs.
- Enhancing the input data or adding complexity in a model may not be worth the time in exchange for the increased modeling accuracy. At the same time it is clear that a change from energy to power focus requires models to capture more dynamics of involved technologies and markets.

3.2 Theme 2: Data Availability as a Barrier to Modeling

A number of efforts exist over the U.S. such as the USGS surface-water data for the Nation (https://waterdata.usgs.gov/nwis/sw), USACE Water Resource Data (http://water.usace.army.mil), US Bureau of Reclamation easier download of water data (https://water.usbr.gov), Open Water Data Initiative (2014-2019, https://acwi.gov/spatial/index.html), and Western States Water Council Water Data Exchange (Larsen and Young, 2014) to provide observed river and reservoir storage information from real time to long historical datasets. Observation datasets have insufficient coverage to power plant locations; they cannot provide adequate hydrology, and potential hydropower datasets, to production cost models on system level. Observed hydropower data is usually available at the monthly time scale and utility level (EIA form 923 - https://www.eia.gov/electricity/data/eia923/), or consists of either observed generation in the best case scenario (USACE) or reservoir levels which are associated with capacity rather than potential generation (USGS). Many hydropower operators and utilities keep their power plant-specific high-temporal resolution hydropower-specific data (generation, turbine flow, etc) proprietary. The lack of information available for identifying important processes such as hydropower flexibility and its variation through time, makes evaluation of hydropower models difficult, eventually making hydropower modeling a "black box" in many research projects.

As discussed in Theme 1, power system models are typically run at the interconnection or balancing authority scale, and hydropower scheduling at watershed to river basin scales. There is a trend towards using larger spatial scales in power system models as markets evolve and cover larger geographical areas as well as higher temporal resolutions (particularly sub-hourly) as growing deployment of renewables increase the sub-hourly variability needs in complementing technologies. Water models are typically watershed-specific, i.e. each watershed is operationally modeled separately with customized parameterization to reflect the unique characteristics of the watershed and the group of stakeholders managing the river system. Water management varies greatly throughout large-scale areas that encompass multi-watershed and river basins and water models might run at hourly to monthly timescales based on the objectives of basin management. Available hydropower potential coming from those watershed-specific models therefore does not cover all hydropower plants represented in the production cost models if running only one or a limited set of water models, and operations might be inconsistent resulting from use of different models, inflow data, and so forth.

Participants discussed how highly resolved data as inputs to production cost models yields more accurate modeling results than aggregated data. This can be seen with utilities like Sacramento Municipal Utility District who use their own data in production cost models such as PLEXOS and with utilities who create their own models like HERMES from Manitoba Hydro. Related to this, participants also discussed how highly resolved data often is not needed to address energy related research questions.

In summary, a lack of publicly available river and powerplant operations data hinders hydropower modeling activities, if not in the development of the models or direct input into the models, at least for the evaluation of the computed hydropower dispatch. There are many ways in which the data challenge could be addressed without needing proprietary data. Participants discussed how an assessment of publicly available data and efforts to consolidate all data into consistent format and single location would be a good starting point for addressing the lack of hydropower-specific data. A concerted effort to incentivize record-keeping at higher resolution, especially sub-hourly, and avenues for sharing that data would help researchers.

3.3 Theme 3: Hydropower Models Lack Effective Validation and Uncertainty Characterization Methods

At the workshop, participants concluded a unanimous need for more systematic validation and uncertainty characterization from hydropower representation in production cost models. There are no standards for evaluating the accuracy of models, or for attributing the origins of sources of error. In addition, it is in general difficult to evaluate stochastic processes such as reservoir operation and scheduling of hydropower plants.

Participants noted how hydropower dispatch models are often criticized for producing unrealistic results, while there has been no clear large-scale quantitative assessment of the errors. Errors were reported by participants to be either associated with structural deficiencies in models, or initial hydropower potential data quality, or other reasons. With models being so complicated and most not open source, identifying sources of errors is difficult. The uncertainty around future markets as another major source of error in investment/planning models and associated hydropower dispatch was emphasized several times. This is especially important because the accurate valuation of market services, such as ancillary services, has a strong influence on how, whether, and when investments in hydropower are made.

Representation of hydropower usually assumes normal conditions; representing more extreme conditions is a challenge without data around how operations deviated from normal conditions and therefore without any flexibility in the modeling representation to reflect human behavior and decision-making. Another source of uncertainty motivating regular updates and emphasizing the dependence of recent data is the need to represent policy and environmental regulation. The uncertainty around climate change was also discussed as it may pertain to water availability for hydropower generation. The validation of hydropower dispatch is therefore complicated given the evolving environmental constraints and uncertainties around the projection of those constraints.

Participants came to consensus on the need for improved methods to validate models as well as an improved approach to characterizing and propagating uncertainty of hydropower representations in power system models. This was seen as a foundational starting point for improving the representation of hydropower in production cost models.

3.4 Theme 4: Traditional Hydropower Modeling Frameworks Might Not Represent Most Recent Dynamics

Participants discussed how the current models and modeling frameworks they utilized were not adequately addressing the nuances of both energy management and water management decisions. Participants noted how the models they were using to address their research and planning questions were designed to address past research questions and may no longer be suitable for their current needs as hydropower's role has changed (Appendix E and F). Participants also noted how computing power is consistently increasing and our ability to model more complexity increases as well. This may open up new avenues for hydrologic and electricity co-optimization. The influence of human decision-making on operations and modeling complexity was also discussed. The soft and hard constraints that influence that agent decision can be modeled, but there is variability in the behavior itself, and it varies from agent to agent.

Participants suggested a few opportunities to address this challenge, including developing new types of models, linking together existing models in improved ways, and performing model inter-comparison studies, recognizing that advances in computing power and modeling techniques increase the complexity and provide new avenues for better modeling.

3.5 Theme 5: Collaboration Across Sectors and Modeling Groups is Needed

As the grid is changing, the role of hydropower is changing (Appendix E and F). Production cost models and their representation of hydropower flexibility, markets, and local versus global optimization of hydropower operations are inadequate to effectively represent hydropower dynamics. Hydropower dynamics include factors that affect water management decisions as well as energy sector decisions. However, hydropower-only or electricity production cost models are often focused on just one sector – water or electricity – and the models do not capture the other sector's dynamics. Further collaboration among energy system modelers and hydropower operators and modelers is needed to improve representation of hydropower.

Participants strongly commended the opportunity to speak with managers and modelers across multiple sectors and suggested additional meetings and working groups would be beneficial to promote information exchange and model improvements. Participants noted that partnerships and collaborative activities that bring together modelers, hydropower operators, companies, and other stakeholders and resources with dedicated time to address targeted questions aimed to improve modeling would be a welcome outcome of the workshop. Working groups formed to meet regularly on hydropower modeling topics could be a relatively simple opportunity to enable partnerships and more communication.

4.0 Summary of Research Needs by Hydropower Research Category

Recognizing that different types of hydropower facilities will have different research and modeling needs, the participants began to organize these differences into categories. Table 3 summarizes the landscape tools, data, modeling and collaboration needs identified by different categories of applications and interest.

5.0 Promising Future Activities

Participants discussed several potential future activities that could benefit the representation of hydropower in bulk electricity system models realizing the benefits from hydropower. Specific activities that the group agreed upon included:

1. **Cataloguing and characterizing the different types of hydropower questions that are relevant at each scale (e.g., long-term planning vs. operations optimization).** This activity would provide additional insights into the types of research questions and research needs that are most relevant to each type of hydropower category.

2. **Cataloguing and characterizing existing production cost, hydropower, reservoir, and other models by how they represent hydropower.** This activity would provide essential insights into the ecosystem of hydropower models available, their current capabilities, and relevant gaps.

3. **Partnerships and collaborative activities that bring together modelers, hydropower operators, companies, and others with dedicated time to address targeted questions aimed to improve modeling.** This activity would facilitate information exchange and advancements in the representation of hydropower in models.

4. **Assessment of publicly available data and efforts to consolidate all data into consistent format and single location.** This effort would address key data challenges for hydropower modeling as well as highlight areas where new data development activities could occur.

5. **Model inter-comparison, model coupling, and model development studies.** This activity would provide insights into how existing and potentially new modeling frameworks could address key hydropower dynamics.

6. **Model validation and uncertainty analysis.** This activity would provide a foundation for evaluating model performance and targeting key areas of improvement. Better understanding of uncertainties can help realize the full range of services that hydropower can provide.

Appendix A reports on activities to date.

Table 3: Research Needs by Scale and Application

	Reliability and Resource Adequacy (regional scale, long term)	**Utility Scale Applications (plant operators and water managers)**	**Grid-Scale (markets, short time)**	**UCED Model Developers**
Motivating questions	What are the water availability conditions that lead to stress? What is hydropower flexibility in times of stress (multi-year droughts, floods, etc.) for reliability metrics?	What are the needs from the grid so that we can evaluate if more flexibility is available? What are the market conditions in order to incentivize more flexibility?	How can flow forecast be improved so that hydropower can commit more firm power? What are constraints on hydropower that can be relaxed to provide more flexibility?	How could more clients/stakeholders benefit from the range of hydropower representations in the models?
Flexibility definition and representation	Parameter range and/or physical representation of dynamic hydropower (capacity and generation)	Physical representation including storage space Frequency of start/stop Frequency-duration-intensity of ramp up/down, efficient use of water	Parameter range (flexibility and min/max hourly generation). Fixed schedules in simultaneous markets.	Parameter ranges, including cascading hydropower.
Research gaps	Lack of data for parameterization or/and exogenous hydropower datasets. Detailed hydropower technology representation in existing model does not support a regionalization of dynamics nor a grid-wide aggregation of the real flexibility hydropower can provide. Lack of backcasting and validation.	Block costs and communication of dynamic constraints are a start. Coupling approaches if more flexibility is required. Most constraints over-estimate the flexibility. Understanding of interdependencies between flexibility across time (river system approach) and ancillary services (turbine level). Need for new metrics more accurately representing hydropower flexibility and facilitate co-optimization Balkanization of hydropower representation and inter-actions with grid. Multi-market scheduling where hydropower provides different simultaneously services.	Lack of data for parameterization. Forecast accuracy.	Lack of data for parameterization or/and exogenous forcing over large domains. Multi-market modelling resulting in product prices.
Notes	Perfect foresight of hydrological conditions is assumed. Computation time is moderately important.	Information compatible to inform models used by markets for resources participating to market. Efficient use of hydropower assets and water for licensing requirements, public and stakeholder perception, and management of multiple water uses.	Computation time is critical. Participating hydropower provides the projected firm flexibility in ramp up/down and hourly capacity and generation.	Customize representations with clients over specific systems

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7.0 Appendix A: Activities to Date

Below is a summary of ongoing projects in the DOE HydroWIRES initiative that have resulted, in whole or in part, from discussions at this workshop. Table 4 maps these projects to the primary gaps and future activities identified above.

6.1. Enhancing the representation of conventional hydropower flexibility in production cost models

Researchers from the Pacific Northwest, Argonne, and Oak Ridge National Laboratories are teaming with the Center for Advanced Decision Support for Water and Environmental Systems to improve the representation of conventional hydropower operations in production cost models across regional power grids. The project targets reliability and resources adequacy studies as main application. The approach addresses the data challenge on the availability of consistent water availability across hydropower plants and for a range of water conditions (wet, normal, and dry years), as well as the associated change in hydropower operations and therefore potential contribution to grid operations. The PNNL-led team is leveraging large-scale integrated water modeling tools and production cost models to i) develop datasets over a number of water year conditions that represent hydropower potential contribution (generation and flexibility potential) consistent with time and space varying water availability across river systems and ii) evaluate the hydropower dispatch across multiple watersheds. The proof of concept is developed over the Western U.S.

6.2. Improving the representation of hydrologic processes and reservoir operations in production cost models

Researchers from the National Renewable Energy Laboratory are teaming with RTI International to improve the integration of intraday and day ahead grid operations models with a river basin model, enabling a global optimization across both grid and reservoir operations. The project targets utilities and system operators for short-term applications. The approach addresses the need for computationally efficient co-optimization to support short term applications; hydropower plants revenues are maximized while meeting river systems objectives, and system-scale cost is minimized. The NREL-led team is using stochastic hydropower forecasts combined with progressive hedging to perform multi-stage, multi-time period optimization. This allows the combined grid and water models to value multiple timescales and uncertainties in a single optimization problem. The approach will provide a more accurate estimate of hydropower potential generation (firm energy) and flexibility. The prototype is developed over a Northern California watershed.

6.3. Improving hydropower and pumped-storage-hydropower representations in capacity expansion models

While capacity expansion models were out of the scope of this workshop, the models were identified as another important modeling resource to evaluate. Researchers from the National Renewable Energy Laboratory aims to improve electricity capacity expansion models by developing new ways to represent hydropower resource, technology, and operational characteristics. The project targets reliability and resource adequacy studies as well as system operators for long term planning questions. Outcomes will include a comprehensive national resource assessment for pumped storage hydropower and methods for modeling multiple hydropower technology categories characterized by technical, regulatory, and economic characteristics. The project will provide guiding principles and strategies for improving hydropower modeling in capacity expansion models and deliver a first-of-its kind versatile PSH dataset.

6.4. Technical assistance to WECC long term planning activities amidst changes in water availability

Researchers from the Sandia National Laboratories, Pacific Northwest National Laboratory and National Renewable Energy Laboratory are teaming up with the Western Electricity Coordinating Council to evaluate the sensitivity of reliability studies and associated production cost model simulations to uncertainties in hydropower parameterization. The project addresses identified collaborative modeling needs to accelerate the transition of research to operations and in this case to provide modeling support toward enhancing robustness in partner's modeling approaches.

6.5. Release of the draft HydroWIRES Research Roadmap for public comment

Informed by a number of workshops and other industry engagements, DOE's Water Power Technologies Office has developed a draft version of the HydroWIRES Research Roadmap, released for public comments as a Request for Information on April 24, 2020. The HydroWIRES initiative includes four interrelated research areas covering value under evolving system conditions, hydropower capabilities and constraints, hydropower operations and planning, and technology innovation. The HydroWIRES Research Roadmap goes into detailed discussion of these research areas and the technical objectives they seek to achieve; relevant objectives for the modeling topic include efforts to improve hydropower representation in power system models, improvements to inflow forecasting, support for resource planning that better captures hydropower capabilities, and optimization of hydropower operations for greater flexibility. Responses to the Request for Information should further illuminate the highest-priority questions that the hydropower and broader power system communities face.

Table 4: Selection of ongoing projects and how they related to identified next steps

Next Steps	6.1	6.2	6.3	6.4	6.5
#1 Cataloguing and characterizing hydropower questions					•
#2 Cataloguing and characterizing hydropower representation in water, unit commitment and production cost models	•	•			
#3 Partnership and collaborative studies with industry	•	•	•	•	
#4 Availability of publicly available datasets	•		•	•	
#5 Model inter-comparison, models coupling	•	•	•	•	
#6 Model validation and uncertainty analysis	•			•	

8.0 Appendix B: Workshop Agenda

Improving hydropower representation in power system models: Insights to inform regional planning

March 6-7, 2019
Meeting location: Western Electricity Coordinating Council, 155 North 400 West, Suite 200, Salt Lake City, Utah 84103

FINAL AGENDA
Organizers: Sam Bockenhauer (DOE), Nathalie Voisin (PNNL), Jordan Macknick (NREL)

What advancements are needed to improve representation of hydropower in power system models to capture the value of hydropower operations and enable hydropower to further support grid reliability?

Workshop Goals:

1. Understand the current state of representation of hydropower in power system models, including challenges of effective characterization of hydropower assets and seams (spatial, temporal, units, computational complexity) between electricity dispatch and water management models.
2. Discuss the perceived negative consequences of modeling limitations in terms of unused flexibility and non-monetized services as well as how improved representation could enhance operations, increase economic opportunities, and inform investment strategies.
3. Identify and prioritize research and modeling activities to improve the representation of hydropower services in power system models.

Session	Description	Time	Discussion Leader
	DAY 1 – March 6, 2019		
	WELCOME	12:45 PM	
1	**Welcoming remarks** - Safety - DOE opening remarks - WECC opening remarks - Workshop format	1 PM	Michael Bailey, Sam Bockenhauer, Ganesh Velummylum, Nathalie Voisin
2	**Introductions**: each participant briefly talks on the following items: - Name, organization, and responsibilities - Expectations from the workshop	1:10 PM	all
3	**Background and workshop goals** - Sam Bockenhauer – EERE and WPTO research agenda - Nathalie Voisin, Jordan Macknick – Introduce breakout sessions and clarify outcome	1:45 PM	

Session	Description	Time	Discussion Leader
4	**Breakout session**		
	DAY 1 – March 6, 2019	2:15 PM	
4.1	Breakout groups to address Focus Questions: - What are planning questions associated with hydropower for power system operations? - Challenges in representing hydropower including its interactions with other resources (water and energy): are there missing tools, data, computational resources? - Current and future challenges in hydropower services valuation and its contribution to the grid?		Facilitators: Michael Bailey, Merrill Brimhall, Jordan Macknick, Nathalie Voisin
4.2	Reports from breakout groups	4 PM	
	DAY 1 ADJOURN – no host dinner (TBD)	5 PM	

Organizers to summarize Focus Question outcomes and distribute to panels. Panel members can use slides to present their perspectives. Targeted questions will be addressed to the panel and then opened to full participant discussion.

Session	Description	Time	Discussion Leader
	DAY 2 – March 7, 2019		
	WELCOME	7:45 AM	
5	**PANEL 1 – Existing tools for hydropower-energy co-optimization**		
5.1	Panelists: - GridView, Hongyan Li - Columbia Grid – Kevin Harris - Energy Exemplar, Steven Broad (PLEXOS and AURORA) - APEP, Brian Tarroja (HiGrid) - SINTEF, Michael Belsnes - ANL – Matt Mahalik - PNNL – Nader Samaan	8 AM	Moderator: Jordan Macknick
5.2	Open Discussion	9:15 AM	

Session	Description	Time	Discussion Leader
6	**PANEL 2 – Challenges in current hydropower representations and modeling seams: perceived negative consequences**	10:00 AM	
6.1	Panelists: - Manitoba Hydro – Kelly Hunter - NWPCC, John Fazio (GENESYS) - PacifiCorp – Jamie Austin - Hydro Tasmania – Cameron Potter - CADSWES, Edith Zagona, Tim Magee (RiverWare) - E3 – Arne Olson		Moderator: Nathalie Voisin
6.2	Discussion	11:15 AM	
7	**WORKING LUNCH - Insights on WECC scenario planning – Michael Bailey and Stan Holland**	12 PM	

Session	Description	Time	Discussion Leader
8	**PANEL 3 – Emerging new water management, grid and market dynamics that could challenge hydropower contribution and valuation to grid operations**	1 PM	
8.1	Panelists: - POWEREX – Dan O'Hearn - CAISO – Xiaobo Wang - PNNL – Michael Kintner-Meyer - USACE – Mark Parrish - Reclamation – Erin Foraker - INL – Thomas Mosier - NREL – Greg Brinkman		Moderator: Michael Bailey
8.2	Discussion	2:10 PM	
9	**Take-aways and next steps**		
9.1	Identify and prioritize research and modeling activities to improve the representation of hydropower services in power system models.	3 PM	Nathalie Voisin, Jordan Macknick, Michael Bailey, Sam Bockenhauer
9.2	Concluding remarks and next steps	4 PM	Sam Bockenhauer
	Meeting Adjourned	5 PM	

9.0 Appendix C: Workshop Participants

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10.0 Appendix D: Day 1 Breakout Session Questions

The first activity consisted of breakout sessions where the attendance was separated in 4 groups and tasked to address all the following questions:

Question #1: What are planning questions associated with hydropower for power system operations?

- Why are you using models?
- What are your planning objectives (e.g., investment planning, operations optimization, reliability assessment, cost projections, etc.) and what tools do you use to address each of them?
- What skillsets, discipline knowledge, training is required to address these planning questions?
- Are the tools you use to address planning questions adequate? If not, describe limitations and the capabilities that are needed to address planning questions.

Question #2: What are current challenges in representing hydropower, including its interactions with other resources (water and energy): are there missing tools, data, computational resources?

- How is hydropower represented in your tools?
- How is representation of hydropower validated in your tools?
- How well do your current tools represent hydropower and its various characteristics (e.g., generation profile on an hourly/daily/monthly/annual basis, flexibility, ancillary services, environmental and regulatory constraints, reservoir storage, etc.)?
- What are the barriers to improving the representation of hydropower in your tools?

Question #3: What are current and future challenges related to valuing hydropower services and hydropower contributions to the grid?

- How can the value of hydropower and its various services be characterized in your tools?
- What are the challenges associated with valuing hydropower services?
- How will these challenges change, or what new challenges will arise, as the electric grid continues to evolve (higher variable renewable penetration, smart devices, electrification, etc.)?

11.0 Appendix E: Breakout Session Outcome Summaries

Breakout sessions coarse notes summary

- There are a lot of different types of models and stakeholders and planning questions; it's hard to talk at the same time about all of them
- Models are good at certain things, not others. There would be value in connecting models or making them consistent.
- Hydro facilities have multiple objectives and hydro models don't often capture market dynamics well, and production cost models often don't model reservoir restrictions well
- PCM modelers want to know how water managers are anticipating changes in the hydro fleet or operations and how they can model that in energy models.
- Data. We need more data.
- Data mismatch between different types of models
- Validation and backcasting. This is needed and essential to hydro modeling, but is difficult and rarely done for energy modeling. Water data is often available, but not market-related data.
- The grid is rapidly changing, and so are hydropower operations. Have an ability to represent generation (with limitations), but not as well ancillary services.
- Model representations of markets are not accurate, as markets designs often do not incentivize hydropower flexibility
- Disconnect between globally optimized models for hydro operations vs. how individual and regional hydro facilities operate
- Water models and management does not monetize water services, but production cost models operate with monetized services.
- Single sector modeling approaches are often insufficient for accurately addressing power and hydropower questions
- Valuation of hydropower services will require understanding of hydropower and variable renewable energy (solar, wind) availability along with projections of price and demand

12.0 Appendix F: Day 2 Panel Questions

Panel 1: Landscape of models and tools.

1. Given the diversity in model types, stakeholders, and regions, what are some fundamental insights and modeling improvements that could benefit all types of models and all types of stakeholders?
2. How well do model tools capture multiple objectives (generation, markets, environmental and regulatory constraints, reservoir constraints), and what are some innovative ideas for how single objective models can capture multiple objectives? How much more parameterization can you do before you reach a limit (vs. new module or model linkages)?
3. Can we continue to modify existing models, or are new model frameworks and designs needed, including formulations of the value of multiple types of services from different sectors?
4. What is the value of dynamic model linkages compared with simple passing of data outputs of one model as inputs for another?
5. Are current models' representations of hydropower able to capture the changes in water availability (due to climate, policy, restrictions, environmental, regulation, etc.) that are modeled and projected by the hydro community?
6. How do we give greater credibility to production cost modeling, given that validation and backcasting have inherent limitations?

Panel 2: Modeling and data needs

1. Should we bring regional models with separate optimizations together, or have a co-optimization framework within one model, given regional differences in priorities and hydro operating rules?
2. What are the consequences for other energy system models (capacity expansion, power flow, etc.) if major changes in hydropower representation are made in production cost models?
3. How can (or should) human decision-making factor into production cost models?
4. If we don't have actual data, what are tradeoffs and best practices associated with simulating scenarios to produce data? Or incentivizing people to produce data? Computational resources for appropriate simulation and data storage?

Panel 3: Challenges and opportunities

1. Noting existing challenges in representing hydropower generation in production cost models, what improvements are needed to better capture hydropower's evolving role in a changing electric grid?
2. What are the data needs (and challenges) to better represent ancillary services in models?
3. How can models represent markets better for hydropower participation for reliability markets?
4. What are new model capabilities needed to account for reliability markets (tradeoffs of participation in one market vs. another, storage, cascading plants, etc.)?
5. How will wear-and-tear of flexible operations affect utilization of hydropower flexibility?
6. Will variable renewable energy (wind, solar) resources become less variable and more controllable or predictable in the future?

This report is being prepared for the U.S. Department of Energy (DOE). As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (public law 106-554) and information quality guidelines issued by DOE. Though this report does not constitute "influential" information, as that term is defined in DOE's information quality guidelines or the Office of Management and Budget's Information Quality Bulletin for Peer Review, the study was reviewed both internally and externally prior to publication.

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