Context, Capabilities, Constraints, and Costs for the Provision of Ancillary Services by Hydropower Assets

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Executive Summary

The capability of hydropower assets to provide ancillary services are enabled and constrained by facility and unit level attributes. The linkages between attributes, capabilities and ancillary services are explored within. The current state of data availability through which one can discern these attributes, capabilities, and services are also explored. At times, the historical provision of services can be well informed despite the lack of adequate means of establishing the capability of hydropower assets that do not currently participate in the provision of these services. Asset owners and operators understand the means necessary for establishing specific capabilities. The quantification of degradation costs ascribable to specific ancillary services and the installed technology levels required to penetrate the market constrain the number of hydroelectric facilities that choose to participate in the provision of each ancillary service.

Acronyms and Abbreviations

ACE	area control error
AGC	automatic generation control
AVR	automatic voltage regulator
BES	Bulk Electric System
EIA	US Energy Information Administration
EUCG-HPC	Electric Utility Cost Group Hydroelectric Productivity Committee
FERC	Federal Energy Regulatory Commission
GADS	Generating Availability Data System
ISO/RTO	independent system operator or regional transmission organization
M&I	municipal and industrial
NERC	North American Electric Reliability Corporation
PFR	primary frequency response
PLC	programmable logic controller
PSH	pumped storage hydropower
RBA	runner blade angle
SCADA	supervisory control and data acquisition
USBR	US Bureau of Reclamation
WGO	wicket gate opening

Glossary

Black start service: The ability to be started without support from the system or to be designed to remain energized without connection to the remainder of the system, with the ability to energize a bus, meeting the transmission operator's restoration plan needs for real and reactive power capability, frequency, and voltage control [1].

Inertial response: the release or absorption of kinetic energy by the rotating masses of online generation and load within an interconnection [2].

Nonspinning reserve: Generating reserve not connected to the system but capable of serving demand within a specified time or interruptible load that can be removed from the system in a specified time, usually 10 minutes, in most ISO/RTOs [1].

Primary frequency response: The immediate proportional increase or decrease in real power output provided by generating units/generating facilities and the natural real power dampening response provided by load in response to system frequency deviations. This response acts in a manner consistent with stabilizing frequency [1].

Secondary frequency response or AGC: The automatic adjustment of generation in a balancing authority area from a central location to maintain the balancing authority's interchange schedule plus frequency bias. AGC might also accommodate automatic inadvertent payback and time error correction [1].

Spinning reserve: Unloaded generation that is synchronized and ready to serve additional demand within a specified time, usually 10 minutes in most ISO/RTOs [1].

Voltage control: An attempt to maintain desired voltage levels irrespective of the reactive power required to do so [3].

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1.0 Energy and Water Context for Hydropower Assets

Operational flexibility is required to operate all grid systems in an economic and economic way and the North American grid is no different. The current Bulk Electric System (BES) requires properly balancing the risks of power outages and the costs of noneconomic operation to assure grid stability and reliability. Flexible operation metrics including minimum and maximum flows, ramp rates, reservoir elevation guidance, unit availability, and plant MW weighted availability allow analysts to identify and quantify the constraints caused by all obligations on hydro assets, whether they be environmental regulations, river network, or power plant equipment capabilities and specifications. River drainage basin wide system forecasting would allow plants to be optimized collectively to maximize the operational flexibility of the fleet as it seeks to meet these more demanding grid objectives.

1.1 Power System Evolution as a Driver for Change

Power system operators balance supply with demand while meeting the evolving grid opportunities and obligations. Power system challenges have changed over time. Until recent years, when scheduling power generation, the accuracy of load demand for electricity was the primary factor of uncertainty for generation schedules. Nowadays, even as load becomes more controllable, generation has become much more complex with large amounts of variable wind and solar energy, real time market opportunities, environmental requirements, abundant data, and other pressures that increasingly force dispatch decisions into the final hours and minutes.

Power system operators need information from river schedulers to know exactly how much hydraulic flexibility they might require in the next weeks, days, hours, minutes, and sometimes seconds before a decision is made to bid this flexibility to the grid. New operational metrics are needed to quantify system-wide operational flexibility because standard measures such as start/stops and capacity factor, or MWh's paint an incomplete picture. The new metrics can help quantify the amount of operational flexibility for the grid and flexibility provided by each facility.

Flexible operation, which includes the ability to quickly adjust the units power output and economically function at off-peak efficiency loading points often involves varying the power output in response to market and electric grid demands in the form of regulation and reserves. Hydroelectric units are used to adjust their production to the remaining residual load profile on the fly, which leads to an underestimation of true hydropower plant value on a day-ahead basis when evaluating based on MW capacity or MWh generated. The future profitability of conventional thermal and hydroelectric power plants has been subject to various studies in the last few years. Some of the most important adverse effects of flexible operation occur because of increased unit start-stops, operating the units at minimum or maximum power levels, and specific to hydroelectric units is the operation of the units in regions of increased cavitation or increased hydraulic instability more than base loaded units [4] [5]. Conventional hydropower units are encountering a changing role in modern society's energy supply. With increased need for flexible operation, engineers and project managers are faced with challenging decisions to address increased equipment degradation rates [6].

With its ability to manage large positive and negative power variations with very short response times, pumped storage hydropower (PSH) is an energy storage technology capable of stabilizing the BES. It accounts for 95% of total utility-scale electricity storage in the United States [7]. With today’s fast growth of variable energy generation, mainly from wind and solar, the existing PSH capacity is not large enough nor spread geographically enough to adequately provide all ancillary service needs. Therefore, with the absence of additional PSH development to support the growing renewable penetration, conventional hydropower projects could be used to provide additional regulating capacity through modified turbine operation. Since these turbines were not originally designed to operate beyond the design criteria damaging operating modes would precipitate asset replacement costs at levels much sooner than original plant performance expectations.

Traditionally, hydropower-generating companies have operated as traditional utilities, and the focus was always the assurance of continued low-cost energy supply and long-term asset management; therefore, the rehabilitation scope of work was often the restoration of mechanical equipment and replacement of components. However, power system operations have changed because of deregulation-privatization, globalization, and environmental requirements. The priorities of electricity-generating companies and plant operation modes have adapted to these new conditions, which in turn has led to modifications in functional requirements for rehabilitation projects. Grid resilience is a major technical issue resulting from changes in the generating mix of the BES and the necessary provision of ancillary services.

1.2 Comparison of the Timescales of Energy and Water Systems

Energy-water systems involve several interrelated factors that influence hydropower operations and planning and that affect the surrounding ecosystem. Factors outside the control of hydropower operators can be broadly categorized as electric power infrastructure, water management and hydrology, and ecological and environmental factors, and these factors affect the energy-water system across different timescales as shown in Figure 1. Over time, these factors fluctuate as they interact with each other and respond to changing water conditions. Examples include increased energy demand, precipitation and runoff variation, and individual organism response. When considering these factors, it is important to understand the timescales across which they influence or respond to changing water conditions to (1) understand opposing forces that constrain, enable or demand flexibility from hydropower (2) understand the timeframe required before impacts can adequately be measured.

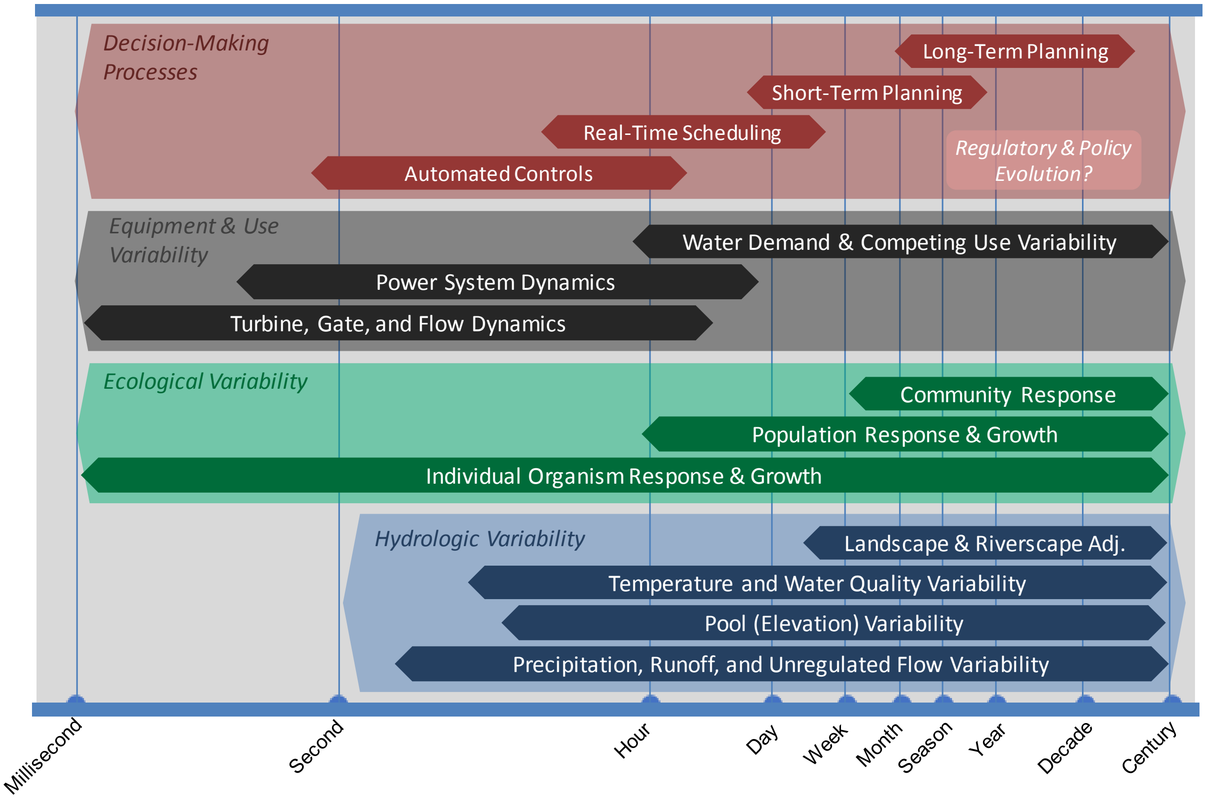

Figure 1. River and hydropower timescales and horizons that impact hydropower operations.

To understand with whom the onus for change belongs, it is important to distinguish between the variability internal to hydropower units and facilities, and the external variability from the surrounding power system and surrounding reservoir and habitat. Figure 2 is a representation of the timescales of internal and external sources of variability in hydropower operations, dispatch and planning. The next two subsections will discuss Figures 1 and 2 by distinguishing between the timescales internal and external to hydropower systems.

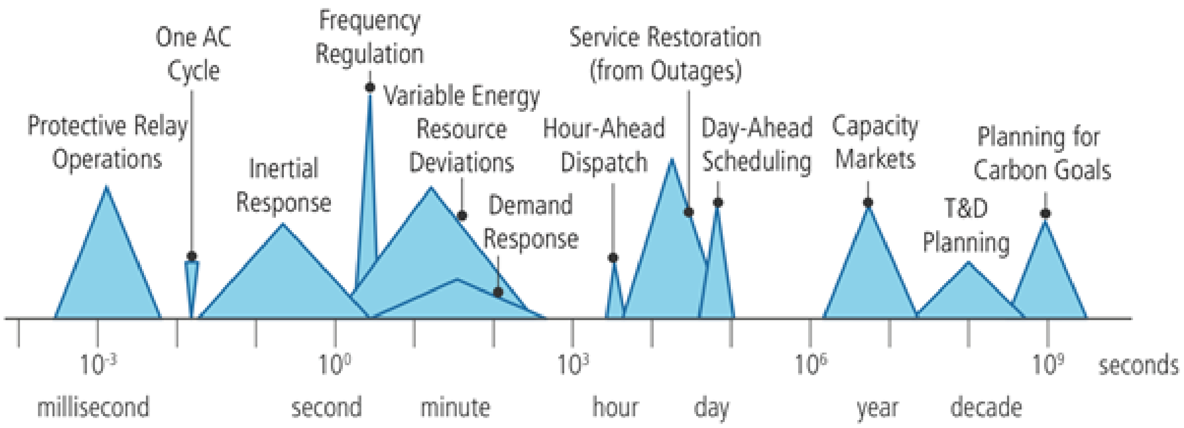

Figure 2. System reliability [8].

1.2.1 Timescales Internal to Hydropower Systems

- **Inertial response and frequency regulation:** These short-term response capabilities of conventional generating facilities occur in the subsecond to multisecond range and balance power supply and demand without manual action. Hydropower operators have no option to withhold electromechanical and inertial responses operating in the subsecond range. The operators can vary governor droop settings, but when connected to an independent system operator or regional transmission organization (ISO/RTO), the droop settings are specified so that all units equally share the burden of primary frequency response (PFR).

- **Provision of automatic generation control (AGC) and reserves:** Automated controls are set by the utility to help restore the grid to the optimal frequency through load following. The AGC software corrects for area control error (ACE) by sending optimized setpoints to generating resources.

- **Planning processes:** Short-term planning for hydropower is focused on meeting multipurpose objectives and maximizing revenue. Long-term planning includes asset rehabilitations, integrated resource plans, and capacity markets.

- **Equipment and use variability:** Turbine, gate, and flow dynamics are governed to minimize damaging effects, such as water hammer effects of pulsating flows when opening or closing a gate and cavitation effects resulting from negative pressures. Water demand from competing uses and hydrologic variability impact the availability of water for power generation.

- **Unit Outages:** Planned and unplanned outages significantly impact the availability of units to provide to the system and participate in the energy market. Outages that are known in advance impact planning, and outages that occur from a failure in service impact operations.

1.2.2 Timescales External to Hydropower Systems

- **Ecological variability:** Water demand is constantly evaluated for competing uses such as recreation, navigation, irrigation, water supply and flood control, and fish health. These can drive constraints on reservoir level, flow rate, water temperature, dissolved oxygen content, and total dissolved gas content.

- **Hydrologic variability:** Changing hydrologic conditions important to hydropower include reservoir elevation, temperature, and water quality variability both in the reservoir and downstream of the dam. The variability of temperature and water quality metrics must be carefully tracked and give rise to actions including power generation and spill flows. Variability occurs on timescales ranging from seconds—for precipitation and runoff estimates—to decades—for increased frequency of extreme weather events particularly flood and drought periods as a consequence of climate change—and affect the quantity of water available in the hydrologic system [9]. Adjustments to the landscape, riverscape, and planned water releases can impact the sojourn time between reservoirs, which in turn can affect the scheduling process for run-of-river facilities in a shared river system.

- **Protective relays:** Located at hydroelectric facilities and other generating sources and transmission facilities, protective relays can cause variability on the power system if they are triggered by damaging grid conditions. Their response rate represents the smallest timescale because they are designed to break electrical circuits if abnormal conditions are detected. Damaging grid conditions can be responded to within 3-5 ac cycles by fast breakers.

- **Variable energy resource deviations:** Power deviations external to the hydropower facility that activate the internal demand response measures of regulation and spinning and nonspinning reserves. Variable energy sources have introduced greater uncertainties into forecasting of energy supply and demand than were previously apparent. Wind and solar generating sources continue to grow their market share, but because they are nondispatchable sources the ISO/RTO's have required additional spinning and nonspinning reserves to compensate for the increased uncertainty.
- **Area Control Error (ACE):** the "mismatch in meeting a Balancing Authority's internal obligations, along with the small additional "bias" obligation to maintain frequency" [10].
- **Service Restoration:** In Figure 2, this refers to black start services that enable system restoration in the event of catastrophic grid events that result in a grid outage.
- **Dispatch and scheduling:** Real-time and day-ahead procurement of energy and ancillary services are subject to a variety of attributes that impact the capability of hydropower units to provide services at certain timescales. Though the dispatch and scheduling of hydropower units occurs externally in the greater context of the BES to the hydropower unit, the dispatch of the hydropower unit results in variability at timescales internal to the hydropower unit. Among these are water hammer effects and rough zones that impact the timing of the start-stop sequence. External sources of variability such as hydraulic head as a result of uncontrolled reservoir inflows, seasonal flow requirements for non-power benefits, and external constraints of maximum and minimum rates of change on flow and elevation impact demand response and unit dispatch. External to the hydropower system, seasonal changes impart variation on power demand as shown in day-ahead markets where the majority of dispatch decisions are made. Multiple years of demand data are used to determine the required hydraulic and generating capacity. External variation, particularly net demand forecasting errors are realized, and additional generating capacity is dispatched in the hourly markets.
- **System planning:** Capacity studies are a yearly exercise to ensure there is adequate generating capacity within each ISO/RTO to meet the peak demand experienced in the previous year [3]. Transmission and distribution planning is a multiyear process that ensures new consumers and new generating facilities are serviced while upgrading current assets to higher voltages to reduce transmission losses. More recently, the multidecade planning efforts to address carbon goals incorporates capacity uprates for existing hydropower facilities and the development of nonpowered dam and new stream reaches for hydropower generation.

2.0 Hydropower Capabilities and Constraints

Specific hydropower capabilities, as enabled by unit and facility attributes, are necessary to enable the provision of specific grid services. Attributes can either enable a capability or impose a constraint on a capability. Likewise, multipurpose benefits, in the form of water management objectives, can constrain the capabilities of hydroelectric unit operations by limiting the dispatch of the unit or by restricting a facility from providing a specific service altogether. Hydropower operations require careful management to meet power demands while meeting potential multipurpose benefits, particularly the environmental regulation requirements and possible competing water uses that are a part of the plant's FERC license. The following discussion is meant to aid the reader in making connections between attributes, capabilities, services, and the multipurpose functions of dams.

2.1 Contextual Attributes and Constraints of Hydropower Assets

Integrated system optimization by grid operators involves the minimization of the total cost to provide power generation (thermal-nuclear-gas-hydro-solar-wind) to meet demand rather than the optimization of the hydro system exclusively. Idealized hydropower operations include optimized reservoir flow releases with a goal of maximizing revenue such as generating power at times of peak demand. The optimal dispatch of hydropower units changes once integrated into the larger grid for various reasons, which could include the factors shown in Figure 3. Competing water use considerations impact the amount of available water in specific seasons. Operational constraints impact the ramp rate of the unit and therefore the changes in water availability. Historically energy mixes that include nuclear, which covers base loads, demand different hydropower operations than those with significant hydropower contributions. More recently the increasing penetration of non-dispatchable renewables demands a different set of hydropower operations as well. These differing local grid mixes result in the reality that even if two hydropower facilities have similar attributes, constraints, and capabilities the hydropower units may be operated quite differently.

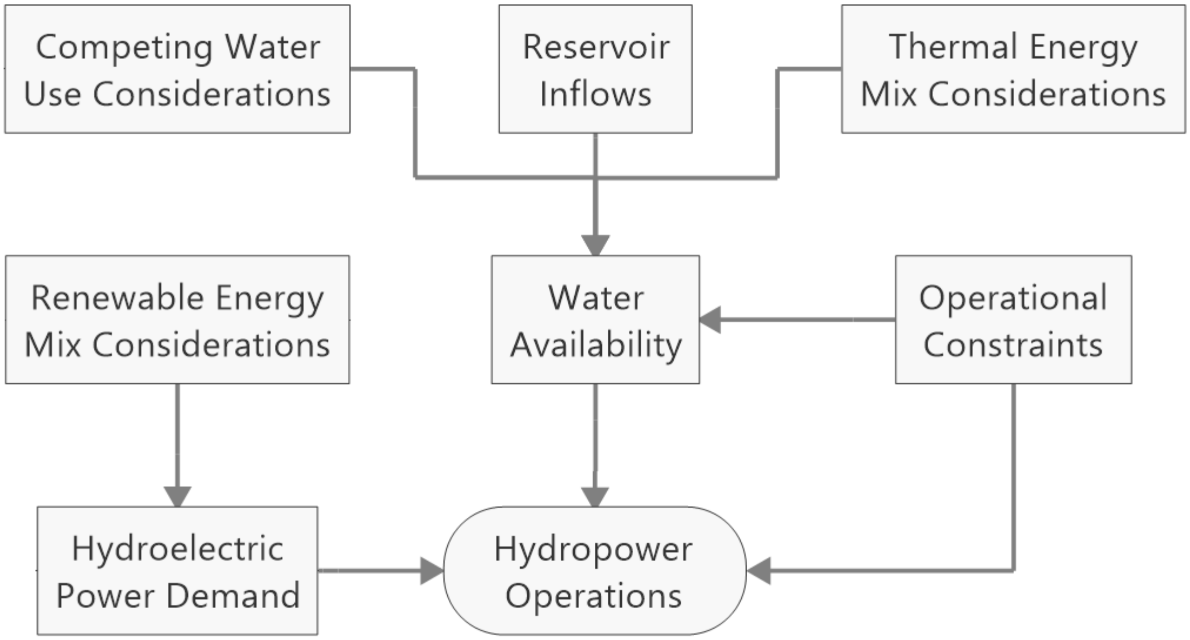

Figure 3. Primary factors affecting hydropower operations.

Attributes of river systems, hydroelectric facilities, and grid interconnections and constraints of hydroelectric unit operations can be discerned as localized or systemic. Those that are systemic can be reduced to certain management practices that are well understood throughout the industry. Localized issues require localized management practices that must be well understood for inclusion in market models.

Given these factors, hydropower generation is often operated under suboptimal water-use efficiency conditions. However, flow control provided by hydropower facilities provides value for other competing water uses through both multipurpose benefits such as municipal water supply, irrigation, stream reach recreation and transportation and through avoided costs to thermal power systems. In this way, hydropower value extends beyond the direct revenue generated through electricity markets. In a well-integrated system, these various considerations are evaluated holistically through system simulation. Though difficult, water availability, power demand, operational constraints, competing water use considerations, and energy mix considerations can be built into a model for simulating and scheduling hydropower operations in real time or as a part of short-term and long-term forecasting. The difficulty in modelling the energy-water nexus that is hydropower dispatch increases as the number of individual parties increases.

Advances in environmental optimization through turbine designs are evident in several research areas. Some of these areas are improvement in fish passage through turbines (fish friendly turbines and others), refinement of second-generation aerating turbine design, and development of tools to capture and address how the technology’s environmental and energy performance characteristics can be integrated into decision support systems and optimized scheduling of hydropower resources.

Within a diverse energy-water system, hydropower operations compete with other water demands such as water supply, cooling water for thermoelectric facilities, and lake water levels. An entire river system can be managed by the same or different entities. Managing water resource constraints on the same or adjoining river networks has the potential to adversely affect or positively benefit various aspects of energy and water resources and operation in and along the river drainage system. The spatial and temporal consideration of competing demands for water quantity and quality with imposed constraints at various locations along a river makes for a complex system. Managing the complex nexus of energy, water, and ecological systems to achieve optimized value requires careful planning, forecasting, and coordinated operation. The following subsections describe how hydropower operations within the broad context of a complex and integrated river system are crucial for meeting overall energy-water objectives.

Impounding reservoirs that provide energy in storage are often referred to as multipurpose reservoirs because they are consistently and reliably meeting the diverse needs of both competing and complementary stakeholders. Valuation of a multipurpose project as a whole should incoporate quantifiable economic benefits of each purpose. This is most readily achieved for energy-related services. Monetization is achieved through a market-driven pricing mechanism when power is generated and sold in a regulated market. Ancillary service benefits are also clearly identified, as their economic contributions to electric power markets have been isolated and quantified since the Energy Policy Act of 1992. Many nonenergy-related benefits, on the other hand, are often overlooked in the context of hydropower multipurpose reservoir use. When these benefits are monetized, their economic value often surpasses that of power generation, contributing substantially to local economies and affecting millions of people as the Corps estimated a flood damage reduction of $19.6 billion from 1998-2007 [11].

Operating policies for multireservoir systems must specify the released flow from each reservoir and the total release flow from the system. Such operating rules usually consider the water balance of the system and the impacts on the various users of water flows and storage volumes. For multireservoir systems, operating policies that define the individual reservoir releases as a function of the existing total system storage volume as well as the individual reservoir storage volumes clearly define the actions to be taken at any time and for any state of the system. System release rules typically indicate the total release to be made from the reservoir system as a function of the water available in the system and the time of year. A comparison of the individual reservoir storage targets to the actual storage volumes in each reservoir identifies which reservoirs should release water and which should not release water to meet the total system release target. Having both system-wide release functions as well as individual reservoir storage volume target functions defines a multireservoir operating policy that permits the coordinated operation of the entire system.

At a basic level, hydropower operations must ensure that multiple operational constraints are met. Example constraints can include dam safety requirements, water levels upstream and downstream of a dam, temperature and other water quality metrics within a body of water, minimum or maximum flow releases, and so on. Related to water use, many water bodies service a broad network of energy systems where water services a diverse energy mix including both hydropower and thermal power plants. Since thermal power plants (i.e., nuclear and fossil) require large volumes of cooling water, thermal demands and flow availability might necessitate hydropower flow releases under suboptimal conditions. The relative scale of hydropower and thermal plant capacities could influence operational priorities for meeting power demand.

The daily schedules for water releases from each dam, including the rate and total quantity of water to be released to achieve the multiple purposes of the reservoir system (flood damage reduction, navigation, power production, water quality, water supply, and recreation) are developed using advanced computer models, rainfall, and stream-flow gauges. These schedules consider the total amount of water stored in the reservoir system, the time it takes to move water through the system, and other reservoir-specific factors such as storage capacity and seasonal operating guides.

The challenge is that tradeoffs between environmental, water, and energy objectives are often treated within a single reservoir only. Environmental optimization should be aimed at improving the capabilities of entire ecosystem. Environmental benefits and cumulative impacts should be combined and optimized with all the multipurpose functions for a system of reservoirs.

2.1.1 Local Attributes and Constraints

Localized attributes vary significantly from site to site based on geographic, riverine, and biological conditions. They must be accounted for during the design process so that the best solution can be chosen during the design process. In some cases, local constraints on water availability and water delivery oppose grid needs and constrain economic optimums at hydropower facilities. Throughout the day, adjustments in water release schedules are made in response to ever-changing weather conditions, fluctuations in power demand, and river system nonscheduled emergencies. Releases from multipurpose dams must be adjusted frequently to optimize water use. Although many reservoir systems in the United States are operated within specified zones or pool levels, river operation schedulers are authorized to make the best decision based on up-to-the-minute assessments of current and expected conditions and needs.

The requirements that impose constraints on hydropower operations can collectively be referred to as multipurpose benefits. The US federal fleet, composed of the US Army Corps of Engineers, US Bureau of Reclamation (USBR), and the Tennessee Valley Authority, includes 157 powered dams and accounts for nearly half of the total installed hydropower capacity in the United States. Most of these dams and their associated reservoirs are authorized for more than one purpose in addition to hydropower generation (Figure 4, left). These purposes include hydropower, navigation, flood control, recreation, irrigation, and municipal and industrial (M&I) water supply.

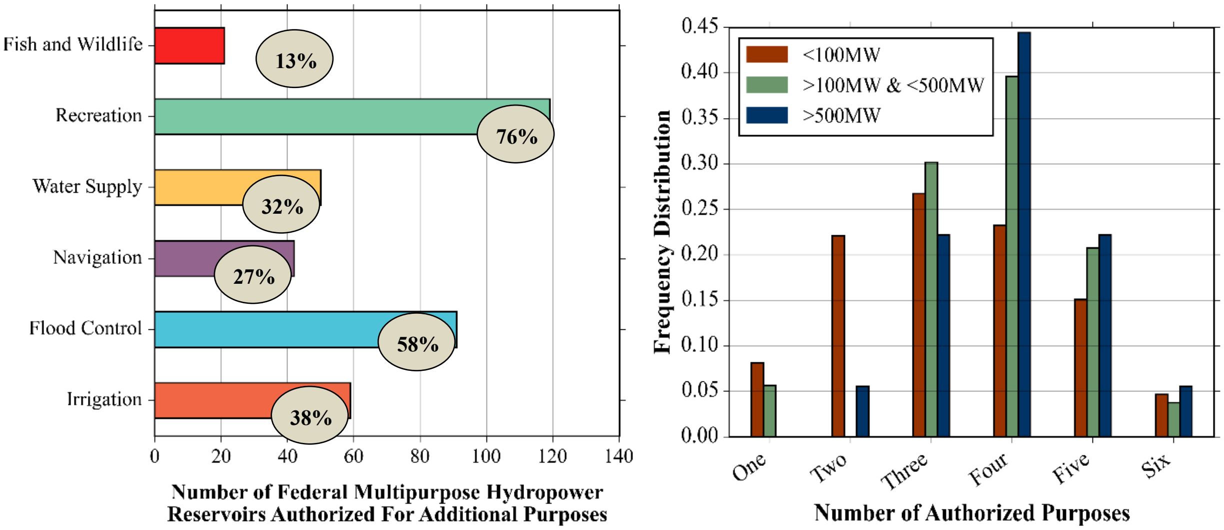

Figure 4. Distribution of authorized uses for all federal multipurpose hydropower reservoirs. On the left in a circle at the end of each bar is shown the percentage of multipurpose hydropower reservoirs authorized for each respective additional purpose. On the right is shown the frequency distribution of authorized uses based on installed hydropower capacity [12].

Typical river operations of an integrated system with multipurpose hydropower reservoirs and thermal power plants requires vigilance in forecasting, scheduling, and operation of the system to meet all the demands and all the environmental requirements of the entire system. River schedulers monitor weather conditions and water quality data, as well as water availability and power demand. The goal of the operations teams at public hydroelectric utilities is to route water through the river system to provide the most public value given changing weather conditions, water needs, and power demand.

The multipurpose benefits attributable to each facility can be mapped to the constraints they impose on hydroelectric facilities, as shown in Table 1. Municipal and Industrial (M&I) water supply and irrigation are water use priority that diverts flows away from power generation and depending on the location of the withdrawal system will require a minimum reservoir pool elevation. Recreation on the upstream reservoir can limit usable reservoir storage as it requires a specific range of pool elevation for access to boat docks. Downstream stream reach recreation can impose constraints on the ramp rate and max flow for fisherman safety. Flood control imposes constraints on the reservoir pool elevation. Navigation imposes minimum reservoir pool elevation and minimum flows to require safe navigation and maximum pool elevation to ensure that the navigational lock is useable. Max ramp rates allow for safe and navigable waters. Fish and wildlife impose constraints on minimum flows to prevent fish from being stranded in certain stream reaches and constraints on ramp rates to maintain wetted areas for spawning habitats. Benefits to thermal power plants are not included in this study but are a function of system operator triage.

The multipurpose benefits of hydropower can constrain the facility's capability to provide specific ancillary services. These relationships are explored in Table 1. Minimum flow requirements impact flexible power dispatch capabilities by providing water constraints in future time horizons that could prevent the ability for a hydro unit to use additional water to deliver its full capacity. This relationship is not well understood because of the dependencies on reservoir residence time and the predictability of future precipitation events. Maximum ramp rates constraints at facilities are imposed to discourage bank erosion and assist the biota of the river as the depth of the downstream stream reach could rise and fall rapidly if unconstrained. These ramp rate constraints prevent the flexible dispatch by preventing the unit to quickly deliver the capacity that may be needed.

Table 1. **Constraints on hydropower capabilities from multipurpose benefits**

	Constraints involved					
Multipurpose benefits	Water use priorities	Min pool elevation	Max pool elevation	Min flow	Max ramp rate	Max Flow
M&I water supply	✓✓✓	✓✓✓				
Irrigation	✓✓✓	✓✓✓		✓		✓✓✓
Reservoir recreation	✓✓✓	✓✓✓	✓✓✓		✓✓	
Stream reach recreation					✓✓✓	✓✓✓
Seasonal flood control		✓✓✓	✓✓✓			
Navigation		✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Fish and wildlife	✓✓			✓✓✓	✓✓✓	✓✓✓
Capabilities constrained	Water use priorities	Min pool elevation	Max pool elevation	Min flow	Max ramp rate	Max Flow
Large inertial constant						
Reactive power control						
Synchronous condensing mode						
Fast cold start-up	✓✓✓					
Flexible power dispatch	✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓✓
Fast ramp rate					✓✓✓	
Isolated Unit start-up					✓✓✓	

✓✓✓ well-understood relationship; ✓✓ relationship exists, not well understood; ✓possible relationship.

Localized attributes other than multipurpose benefits include the width of the turbine efficiency band, the water conveyance design, air suppression system, computer-based controls, and on-site diesel generators. Each of these attributes plays an important role in the determination of whether, or to what extent, a hydropower unit has specific capabilities. The multipurpose benefits discussed then impose constraints at the local level. Taking the constraints from Table 1 and the attributes from Table 2 to understand the capabilities of hydropower units, one can then determine the extent to which the unit can provide each service to the system operator, as shown in Table 2. Hydropower attributes and

- Width of the turbine efficiency band: This attribute refers directly to the range of efficient power outputs a unit can provide. Typically, Kaplan turbines with their adjustable blades offer a wider efficiency band than other turbine types. This attribute governs flexible dispatch capability as small turbine efficiency bands incur greater opportunity costs for operating away from peak efficiency.

- Water conveyance design: The length of the water conveyance and intake structure directly affects transient pressures that occur during starts, stops, and ramp events. These transient pressures, of which the water hammer effect is the most notable, must be properly managed and offer lower limits to the ramp rate and start-up times. On the timescale of a 10-minute start, the water hammer effects are minimal but must be given time to adequately dissipate.

- Air suppression system: This unit-level technology enables synchronous condensing capabilities by allowing the unit to suppress the water below the turbine. With closed gates, this allows the turbine to spin with only air friction.

- Computer-based controls: The ability to control power dispatch with computer-based controls rather than manual operation allows for increased flexible dispatch as it reduces the time spent on the decision-making process. This is key to flexible operation of generating units as it is necessary for multiple services that hydropower can provide. This attribute is not the same as remote operation, which has cost reduction benefits but does not factor in the capabilities discussed herein. Computer-based controls can reduce the time required to make and implement dispatch decisions.

- On-site diesel generators: This facility-level attribute allows for isolated unit start-up of a single unit at the facility. Once the first unit is restored, it can provide the power necessary to facilitate starting the rest of the units at the facility. Though the number of diesel generators housed at a facility is chosen based on the several requirements, it needs to only include the power requirements to start one unit to enable the facility's capability. This is independent of which unit of the facility is chosen because it is a facility-level attribute.

Table 2. Hydropower attributes and capabilities

		Capabilities						
	Attributes	**Large inertial constant**	**Reactive power control**	**Synch. Cond. mode**	**Flexible power dispatch**	**Fast cold start-up**	**Fast ramp rate**	**Isolated unit start-up**
Unit-level design	Rated speed	✓✓✓						
	Turbine/generator physical design parameters	✓✓✓	✓✓✓					
	Wide efficiency band				✓✓✓			
Unit-level Technology	Air suppression system			✓✓✓				
	Governor controls		✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
	Automatic voltage regulator		✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Facility level	Energy in storage			✓✓	✓✓✓			
	Reservoir elevation flexibility				✓✓			
	Water conveyance design				✓✓	✓✓✓	✓✓	
	Computer-based controls				✓✓✓	✓	✓	
	On-site diesel generator							✓✓✓

✓✓✓ well-understood relationship; ✓✓ relationship exists, not well understood; ✓possible relationship.

2.1.2 Systemic Attributes and Constraints

Systemic attributes are imposed on units and facilities and are not easily altered outside of a redesign of the turbine-generator system. When taken in harmony with the local attributes and multipurpose benefits of the facility, operators can determine the capabilities of the unit that enable the provision of system services.

- Energy in storage: The stored potential energy impounded by a dam, also termed active storage. This affects both the maximum efficient load and maximum sustainable load that must be used instead of nameplate capacity when incorporated into a market structure.
- Reservoir elevation flexibility: Attribute that can vary seasonally as utilities prepare for winter flood control elevations and summer recreation pool elevations. Quantifying reservior elevation flexibility enables a direct comparison of the ability of a facility to shift power output to the most economical parts of the day. Utilities that manage integrated river systems incorporate reservoir guide curves into the model structure as constraints that inherently limit the available flexibility. The looser the constraints, the more capable the facility is of operating flexibly.
- Rated speed: The speed at which the unit rotates when synchronized to the grid. This angular velocity is one aspect calculating the kinetic energy of the rotating mass and the total inertia of the generating unit.
- Physical design parameters: Turbine and generator design parameters, which are crucial in the determination of the unit's distribution of mass relative to the rotating axis. This has a direct effect on the moment of inertia. Specific turbine types abide by specific geometric distributions of mass, but the generator's distribution of mass varies only with generator size.
- Automatic voltage regulator (AVR): Automatically maintains generator voltage output. This attribute enables dynamic reactive power control and synchrounous condensing mode. It is also necessary for isolated unit start-ups and is crucial in providing system stability when units operate in flexible power dispatch.
- Governor controls: Mechanical, analog or digital electronic controls that convert electrical signals to mechanical attributes which adjust gate openings to provide frequency control and meet power requirements. Governor controls are necessary for a wide variety of capabilities. Poor governor controls can lead to hunting, an unstable condition in which the governor cannot maintain frequency at an acceptable level when operating off-line. Some movement of the wicket gates and frequency wander is normal for a mechanical governor, but if the frequency wander exceeds 0.2 Hz peak to peak or if the automatic synchronizer cannot put the unit online, it is considered excessive.

2.2 Design Attributes and Capabilities of Hydropower Assets

The services hydropower can provide can be classified as bulk energy services, ancillary services, or grid stabilizing services. Table 3 documents the connection between capabilities and these services. Unit and facility attributes provide specific capabilities that either enable or lower the cost of the provision of services and products relative to other generating sources. Inherent and installed attributes therefore allow hydropower to be an integral part of the modern electric grid.

The capability of hydropower to provide bulk energy services of active power generation and firm capacity is well known, although it is dependent on variations in annual precipitation as discussed in previous case studies and those constraints which have been presented. As such, the focus here is on the ancillary services provided to the electric grid that facilitate and support the continuous flow of electricity to reliably and continuously integrate resources and meet demand. This report covers the capabilities required to provide the inherent "must give" grid stabilizing benefits of inertial response and primary frequency control as well as the ancillary services of secondary frequency response, voltage support, spinning and nonspinning reserves, and black start operations.

Hydropower's long-term availability provides adequate capacity to swiftly back up intermittent power sources. The utility's and unit's "ability to react and provide the needed services will determine which technology will primarily act as back-up to variable renewables. In some market this will be done by natural gas-fired generators; however, when available, "hydropower with large storage capacities will be the preferred choice" [13]. Hydropower plants with storage have large volume capability to handle excess wind generation; pumped storage has smaller storage volumes but high-power capacity.

Table 3. Hydropower capabilities that enable or assist in the provision of services and products

	Services or products	**Large inertial constant**	**Reactive power control**	**Synch. Cond. mode**	**Flexible power dispatch**	**Fast cold start-up**	**Fast ramp rate**	**Isolated unit start-up**
Must give	Inertial support	✓✓✓		✓✓✓				
	Primary Frequency Response	✓✓✓					✓	
Chosen to provide	Voltage control		✓✓✓	✓✓✓				
	Secondary Frequency Response (AGC)						✓✓✓	
	Spinning reserves				✓✓✓		✓✓✓	
	Nonspinning reserve				✓✓✓	✓✓✓	✓✓✓	
	Black start	✓✓✓	✓✓✓		✓✓	✓✓✓	✓	✓✓✓

✓✓✓ well-understood relationship; ✓✓ relationship exists, not well understood; ✓possible relationship.

2.2.1 Large Inertial Constant

In conventional synchronous generators (i.e. steam turbines, gas turbines, hydro turbines, etc.), inertia is created when the rotating mass gains speed and is a function of how the mass is distributed around the axis of rotation, the mass itself, and the rotational speed of the component.

The kinetic energy in the form of inertia spontaneously compensates for momentary deviations in load, thereby accelerating or decelerating the rotating machinery. Many generating types, excluding solar power, can provide inertia by using the turbine and generator connected through the shaft as the rotating mass.

To provide inertial support, the units must be spinning and connected to the grid. The mass of the rotating machine and its mass distribution determine the moment of inertia of the turbine. The diameter and mass of the hydroelectric turbine and rotating generator components play a significant role in the moment of inertia and thus the amount of kinetic energy stored in the rotating machinery, as seen in the following equation:

$$\mathrm{E_{kin}} = \frac{1}{2}\mathrm{J}\omega^2 = H * MVA \text{ ,}$$

where ω is the angular velocity (rad/s) and J is the moment of inertia (kg-m^2), which is a function of mass and radial distance to axis of rotation squared [14]. The inertial constant H relates the available inertia to the mega-volt-amp rating of the unit. Increased inertial support can be accounted for during the design process as increasing the diameter and/or mass of the generator would increase the inertial support available to the system. This does come at an increased cost for the generator, a decrease in efficiency, and the requirement for a larger crane and powerhouse structure. Thus, it can become cost prohibitive to increase the inertial support capabilities of a hydroelectric unit. Additionally, in pump turbines, it could lead to an increased start-up time for pumping operations. The rotating mass used to determine inertia includes the rotating generator components in addition to the turbine runner. Because of the large mass and geometry of hydroelectric turbine-generator components, the units provide ample inertial response when energy imbalances occur relative to their generation share.

Existing consortia data sources do not contain inertial support, flywheel effect, J, or H; however, turbine characteristics of revolutions per minute and turbine diameter are commonly available as part of design data. These allow for an estimation of the moment of inertia because of the strong correlation between turbine diameter and mass [15]. Though turbine diameter and mass are well correlated, the total inertia of the unit is dependent on the mass of the turbine and generator. The actual moment of inertia can be found in the facility design documents that detail flywheel effect and rated speed, though access to this information is limited and likely tedious.

By acknowledging the turbine-type geometries, assumptions on relative mass distributions could be drawn. Thus, if given a small sampling of actual inertial support capabilities and the necessary information on a larger fleet, the amount of inertial support each unit provides when spinning could be assessed.

2.2.2 Reactive Power Control

Reactive power is a necessary part of the power system that must be supplied regionally. Conventional generators, including hydropower, can provide dynamic voltage support that can increase or decrease reactive power during power generation and synchronous condensing operation independent of voltage fluctuation. In the interest of voltage support, reactive power sinks introduce the problem and reactive power sources offer the solution. Because the needs of the reactive power sinks vary constantly, reactive power controls are necessary to properly respond to this changing demand.

Automatic voltage regulators (AVR) at hydroelectric facilities enable reactive power control. The AVR works in combination with governor speed controls to adjust real and reactive power output to compensate for reactive power needs in the most effective way possible. The capability of hydropower to provide dynamic reactive power controls during synchronous condensing mode also separates it from other conventional generators as this capability is no longer tethered to real power generation.

2.2.3 Synchronous Condensing Mode

Grid voltage and power quality is regulated through reactive power dispatch in conjunction with active power dispatch. Conventional generators provide reactive power during power generation and synchronous condensing operation. Synchronous condensing operation increases grid stability by providing additional inertial and voltage support without the use of water or other fuel. For hydro units, synchronous condensing operation requires plant modifications including a control system and air compressors that enable the unit to blow down water 3 ft below the turbine runner [16].

Since reactive power is a localized issue, support from hydroelectric facilities in remote areas is essential to grid stability. And because hydroelectric units do not typically generate power during all hours of the year, synchronous condensing operation allows hydroelectric units to provide valuable reactive power and inertial support without using water stored in the reservoir.

Recent fatigue stress tests of Francis turbines use the number of condensing events rather than the total condensing hours to estimate the incurred degradation [5]. The Generating Availability Data System (GADS) stores this information but the blinded nature of the GADS data allows only for national trends to be ascertained.

2.2.4 Flexible Power Dispatch

The dispatchability of hydropower is the key capability that traditional variable renewables lack. This is primarily enabled by the energy in storage that hydropower reservoirs provide to hydroelectric facilities. Though wind and solar can be selectively withheld at an economic cost, they cannot be purposefully dispatched to their max capacities as can hydroelectric units. The width of a turbine’s efficiency band increases the flexibility of the hydroelectric unit’s power dispatch by enabling larger ranges of efficient operations that other conventional sources cannot match. Though usually achieved by adjustable blade Kaplan turbines, other turbine types can achieve wider bands if peak efficiency is sacrificed during the design stage.

The amount of sustained flexible power dispatch that hydropower facilities can provide is dependent on the current reservoir head, the acceptable range of available head for that reservoir at that time of year, and expected water inflows. Flexibility can be accomplished at run of river facilities through combined optimization with upstream peaking facilities [17]. As a reservoir approaches maximum elevation, inflexible operations occur to prevent spill to provide necessary room for inflows. As the reservoir approaches minimum elevation operations might be constrained to ensure that environmental flows can be met.

Because 74.91% of conventional hydropower facilities report start times of 10 minutes or less, the actual start-stop process including achieving speed-no-load and navigating turbine rough zones rarely constrains unit dispatch. Consequently, hydropower with flexible reservoir elevation goals can follow major variations on multiple timescales with regulation and reserves. As non-dispatchable renewables displace higher-cost generation, the responsiveness of hydropower becomes more critical to grid resilience. Penetration of non-dispatchable renewables will shift the mode of operation for base-loaded hydropower to favor flexible operation of the hydroelectric facility whenever possible. This can increase the available spinning reserves by operating in part-load mode even though the reliability impacts are currently unclear [18].

In the selection of black start resources, fast-start and isolated-start capabilities are necessary. Flexible power dispatch of hydroelectric units is also integral to system restoration, though not necessarily black start capability as it is necessary for the grid operator to be able to quickly balance power dispatch when restore system services. By increasing the width of the efficiency band, part-load operations become more economical as the range to provide up and down regulation and reserves increases which also benefits the system restoration process. However, if the turbine will be operating below the vortex-free zone of the hill chart increased degradation could occur.

To provide AGC, units must be capable of quickly providing both up and down regulation. If the area frequency drops below 59.98 Hz, AGC units will increase output. If the area frequency rises above 60.02 Hz, AGC units will decrease output, providing ±20 mHz of dead-band before regulation sources are activated. The amount of AGC that a unit can provide is governed by the deviation from the current power setting that the owner is able to accommodate. This operating range is largely governed by the rated megawatt capacity of the unit and the width of the turbine efficiency band in percent capacity. Kaplan turbines with adjustable blades offer this larger efficiency band and can provide more fuel-efficiency regulation than Francis units with their larger capacity ratings. Power-head-flow curves, cam curves, and other hierarchical data provide guidance as to this regulating range and information on rough zones that should be avoided to minimize the risk of cavitation damage to the turbine runner. Lastly, the operating point divides the operating range into up-regulation and down-regulation capacity.

Provision of reserves is indecipherable from other services, including bulk energy, when restricted to only power output data. Utilities can record a service mode, or ISO/RTOs can provide aggregated reports of ancillary service bids. If provided a comparative analysis of day-ahead schedules and actual power output, data can show results but the difference in power outputs can be attributable to PFR, AGC, or reserves. Evaluation using power output data also only registers reserve capacity that is called into service rather than reserve capacity that is obtained by the ISO/RTO.

2.2.5 Fast Cold Start-Up

USBR guidelines suggest a 10% capacity per minute ramp rate during unit starts, although Nordic utilities routinely operate with 20% capacity per minute. The design ramp rate is established to minimize transient pressures, including the water hammer effect [19] that produces dynamic loads on the gates and valves. The amount of time required to adequately dissipate transient pressures is related to the length of the water intake classification attribute.

The gradual closure of the valve and wicket gates reduces the transient pressures produced compared with an instantaneous closure [20]. Thus, appropriate setting of closing/opening times of the shutoff valve contributes to safer operation in emergency situations [19]. Surge chambers and pressure relief valves are designed to help avoid an excessive rise in pressure and stabilize the flow to reduce the effects of water hammer events. Water hammer events are currently studied using deterministic software models. Analytical and numerical solutions used in water hammer analysis are described in [21]. Alternatively, the minimum local pressure of the water column must not drop below 50 kPa to avoid the consequential large pressure loads from cavity collapse [19].

The governor controls the speed and loading of the unit by controlling the flow through the turbine. The flow is controlled by the wicket gate opening. The wicket gate closing time is set as a compromise between maximum overspeed and water hammer design stresses. Specifications for wicket gate opening range from between 8 and 20 seconds for full closure. For adjustable-blade Kaplan units, movement through the full range of runner blade angles takes between 20 and 60 seconds. These movements impose limits on the rate of governor response when accounting for the unit capacity and the power-flow-efficiency curves. The governor controls respond similarly but in opposing directions to overfrequency and underfrequency events given similar area control error and total area interchange.

At the beginning of and throughout most of the 20th century, when hydropower was predominantly used as base load power generation, units had slow start-up rates that reduced transient pressures experienced by the turbine system. As the role of hydropower has changed in the modern electric grid, technological advances have enabled faster ramp rates. Hydropower units with large storage reservoirs can provide peak load power. This changed their reference mission from as few as one start per week to more than two starts per day with regional variations based on the markets in which they participate. Start-stop counts are reported to NERC GADS, though for end users the database is blinded. This allows for trending market changes but denies analysts the ability to identify specific units.

Before a start event occurs at a hydroelectric unit, the facility's utility-wide dispatch center has scheduled the daily, hourly, and possibly the subhourly water and power dispatch for the facility. The facility operator, located at the dispatch center, then chooses how best to dispatch the units at the facility to meet the grid and water management needs-assuming a vertically integrated utility. Depending on the level of staffing and automation, the unit start sequence can occur on-site or remotely. The unit start and stop schedules are a predetermined sequence of opening valves and gates to minimize deleterious effects. This involves running "up to nominal speed as quickly and smoothly as possible" [22]. During both the start and stop events, operators aim to avoid spending excessive time in the cavitation zones that typically occur at lower capacity outputs. Newer state-of-the-art turbine runners are commonly made with ASTM A487/A743 CA6NM stainless steel [23], which is cavitation resistant. Stress tests can be used to compare the stresses experienced during a unit start with those experienced during normal operation.

In spinning reserve mode, the turbine is ready for fast load acceptance and it might also be kept at speed in the no-load state for quite a long time waiting for a full-load order. This mode of operation is sometimes necessary when the owner has commitments to put power on the grid with extremely short notice, but there are consequences from operating in these severe conditions. In cases where a change in dispatch is required to provide reserves, especially from higher-cost generators, the total cost of providing reserves adds about 2% to the total costs of providing energy [18].

2.2.6 Fast Ramp Rate

The fast ramp rate of hydropower is a result of multiple attributes working in unison. The energy in storage enables work in unison with governor controls to quickly increase or decrease the power output of a hydroelectric unit. The intake classification imparts constraints based on water hammer and mechanical gate movement speeds on the timescale of seconds to minutes.

Operators are not required to report a unit's ramp rate to industry data consortia but using 1-minute data it is possible to discern the physical capability. In a practical sense, ramp rates faster than the 10%/min required for spinning reserve cannot be given additional value by the energy markets as they do not enable any additional provision of services. Current ramp event analyses include mileage calculations and ramp event distributions.

Mileage calculations sum the absolute value of the differences in the runner blade angle (RBA), wicket gate opening (WGO), or power output fields. These analyses conflate movement for PFR, AGC, and hourly load following and start-stops. The last two can be screened out if desired but distinguishing between PFR and AGC response in data analysis is impractical if the time step of data is on the scale of minutes rather than seconds.

Though governor controls play a significant role in enabling fast ramp rates, there is little information about the currently installed governor technology for hydroelectric units. The hydroAMP database managed by CEATI provides a yes/no field to determine whether the unit is enabled to provide AGC. Since the Electric Utility Cost Group Hydroelectric Productivity Committee (EUCG-HPC) collects facility-level data, the field is numerical and asks how many AGC-enabled units are located at the facility. NERC GADS has a field for "Governor Type" but does not ask specifically about AGC operations.

2.2.7 Isolated Unit Start-Up (i.e. Black Start)

The ability for a unit to start in isolation is often conflated with the ancillary service of black start capability. Isolated unit start-up is a hydropower capability that is enabled through a functional on-site diesel generator or other independent power source and is a necessary capability to be deemed a black start resource. NERC defines a black start resource as "a generating unit(s) and its associated set of equipment which has the ability to be started without support from the System or is designed to remain energized without connection to the remainder of the System, with the ability to energize a bus, meeting the Transmission Operator's restoration plan needs for Real and Reactive Power capability, frequency and voltage control, and that has been included in the Transmission Operator's restoration plan" [1].

Individual ISO/RTO's have established requirements surrounding the dispatch capability requirement for black start service provision, typically on the order of 1 to 2 hours. Hydropower fulfills this requirement and adds resiliency to the grid because of the quick responsiveness of hydropower when black start capabilities are required by the grid. Hydropower facilities need only to size diesel generators to provide enough power to open the gates and excite the magnetic field in the hydroelectric unit. Facilities with multiple units are favored to ensure against the unavailability of units. There are also geospatial aspects to the distribution of black start–enabled facilities with those close to major load centers being favored, which is counter to the geospatial needs of reactive power control discussed earlier. Therefore, only one unit at each hydroelectric facility is needed to provide black start services, though all units equipped with a diesel generator on-site would be capable.

3.0 Provision of Power System Services by Hydropower Assets

3.1 Indicators and Metrics of Capabilities and Services

To quantify the share of hydroelectric units capable of providing specific services to the grid, indicators and metrics can prove valuable given specific and reliable data inputs. These indicators and metrics can be reported directly to the US Energy Information Administration (EIA), NERC, or industry consortia or can be calculated using granular operational data.

3.1.1 Start-Up Timing

A cold start-up time of less than 10 minutes is found abundantly in EIA Form 860 data for hydroelectric units, as shown in Figure 5. This cutoff is chosen since when providing spinning or nonspinning reserve, a cold start-up time of less than 10 minutes allows the full capacity to be bid as reserve capacity when the unit is not in use. With this metric, hydropower compares favorably with natural gas units, even after excluding slower ramping combined cycle facilities, with 74.91% of hydropower units being capable of starting in less than 10 minutes compared with only 23.6% of natural gas units.

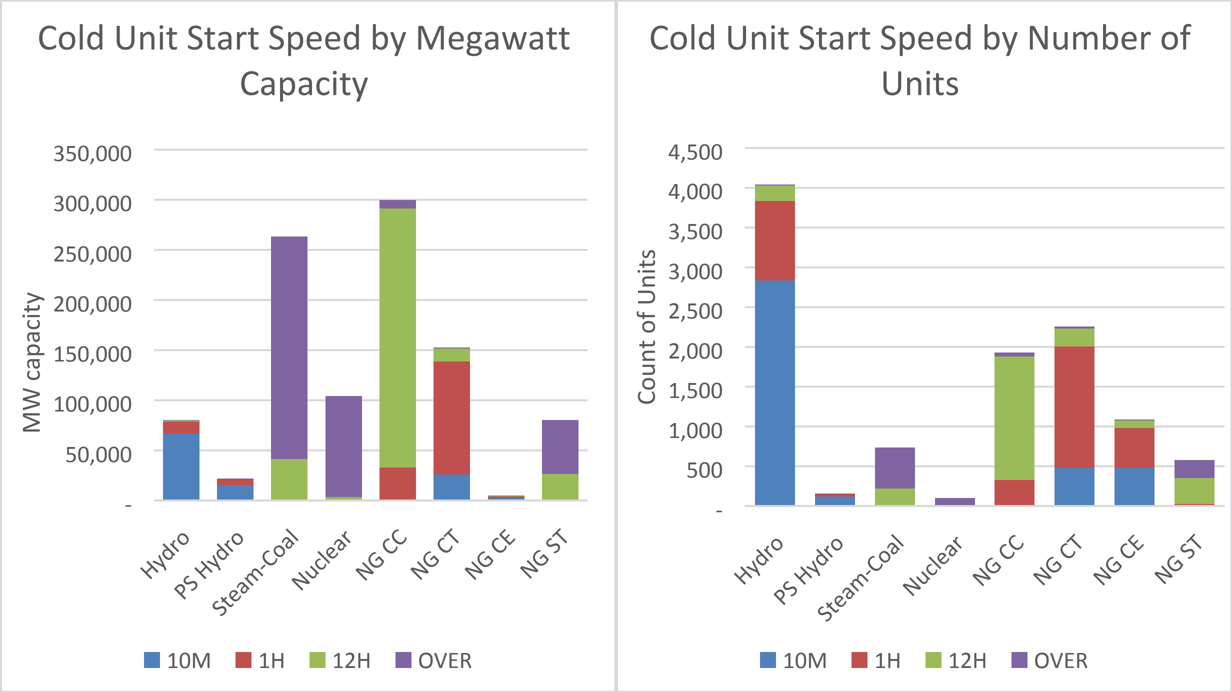

Figure 5. Cold start speeds for hydropower and natural gas generators (from EIA 860) by MW capacity (left) and unit count (right).

Though it is unclear whether these values include specific restrictions, such as the time required for human communications necessary to dispatch the units and any environmental provisions, this would hamper hydropower units more than natural gas units. Analyses of 1-minute operating data and discussion with system operators revealed that the logistical and communication requirements can take longer than the actual unit ramping at certain facilities. In addition to the ramp rate and cold start speed, the amount of reserve capacity available is dependent on the current operations of other units at the facility and the head-power-flow-efficiency curves that constrain the maximum dispatchable power for the unit.

3.1.2 Mileage Indicators

Indicators that use actual operating data must be interpreted carefully because they show only what the units were directed to do rather than what they are capable of doing. Mileage calculations describe the total movement of the mechanism and can quantify the amount of time hydropower units follow a regulation signal. Only adjustable-blade turbines, like Kaplan units, are capable of adjusting the runner blade angle to maximize the efficiency of the unit. The WGO controls flow rate and adjusts to increase or decrease the power output based on the frequency response signal provided from the governor. To capture the total RBA mileage, WGO mileage, and Power output mileage, the movement distances are described as sums of the absolute values of the differences in sequential data points. The smaller the time interval, the more accurate the result will be. Power output mileage is used by some markets such that utilities can put a cost on ramping, but utilities still lack the ability to accurately determine the cost of these ramps.

$$\mathrm{Y}_{\mathrm{RBA,dist}} = \sum_i^N |a_i - a_{i-1}| \, ,$$

$$\mathrm{Y}_{\mathrm{WGO,dist}} = \sum_i^N |y_i - y_{i-1}| \text{ , and}$$

$$\mathrm{Y}_{P,\mathrm{dist}} = \sum_i^N |P_i - P_{i-1}| \, ,$$

where N is the total number of samples, a is the RBA, y is the WGO, and P is power output. The importance of highly granular data can be shown by considering the impact of data granularity on mileage as it impacts each unit differently based on the amount of variable operation asked of the unit. Ramp events can alternatively be aggregated by the magnitude of each ramp event as shown in [24]. The results can be shown as a histogram to understand how groups of units compare with others within a utility, ISO/RTO, or with other generating types.

3.1.3 Correlation Analysis of Power Output

Correlation analysis determines the correlation between the power output of wind power farms and the power output of hydroelectric units. A strong negative correlation, as shown by [25], is indicative of a hydroelectric unit that increases power output as wind power output decreases and decreases power output as wind power output increases. A correlation analysis can determine which units the utility or balancing authority are using to firm up nondispatchable energy sources. This type of analysis can be done at the facility or unit level but can only detect historic correlations rather than predict changes to future power dispatch or capabilities.

3.1.4 Synchronous Condensing Hours and Events

Synchronous condensing operations are recorded by NERC in GADS. Utilities report both the total condensing hours and the number of condensing events. The “2017 Hydropower Market Report” [1] trends hydropower availability through GADS where condensing is one of seven operating states. Medium units, 10–100 MW, report the largest share of condensing hours on average, as seen in Figure 6. Due to the blinded nature of GADS, this is only capable of providing fleetwide trending analysis.

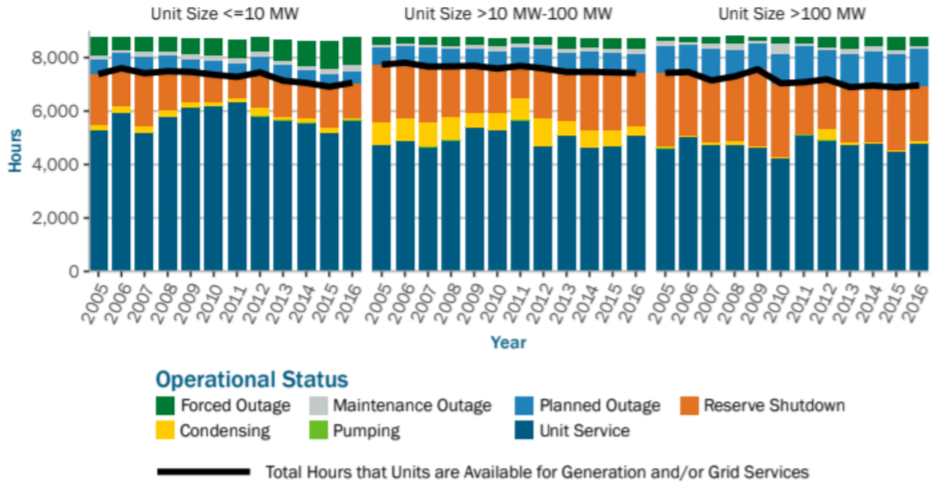

Figure 6. Availability trends in hydropower. Trends show that the greatest portion of condensing hours are logged by medium-capacity units ranging from 10–100 MW [7].

3.1.5 Black Start Testing Events

There is little data analysis available regarding the distribution of black start capabilities. Current North American Electric Reliability Corporation (NERC) guidelines require black start testing once every three years. NERC’s Generating Availability Data System (GADS), which is now mandatory reporting for all units of 20 MW or greater, records these testing events with a specific outage code. The number of units that recorded black start testing events in a three-year span, as prescribed by NERC, were summarized for the five generating types with pertinent data shown in Figure 7. When looking at a regional level it is apparent that several NERC regions report zero black start testing across all generating types, suggesting a significant data quality issue.

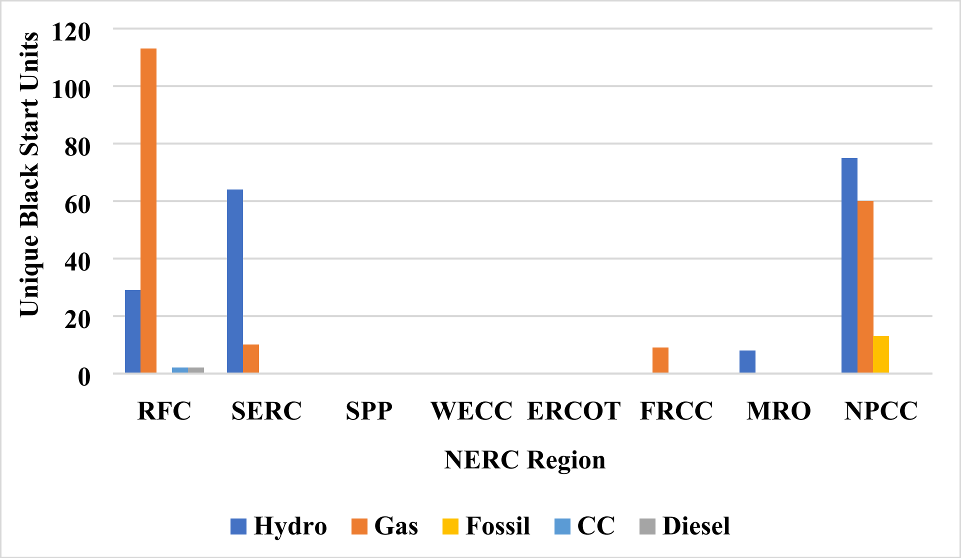

Figure 7. Distribution of black start units by NERC region.

3.2 Costs of Services Provided by Hydropower

Each service described has a cost associated with it that must be well understood to ensure profitability. Hydropower's capability to provide flexible generation, ancillary services, and grid stabilizing services allows it to provide significant value to the grid, and the value of these capabilities increases in markets with high levels of variable energy generation. However, there is also a cost to providing these services and the evolving generation mix where certain generating sources are incapable of providing specific services. The challenge of providing these services with an increased operational flexibility is to (1) quantify the accelerated degradation of components and associated infrastructure and (2) find the best practices and new technologies to both mitigate damage and increase flexibility.

The off-design conditions that occur during flexible operating modes can cause adverse effects to the systems and components of hydroelectric units, including turbines and related components; generators and related components; gates and valves; circuit breakers, switchgear, and transformers; instrumentation and controls; and other components and systems [4]. Aggressive participation in the ancillary services market could impact the repair and replacement intervals for these key components that must be accounted for in the cost equations used to bid units to the Bulk Energy System. Before participating in ancillary service markets that would significantly impact the daily load profiles of a utility's assets, the potential effects and their costs must be considered:

- Increase in asset maintenance costs due to the implementation of a shorter time interval or expectation to meet condition-based maintenance points more rapidly.
- Reduction in the asset's useful life.

- Reduction of high economic returns of current hydro project investments.
- Alteration of the rate of return on new installations.

Alternatives to high-frequency start-stop operations include the following:

- Condensing of units that are not producing electricity for the grid as a way to achieve constant “on/off” capability. Condensing would leave the machine running at speed during off periods, which would maintain operating temperatures, save bearing wear, save generator breaker wear, and keep generators dry.
- Using electronic controls hardware (like frequency conversion equipment) to achieve on/off capability.

To counter the increased degradation of flexible operations, original equipment manufacturers might consider design improvements to the turbine runner, bolting assembly, water hydrostatic bearing, and thrust bracket. Turbine redesigns could reduce the impact of low-load operation by increasing the operating range. Any design alterations that impact efficiency would have to be evaluated for economic tradeoffs. The bolting assembly could be redesigned to reduce fatigue stresses and avoid the unsticking of flanges. Redesigns to the water hydrostatic bearing and thrust bracket could decrease vibrations by increasing rigidity and stiffness.

3.2.1 Hydraulic Impacts from Flexible Operations

The hydraulic impact from flexible operations is focused on the turbine and water delivery components of the hydroelectric powertrain. Though these impacts occur during set point operation with weekly start-stops, they occur more frequently when a unit operates flexibly to meet the wide variety of ancillary services it might be capable of.

Potential impact characteristics include:

- Turbines and related components: More frequent start-stops increase vibrations and dynamic stresses. These effects reduce the fatigue life of turbines, turbine shafts, wicket gates, headcovers, and headcover bolts and increase the wear of turbine guide bearings, thrust bearings, shear pins, brakes, and wicket gates.
- Gates and valves: More frequent opening and closing leads to more frequent pressure pulsations, vibrations, and dynamic stresses. These effects potentially reduce the fatigue life of gates and valves and associated studs, bolts, shafts, actuators, penstocks, and penstock rivets and increase wear of gates and valves.

The physical phenomena and impacts stemming from partial load are well known because of industry’s previous efforts. Partial load enables increased spinning reserve capacity and greater capability to load-follow. During the sequence of transitioning to low load, power output is reduced by closing the wicked gate angle, giving a reduction in flow while the blade speed is constant that produces a swirl at the runner’s leading edge. Partial-load operation also creates the potential for “deflection,” so the mechanism links could be subject to abnormal stresses, resulting in abnormal shear pin failure.

The change in operating pattern of a turbine towards partial load could cause the occurrence of cracks within a few months or years. When operating with intermittence in such a mode, the lifetime of the equipment is decreased. To minimize and monitor the impact and preserve the fatigue lifetime, typically, some mode of operations and measures should be applied:

- ` the continuous area of operation to a band centered on optimal discharge. Currently, however, there could be a constraint because of the new grid requirements.
- Measure the mechanical load by measuring the levels of pressure pulsations.
- Measure the runner stress level using strain gauges on the runner.
- Conduct physical scaled or lab model tests.
- Conduct computational fluid dynamics modeling.

3.2.2 Mechanical Impacts of Flexible Operations

For mechanical and electrical assets, the largest contributor to degradation of the machine is due to thermal cycling induced by starts and stops. In generator assets, increased cycling leads to increased vibrations, dynamic stresses, and thermal stresses. These effects reduce the fatigue life of rotors, stators, end windings, spider arms, and support brackets; increase the wear of generator guide bearings, thrust bearings, and generator cooling systems; and increase the probability of insulation failure.

For electrical assets such as circuit breakers, switchgear, and transformers, the increased cycling leads to increased vibrations, dynamic stresses, and thermal stresses that reduce the life of the asset. For instrumentation and controls assets, the increased cycling leads to increased vibrations. These effects potentially reduce the life of instrumentation and controls.

3.3 Data Gathering Initiatives

Data gathering for assessing capabilities and constraints of the current hydroelectric fleet would require a comprehensive multipronged effort. This process is benefiting significantly from efforts being undertaken as part of Oak Ridge National Laboratory's Hydropower Fleet Intelligence project to harmonize availability, cost, and condition data from industry level databases. The additional effort required would be an incorporation of FERC license information and actual installed technology, which would likely require direct utility correspondence. Though several data availability gaps were discussed, it is a slow process to add additional fields at the consortia level.

- **Availability data** can most readily be obtained from individual sources because of the blinded nature of NERC GADS data and the difficulty of extracting information through their in-house software. This effort is to include time spent in variable operational modes in addition to RBA, WGO, flow, spill, reservoir elevation, and efficiency data. Black start and condensing operations are to be incorporated as well. Using large amounts of historical timeseries data, it is possible to reconstruct operational rules for flow and reservoir elevation that come from FERC license information.

- **Cost data** is currently well structured by the EUCG-HPC, though access is limited unless obtained directly from the utility. ORNL’s current relationship with the EUCG-HPC enables data access for analytics used in the delivery of an annual report, though utility and facility names are blinded. The importance of cost data is in the insights it can give to the cost of variable operations that enable the provision of services discussed within this document.
- **Condition data** across the industry varies in format, though with the USBR and the US Army Corps of Engineers using the hydroAMP methodology, it has a significant advantage over other forms based solely on sample size. Others within the industry have referenced the hydroAMP methodology when developing their own condition indexing methodologies, though not all use a 0–10 scale, which can make data harmonization complicated.
- **FERC license information** on flow and reservoir constraints will provide operational constraints to specific capabilities. As mentioned previously, the most easily interpreted are those governing ramp rates, flow rates, and reservoir elevations.
- **Installed technology** levels will be difficult to assess. Though GADS, hydroAMP, and EUCG each have specific design data fields, there is little harmonization among them. Key technology upgrades are necessary if a facility or unit is to provide AGC, synchronous condensing, or black start capabilities. A disconnect appears because the current design data fields are meant to provide additional criteria for benchmarking purposes rather than to predict future capabilities.

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