# Environmental, Economic, and Social Trade-Offs of Hydropower Relicensing: A Case Study of the Yuba River Development Project

by

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# Contents:

## Abbreviations:

| | |
|---|---|
| ALP | Alternative Licensing Process |
| AS | Ancillary Services |
| CABY | Cosumnes, American, Bear, and Yuba Rivers |
| CAISO | California Independent System Operator |
| ECPA | Electric Consumers Protection Act |
| FERC | Federal Energy Regulatory Commission |
| FLA | Final License Application |
| FPA | Federal Power Act |
| GW | Gigawatt |
| ILP | Integrated Licensing Process |
| IPCC | Intergovernmental Panel on Climate Change |
| LMP | Locational Marginal Price (energy price, $/MWh) |
| MW | Megawatt |
| MWh | Megawatt- hour |
| NBB | New Bullards Bar |
| NGCC | Natural Gas Combined Cycle |
| SCC | Social Cost of Carbon Dioxide |
| SONGS | San Onofre Nuclear Generating Station |
| TLP | Traditional Licensing Process |
| TW | Terawatt |
| WYT | Water Year Type |
| YRDP | Yuba River Development Project |
| YCWA | Yuba County Water Agency |

# 1. Introduction

## *1.1. Background*

In 2014, the United States Department of Energy (DOE) Water Power Program initiated the development of a long-range hydropower vision, which seeks to understand and address the challenges to achieving higher levels of hydropower deployment in the United States. (U.S. DOE, 2014). In California, recent policy such as California Assembly Bill 32 have placed an emphasis on developing and maintaining hydropower in order to curb greenhouse gas (GHG) emissions and sustain developed energy sources (Viers, 2011). Despite providing low-cost, flexible, low-carbon electricity, large-scale hydropower is widely criticized for causing environmental and social harms, such as damaged wildlife habitat, impaired water quality, impeded fish migration, reduced sediment transport, and diminished cultural, aesthetic, and recreation benefits of rivers (Poff et al., 1997; Bunn & Arthington, 2002; Koch, 2002). It has been demonstrated that the environmental and social impacts of large hydropower can, to some extent, be alleviated through management and operational requirements (Leimbach, 2009). However, environmentally protective operating requirements come at a cost to the hydropower operator by reducing electric generation and therefore revenue (Rheinheimer et. al, 2013, Madani & Lund, 2010). Thus, the objectives of a hydropower operator may, at times, be in direct conflict with the objectives of social and environmental interest groups. *This conflict raises the question of how the DOE "hydropower vision" objectives may be translated into policy, and ultimately how large hydropower can be managed to become an environmentally sustainable and socially acceptable source of electricity in the United States*.

In a 2016 New York Times editorial, Senator Lisa Murkowski (R-AK) argued fervently for changes to increase the U.S. hydropower capacity. Murkowski called the FERC permitting process "broken," and suggested that relicensing delays and roadblocks are compounded by environmental groups that have "remarkably outdated views of hydropower and its benefits" (Murkowski, 2016). Murkowski calls for a more efficient, streamlined relicensing process to unlock the potential of American hydropower. However, Senator Murkowski's proposed "Hydropower Improvement Act" (S 1236) has caused great controversy among environmental and social groups. American Rivers has called the bill a "hydropower grab" that would "create massive loopholes for hydropower dam operations that would take us back to a time when dam owners could destroy rivers without concern" (American Rivers, 2016). This ongoing debate suggests that social conflict around hydropower operations and management is alive and strong in the United States today.

As of the end of 2014, there was approximately 78.8 Gigawatts (GW) of hydropower capacity installed in the United States (EIA, 2014), representing about 7% of U.S. installed electricity generating capacity. Of this installed capacity, about 24 GW (30%) are operated by federal government agencies such as the Bureau of Reclamation and the Army Corps of Engineers (FERC, 2016). The remaining 54.8 GW are owned and operated by the private sector, public utilities, and state or local governments (FERC, 2016; NHA, 2016). The Federal Power Act (FPA) made the Federal Energy Regulatory Commission (FERC) responsible for licensing and regulation of all non-federal hydropower operations. As of April, 2016, FERC currently manages over 1,030 active hydropower licenses spanning 47 U.S. states. (FERC, 2016).

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*1.2. Hydropower Relicensing:*

FERC hydropower licenses regulate how non-federal hydropower projects in the U.S. will be constructed, operated, maintained, and decommissioned. FERC hydropower licenses determine how to allocate river flows between energy generation and other beneficial uses recognized by the Federal Power Act (FPA), National Environmental Policy Act (NEPA), Endangered Species Act, Clean Water Act, Wild and Scenic Rivers Act, and other applicable laws (HRC, 2016a). These licenses, however, do not last forever; original hydropower licenses authorize construction of the project and operation for a term of up to 50 years. Five years before the current license expires, the licensee may apply for a new 30-50 year operating license through a process known as *relicensing* (FERC, 2010; HRC, 2016a). The relicensing process allows FERC, state and federal resource agencies, environmental advocacy groups, and the general public to reconsider appropriate hydropower operations and management for each project, accounting for current social, cultural, environmental, and economic concerns (HRC, 2016a). Relicensing is thus seen as a “once in a lifetime” opportunity for resource agencies, environmental groups, and other stakeholders to restore rivers, enhance the environment, and improve recreational opportunities through operating requirements under the new license. In short, it is through this relicensing process that FERC evaluates the expected future costs and benefits of a non-federal hydropower project over a term of 30-50 years.

Under the Electric Consumers Protection Act (ECPA) of 1986, FERC was given a mandate to give "equal consideration" to electric power generation, protection of fish and wildlife, environmental quality, and "other beneficial public uses, including irrigation, flood control, water supply, recreational, and other purposes" (ECPA, 1986). This mandate requires FERC to consult with federal, state, and local agencies to assess the impact of a hydropower project on these environmental and public-benefit objectives (ECPA, 1986). As such, the relicensing process must engage a wide array of stakeholders with disparate and seemingly irreconcilable objectives.

Unsurprisingly, hydropower relicensing negotiations in the U.S. have been rife with conflict between state and federal governments, tribes, environmental groups, hydropower operators, and other parties (see, for example, Gowan et al., 2006; Richardson, 2000; McCann, 2005; Burkardt et al., 1998; Clarke, 1997). Navigating these conflicts to find a social, environmental, and economic optimum has not proven to be a simple task for FERC. Frans Koch (2002) summarized the social, environmental, economic, and technical complications of hydropower relicensing: "There is no obvious way to arbitrate among the claims of persons who are positively and negatively affected by hydro projects, and among the economic and environmental benefits of a project versus adverse social and environmental impacts" (Koch, 2002, p. 1211). Nonetheless, we rely on FERC as an arbiter and ultimate decision maker in hydropower management.

Until recently, hydropower projects were relicensed under a formal Traditional Licensing Process (TLP), in which a hydropower operator develops an application for a new license and submits it to FERC. After this point, resource agencies, tribes, and the public were allowed to comment on the application and the environmental assessments. This segregated process led to significant delays and stakeholder conflicts. These delays and conflicts, along with the "equal consideration" for environment and public benefits clause of the ECPA, led FERC to increase the potential for stakeholder collaboration in the pre-application stages of relicensing. In 1992, FERC introduced the Alternative Licensing Process (ALP), under which the licensee commits to work collaboratively with stakeholders to develop an impact assessment study plan, and to negotiate a settlement that will become the basis for the license application. The ALP thus created incentives for stakeholders to collaboratively resolve disputes about the license application, and did tend to reduce the costs of relicensing. However, the ALP did not alleviate the lengthy relicensing times under the TLP, which were sometimes over 10 years (Ulibarri, 2015).

In an effort to identify and resolve conflicts early in the relicensing process, provide structured deadlines for all participants, and alleviate relicensing delays, FERC introduced the Integrated Licensing Process (ILP) in July of 2003 (FERC, 2012). The ILP was designed to be a more collaborative process between FERC, licensees, resource agencies, Tribes, NGOs, and other stakeholders (FERC, 2012). The result, according to the Hydropower Reform Coalition, "offers more opportunities for public participation with very tight deadlines, especially in the initial information-gathering stages of the process" (HRC, 2016b). The ILP became FERC's default hydropower licensing process in July, 2005 (FERC, 2012). Through a number of relicensing case studies, Avinash Kar (2004) showed that the collaborative approach utilized in the ILP avoids confrontation, improves the quality and relevance of environmental studies, is less time- and resource-intensive, improves the potential for long term collaboration, and enables more informed choices, in general (Kar, 2004). In 2009, even President Obama iterated the value of collaborative governance by issuing a directive for all federal agencies to "cooperate among themselves, across all levels of Government, and with nonprofit organizations, businesses, and individuals in the private sector. Executive departments and agencies should solicit public feedback to assess and improve their level of collaboration and to identify new opportunities for cooperation" (Obama, 2009).

While most stakeholders agree that the more collaborative ILP is much improved over the former "Traditional Licensing Process," there remain a number of shortcomings in the depth and breadth of analyses undertaken in the ILP, which weaken the ability of the process to achieve the best possible outcome. Addressing these shortcomings is important, because they affect the perception of *fairness* in the planning process. Social scientists have correlated perceived fairness with higher levels of planning success and lower levels of social conflict, while processes perceived as unfair are more likely to result in damaged relationships and divided communities (Wüstenhagen et al., 2007).

Some shortcomings of the ILP, as identified by relicensing participants, include:

(1) Although FERC is required to equally consider revenue impacts and other beneficial public uses under the EPCA, analyses of the impacts of alternative operating conditions on generation and revenue are typically very coarse. These analyses do not account for all potential

revenue streams in complex, deregulated electricity markets (i.e. day-ahead energy market, spot energy market, capacity market, and ancillary services market). Moreover, these analyses of generation and revenue are not conducted in a manner that is transparent to participants, and are seen as a "black box" by some stakeholders (Dave Steindorf, personal communication, 2015).

(2) Hydropower licensees and FERC do not examine how the impacts of environmental operating requirements on hydropower generation and revenue vary by Water Year Type (WYT). WYT is defined by runoff in the current year compared to average historical runoff, with thresholds categorizing dry, normal, and wet years. WYT indices are helpful to understand flow parameters and ecological conditions with varying water availability, and are often used to guide water operations (Null & Viers, 2013). In California, water allocations are largely based on WYT; analyses of different hydropower operating regimes should therefore examine impacts by WYT.

(3) FERC explicitly refuses to analyze the impacts of climate change on hydrology, electric generation, and environmental conditions around a hydropower project in the relicensing process (Viers, 2011).

(4) Ecosystem services and social benefits are difficult to quantify in terms comparable with economic benefits (i.e. hydropower revenues), and therefore may be given less weight in policy decisions (Gowan et al., 2006).

(5) Potential greenhouse gas (GHG) impacts of reduced hydropower generation due to environmentally protective operational requirements are not quantified at any point in the relicensing process.

(6) Under the federal relicensing process, projects are licensed in isolation of other hydropower systems and downstream users that are hydrologically connected. There is room for more coordination among stakeholders to reduce impacts on downstream hydropower systems, drinking and irrigation water providers, ecosystem maintenance, and other needs (Viers, 2011).

(7) There is little to no possibility for "adaptive management" of hydropower operations to account for changing environmental, social, or climatic conditions over the course of a 30-50 year license. Viers (2011, p. 659), for example, suggested that "fixed long-term licenses are not in the public's best interest and a more frequent review of license conditions is warranted."

Given the federal and state-level goals to maintain (or even increase) the U.S. deployed hydropower capacity, the range and severity of potential social and environmental impacts of hydropower, and the fact that operating requirements of such projects are re-examined only once every 30-50 years, it is imperative to develop a thorough understanding of the economic, environmental, and social trade-offs of hydropower operations. Moreover, a deeper analysis of these gaps will aid FERC, the hydropower licensee, and environmental agencies to reach a more sustainable, socially acceptable, and efficient outcome in the relicensing process.

In this study, I use a case-study of a hydropower project undergoing relicensing and examine the impacts of environmental operating requirements, climate change, and potential GHG emissions in order to understand these trade-offs and illustrate how such analyses could affect relicensing decisions.

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*1.3. Case Study: The Yuba River Development Project*

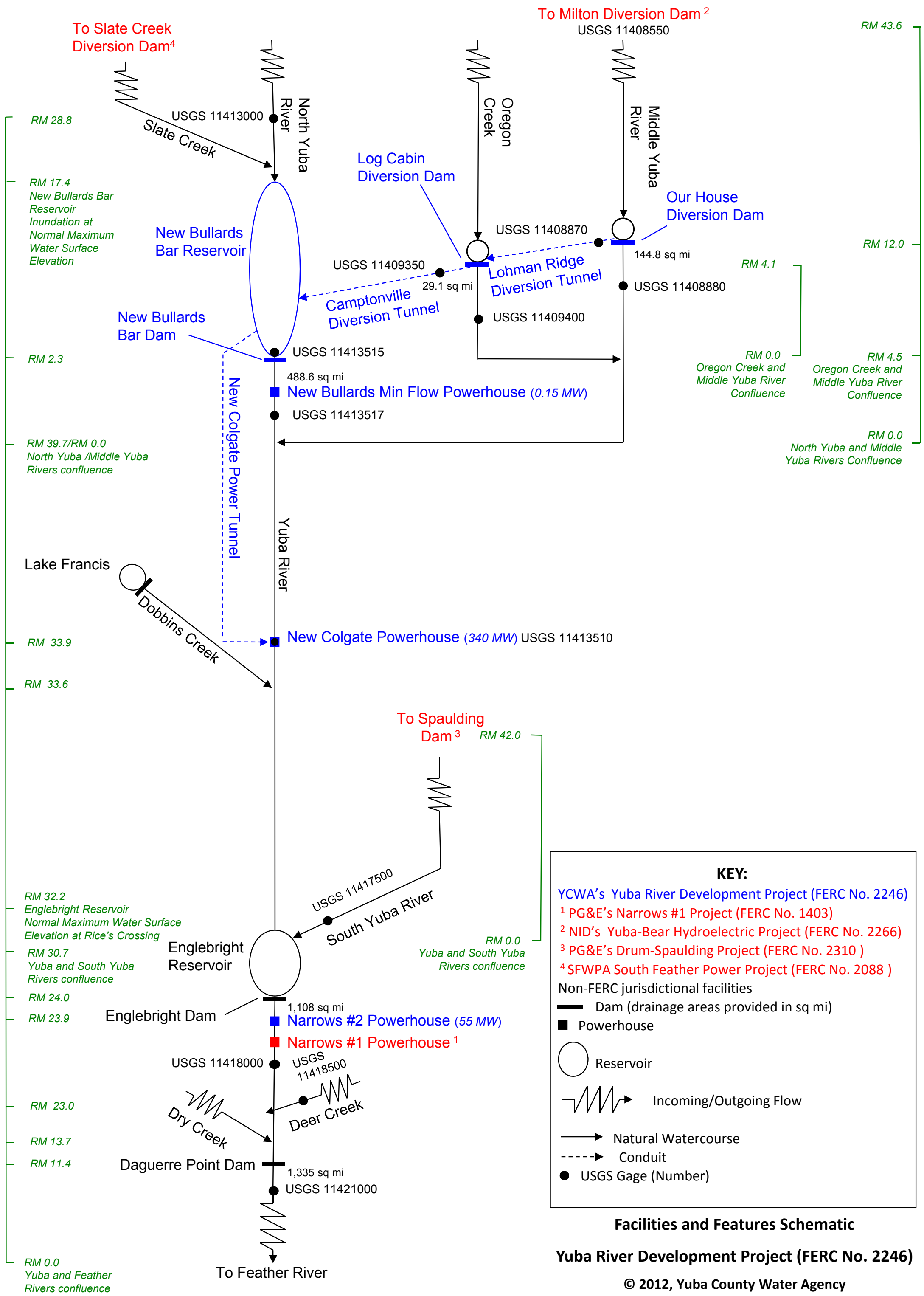
The Yuba River Development Project (YRDP) is a large hydropower project located on the Yuba River, Middle Yuba River, and Oregon Creek in California. The project consists of one reservoir, two diversion dams, and three powerhouses, with a total installed power capacity of 361.9 megawatts (MW). The initial Federal Energy Regulatory Commission (FERC) license for the YRDP expired on April 30, 2016. The Yuba County Water Agency (YCWA), the licensee of the project, has expressed a goal to "obtain a new license of maximum term for the Project at a minimum cost… that allows the Project to maximize profits from the production of electrical power while also meeting environmental, recreational, irrigation and other non-power requirements." (YCWA, 2016)

The YRDP is used primarily for "peaking" generation, meaning it is not operated as a baseload power plant (YCWA, 2016). Instead, it provides fast ramping capacity both up and down to help ensure that electrical supply meets demand in California's power system. In addition to this load-following generation, the main powerhouse is co-optimized to provide grid-regulating *ancillary services*. Ancillary services (AS) provide flexible capacity to even out any imbalances between energy supply and demand in order to maintain stability of the electric power system (MacDonald et. al, 2012). AS provided by the YRDP include "regulation up," "regulation down," and "spinning reserve." Regulation up is generating capacity that is reserved to increase generation when needed to balance the system (requiring the YRDP to have headroom between its actual energy generation and its total capacity). Regulation down is capacity that can be called on to rapidly decrease generation when needed to balance the system.

Spinning reserve is capacity that can be called on during contingency events to increase generation (CAISO, 2009). Regulation up and down regularly result in changes in the generation of the hydro plant under normal conditions, whereas capacity that is providing spinning reserve is called on much more infrequently. The prices for the ancillary services depend in part on the opportunity cost of reserving capacity that could otherwise be used to provide energy (CAISO, 2009). AS revenues can be significant for hydropower projects. The YCWA estimates that AS revenue may increase total project revenue by up to 24% during certain years (YCWA, 2016).

A schematic of the YRDP illustrating the main project features is shown in Figure 1.1. Important features of note are the New Bullards Bar (NBB) Dam and reservoir, the New Colgate Powerhouse, Our House Dam on the Middle Yuba, Log Cabin Dam on Oregon Creek, and their respective diversion tunnels, which convey water from the Middle Yuba and Oregon Creek into the NBB reservoir.

*Figure 1.1: Yuba River Development Project Facilities and Features Schematic (YRDP, 2012)*



Through the formalized structure of the ILP, the relicensing of the YRDP has engaged over 60 agencies and groups, including Federal agencies, State agencies, City and County governments, NGOs and Environmental groups, Native American Tribes, Businesses, and Water Districts. Table 1.1 displays the full range of agencies and organizations that have formally engaged in the relicensing process of the YRDP (YCWA, 2016). A subset of these have actively participated in negotiations of the new license and operating requirements of the YRDP.

*Table 1.1: Organizations, Groups, and Agencies involved in YRDP relicensing (YCWA, 2016).*

| NGOs / Envi. | Federal Agency | State Agency | Water Districts | Tribes | City / County | Businesses |
|---|---|---|---|---|---|---|
| American Rivers | Fed. Emergency Mgmt. Agency | Bay-Delta Authority | South Yuba Water Dist. | Maidu | City of Marysville | Pacific Gas & Electric |
| American Whitewater | National Park Service | CA Dept. of Boating & Waterways | Browns Val. Irrigation Dist. | Washoe | Nevada County | Emerald Cove Marina |
| CA Hydropower Reform Coalition | National Marine Fisheries Service | CA Department of Fish and Game | Brophy Water Dist. | Mechoodpa | Sierra County | |
| CA Sportfishing Protection Alliance | US Forest Service | CA Department of Forestry & Fire Protection | Dry Creek Water Co. | Miwok | Yuba County | |
| CA Trout | US Army Corps of Engineers | CA Department of Parks and Rec. | Hallwood Irrigation Co. | | | |
| Comptonville Community Partnership | Bureau of Indian Affairs | Central Valley Reg.Water Quality Control Board | Ramirez Water Dist. | | | |
| Environmental Defense Fund | Bureau of Land Management | Native American Heritage Comm. | Wheatland Water Dist. | | | |
| Federation of Fly Fishers | US Fish and Wildlife Service | Sierra Nevada Conservancy | Nevada Cty Irrigation Dist. | | | |
| Foothills Water Network | US Geological Survey | State Water Res. Control Board | Placer County Water Dist. | | | |
| Friends of the River | Federal Energy Reg. Comm. | CA Department of Water Resources | Cordua Cty Irrigation Dist. | | | |
| Natural Heritage Institute | | | | | | |
| Sierra Club | | | | | | |
| Sierra Nevada Alliance | | | | | | |
| South Yuba Riv. Citizen's League | | | | | | |
| Trout Unlimited | | | | | | |
| Yuba Watershed Council | | | | | | |
| Gold Country Flyfishers | | | | | | |
| Save Sierra Salmon | | | | | | |
| Social Alliance Network | | | | | | |
| Environmental Advocates | | | | | | |

The subset of active relicensing participants taking part in ILP negotiations is made up of state and federal resource agencies like California Fish and Wildlife and the USDA Forest Service alongside environmental and social interest groups such as American Rivers, South Yuba River Citizen's League, California Sportfishing Protection Alliance, and American Whitewater. In addition to submitting requests for improved studies of environmental, social, and recreational impacts of the new YRDP license, this subset, henceforth referred to as the "environmental coalition," developed an alternative proposal of operating conditions and constraints for the YRDP for FERC to consider alongside the licensee's Final License Application (FLA). The environmental coalition's recommendations are centered around operating conditions that will more closely mimic the "natural hydrograph"[1] of the North Fork Yuba River, Middle Fork Yuba River, and Oregon Creek.

The environmental coalition's hydropower operations proposal represents a significant shift away from normal operations, which have prioritized water for hydropower generation when it is most valuable. The YCWA's FLA does make some small concessions for increased minimum required instream flows compared to historical operations, but the environmental proposal includes improved year-round minimum instream flows to provide habitat for native species, periodic high-flow events for sediment transport, periodic flows for whitewater recreation, and restrictions on the recession rate of spill events when water must be released for flood control. These conditions apply to the North Fork Yuba River below the NBB dam, the Middle Fork Yuba River below Our House Dam, and Oregon Creek below Log Cabin dam.

In negotiating for improved operational requirements and environmental flows, it is important for relicensing participants and stakeholders to understand the specific and detailed costs and trade-offs associated with the various hydropower operating regimes. During the relicensing process, impacts on electricity generation and project revenue are typically described to stakeholders and participants coarsely – sometimes only in the form of annual generation. Using the metric of annual generation homogenizes generation (and economic value) into a single number that bears little resemblance to the actual power products sold into electricity markets in California. Using a case-study to examine the impacts of environmentally protective

[1] See Section 2 for more detail about the natural flow regime and how it can be mimicked via hydropower operations. According to Poff, et al., "Flow regime is of central importance in sustaining the ecological integrity of flowing water systems. The five components of the flow regime - magnitude, frequency, duration, timing, and rate of change - influence integrity both directly and indirectly, through their effects on other primary regulators of integrity. Modification of flow thus has cascading effects on the ecological integrity of rivers" (Poff, et al., 1997).

hydropower operations on a single hydropower project allows for a much more detailed analysis of specific market and non-market impacts, including: hourly electricity generation and revenue, hourly ancillary services provision and revenue, greenhouse gas emissions, environmental services, recreation, and more. Such detail allows for greater transparency among all reclicensing participants, increasing the chances for a more optimal social, environmental, and economic outcome.

In this analysis, I examine the impacts of an environmental hydropower operation regime developed by resource agencies (i.e. California Department of Fish and Wildlife, the USDA Forest Service, and the US Fish and Wildlife Service) and other NGO stakeholder groups (henceforth called the "environmental operation regime") when compared to the YRDP Base Case (recent operations overlaid on historic hydrology) scenario, and the YCWA's Final License Application (FLA) flow proposal (which included some proposed changes to minimum instream flows and spill recessions rates compared to Base Case).

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The rest of this paper is structured as follows: In Section 2, I discuss some of the *environmental and social impacts* of large hydropower projects, and the methods employed to alleviate these impacts. Section 3 describes the *methods* used in this study. In Section 4, I quantify the *lost revenue* (in dollars) and *reduced electricity generation* (in MWh) of the environmental proposal. In addition, I examine the impact of the environmental proposal on the licensee's *provision of capacity in the ancillary services market*. In Section 5, I demonstrate the *greenhouse gas impacts* of reduced hydropower generation which results in increased natural gas generation, calculate the social cost of carbon associated with these emissions, and discuss impacts to the California electricity market. Next, in Section 6, I break down the revenue and generation impacts of environmentally protective flow regimes by *Water Year Type (WYT)* in order to understand how water availability affects the hydropower operator's ability and costs of environmental management. In Section 7, I examine how *climate-change induced hydrological change* will affect hydropower generation, revenue, and provision of ancillary services over the next 50-100 years. Section 8 is a *discussion of implications and limitations* of these findings, and Section 9 presents a summary of key findings and concluding remarks.

# 2. Review of Environmental & Social Impacts of Large Hydropower

## *2.1. Background*

Large hydropower projects offer important benefits such as low-cost, low carbon electricity generation, but they also incur significant environmental and social costs. The implementation of the ILP encourages negotiation of hydropower operational requirements in order to mitigate the adverse effects of hydropower. This section will provide an overview of some of those impacts and the methods employed to alleviate them, such as hydropower operational requirements (i.e. minimum instream flows and ramping rate restrictions) or dam removal.

Although the majority of analysis in this paper is structured as economic cost-benefit analysis, there are currently no suitable monetary measures to quantify the ecosystem or social benefits of environmentally protective hydropower operations (Niu & Insley, 2013). Gowan, et al., (2006), however, suggest that ecosystem valuation techniques are rarely employed in decision-making around hydropower relicensing or dam removal. Instead, the authors state, "participants are willing and able to weigh ecosystem services against market outcomes ... without the aid of ecosystem valuation." (Gowan et al., 2006, p. 521). My goal in presenting the environmental and social impacts of hydropower in this section is to help the reader understand the true costs of these tradeoffs, even if they cannot be compared "dollar for dollar" with reduced hydropower revenues.

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## *2.2. Environmental Impacts of Hydropower*

Hydropower systems adversely impact river ecosystems in a number of ways, including:

1. Alteration of the downstream flux of water and sediment, which affects biogeochemical cycles as well as aquatic and riparian habitats (Poff & Hart, 2002). In addition to depriving downstream areas of water and sediment, these changes can also create conditions of scour and incision in the river bed (Viers, 2011).

2. Impaired water quality – primarily by changing water temperatures downstream of dams. Dams may also affect dissolved oxygen and nutrient levels in river systems. These impacts negatively affect the health and survival of downstream biota (Poff & Hart, 2002).

3. Creation of barriers to upstream and downstream migration of organisms – which is particularly important for anadromous fish such as Chinook Salmon, Coho Salmon, and Steelhead trout (Poff & Hart, 2002; Raymond, 1979).

4. Alteration of the timing, magnitude, frequency, duration, and rate of change of natural river systems (i.e. the natural flow regime). A large and growing body of literature shows that the natural flow regime of virtually all rivers is highly variable, and that this variability is critical to ecosystem function and biodiversity (Poff, et al., 1997). Hydropower systems can drastically reduce and homogenize this variability, causing a range of negative impacts on river ecology and biodiversity (Poff et al., 2007).

The Yuba river watershed, home to the YRDP, is an important habitat for a wide variety of plant and wildlife species. According to the Integrated Regional Water Management Plan for the Cosumnes, American, Bear, and Yuba (CABY) watersheds, "the region supports 121 species and nine habitats of special concern. Sensitive, threatened, and endangered wildlife species include the peregrine falcon, bald eagle, golden eagle, long-horn beetle, foothill yellow-legged frog, river otter, Townsend big-eared bat, and more than 86 butterfly species. There are several sensitive, threatened, and endangered plants in the region" (CABY, 2013). The YRDP, being a large hydropower project, does incur all of the environmental costs described above, and faces significant pressure from environmental groups and resource agencies to alleviate these impacts through operational changes.

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### *2.3. Social and Recreational Impacts of Hydropower*

Hydropower projects can create a range of social benefits, such as low-cost electricity, irrigation, flood control, job creation, and tourist and recreation facilities (Koch, 2002). But these projects can also cause a range of negative social impacts, including:

1. Forced displacement of people when reservoirs are filled (Tilt et al., 2009), however this effect is more pertinent for new dam construction rather than relicensing.

2. Damage to fisheries used for human diet (Stillwater Sciences, 2006).

3. Diminished scenic integrity due to dams, reservoirs, transmission lines, roads, etc. (Stillwater Sciences, 2006).

4. Disturbance or destruction of cultural resources (Stillwater Sciences, 2006).

5. Diminished river recreation – whether it is in the form of swimming, boating, fishing or wading, due to reduced water levels (Stillwater Sciences, 2006). Indeed, in the case of whitewater recreation, the same river characteristics that boaters find desirable for recreation also often make good locations for hydropower (Ligare et al., 2012).

Recreation is an important beneficial use of rivers, and therefore must be recognized and given consideration in relicensing under ECPA requirements. However, because they are not quantifiable in market terms, recreation benefits can be difficult to convey in cost benefit analysis (Ligare et al., 2012). Some economic valuation studies, however, have shown that the public places a high value on instream flows for recreation and aesthetics, and that minimum instream flow regimes often allocate far less than the optimum amount of water to instream uses (Loomis, 1998).

Many rivers in the Sierra Nevada, including the Yuba, are heavily regulated for hydropower production. This results in low-flows and/or bypassed stretches of river that are only suitable for recreation during spill events or mandated recreational releases. Through the relicensing process, flow regimes are increasingly examined for their effects on recreation, and hydropower projects are relied on to meet demand for recreation (Ligare et al., 2012).

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*2.4. Methods and Mechanisms to Alleviate Environmental and Social Impacts*

In many cases, the mechanisms to alleviate environmental impairments compliment the mechanisms to alleviate social impairments from hydropower projects. In other words, a flow regime that benefits downstream ecological conditions may also be a favored flow regime for social benefits. Unsurprisingly, the preferred flow regime for both environmental and social benefits is the natural flow regime. This was shown nearly 30 years ago in a landmark study of willingness to pay for flow regimes from the Glen Canyon Dam that would protect the natural resources and provide better recreation opportunities in the Grand Canyon. The results showed strong support for the natural flow regime, both for recreation and for endangered fish, vegetation, and birds that were negatively affected by hydropower operations (Bishop et al., 1989).

Poff et al. recommend incorporating five components of the natural flow regime (magnitude, frequency, duration, timing, and rate of change) into a framework for ecosystem management, instead of focusing merely on minimum instream flows and just a few key species

(Poff et al., 1997). Environmental groups and resource agencies are increasingly using the natural flow regime paradigm in their recommendations to FERC through the ILP.

Resource agencies and NGOs have become interested in assessing how hydropower operations affect recreation, and studies of flows-recreation relationships have become commonplace in FERC relicensing proceedings (Whittaker et al., 2005). In the case of the YRDP, environmental and resource agencies such as the California Department of Fish and Wildlife have collaborated with recreational organizations such as American Whitewater and the California Sportfishing Protection Alliance to create a unified hydropower operations proposal that more closely mimics the natural flow regimes of the North Fork Yuba, Middle Fork Yuba, and Oregon Creek. This proposal calls for improved year-round minimum instream flows to provide habitat for native species, periodic high-flow events for sediment transport, periodic flows for whitewater recreation, restrictions on the recession rate of spill events, and the closing of the two diversion tunnels from Oregon Creek and the Middle Yuba River during especially wet years. All of these recommendations are in accordance with the natural flow regime.

In general, it is clear that the collaborative process of the ILP offers the potential to alleviate some of the negative environmental and social impacts of hydropower. Poff et al. (2003) emphasize the need for partnerships and collaboration among scientists, managers, and other stakeholders in order to address conflicts between ecosystem and human uses of fresh water. Reducing the impacts and recognizing the multiple needs and benefits of rivers as a public good will require regulators to truly consider ecosystem health, sustainability, and social welfare equally alongside energy generation when determining hydropower operating conditions.

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## 3. Analysis Methods

*3.1. Methods to Analyze Revenue and Generation Impacts of Environmental Flows*

The primary analysis for this study was conducted using a generation post-processing model, which was developed by the licensee, YCWA, as a required component of their Final License Application in order to model future hydropower generation and revenue. Before running the post-processing model, each hydropower regime was developed using the licensee's operations model. The operations model is a tool developed during FERC relicensing that includes minimum instream flows, ramping rates, required reservoir elevations, downstream requirements, water diversions, water year types, and input hydrology along with a very complex set of operating requirements to iteratively determine a solution for how much water will be stored or released at each node on each day in the system during the period of hydrologic record.

The resulting output from the operations model – henceforth called an "operating regime" – is input into the post processor in order to model hydropower generation and revenue. The post-processor uses the operating regime as a set of constraints as it iterates across the historical water resource data and electricity prices based on the time of day in order to allocate water for hydropower generation. Both the generation post-processor and the operations model were constructed in Microsoft Excel, using Visual Basic Macros to run extensive scripts.

Historical water resource data was analyzed for 39 years: 1971 – 2009. This period included a wide variation in water year types – from "wet" to "extreme critical dry", but ends before the historic drought of water year 2011 through the present.

Electricity prices were drawn from the CAISO Oasis system of electricity data for the state of California. In order to smooth out annual variation in wholesale electricity prices, hourly price data was drawn for three years (2010-2012). Each hour was averaged across the three years to produce a three-year average hourly price for every hour of the year. Hourly prices were retrieved for (1) Day-Ahead Energy (locational marginal price [LMP]), (2) Regulation Down, (3) Regulation Up, and (4) Spinning Reserve.

Day-ahead energy is the hourly schedule of energy generation, determined in the day ahead of actual dispatch. Regulation down is capacity that can be called on to rapidly decrease generation when needed to balance the system. Spinning reserve is capacity that can be called on during contingency events to increase generation (CAISO, 2009). Regulation up and down regularly result in changes in the generation of the hydro plant under normal conditions, whereas capacity that is providing spinning reserve is called on much more infrequently. The prices for the ancillary services depend in part on the opportunity cost of reserving capacity that could otherwise be used to provide energy (CAISO, 2009).

In addition to examining prices and hydropower revenues by hour, day, month, or year, the model also allows set parameters for peak, partial peak, off peak, and super off peak hours during summer and winter periods. These parameters are displayed in Table 3.1, however no analysis was done with respect to peak or off-peak pricing and revenue.

*Table 3.1: Peak and Off-Peak Hour Parameters Used for Model Runs*

| ***Period*** | **Summer** | | **Winter** | |
|---|---|---|---|---|
| *Month Start:* | May | | November | |
| | Morning | Evening | Morning | Evening |
| *Peak Hour:* | | 12:00 PM | | |
| *Partial Peak Hour:* | 8:30 AM | 6:00 PM | 8:30 AM | 12:00 PM |
| *Off Peak Hour:* | 5:00 AM | 9:30 PM | 5:00 AM | 9:30 PM |
| *Super Off-Peak Hour:* | 1:00 AM | | 1:00 AM | |

Other parameters of the model model were (1) Maximum hourly generation (MW), (2) Maximum hourly ancillary services provision (MW), and (3) Maximum water flow release from Colgate powerhouse (cubic feet per second [cfs]). Maximum hourly generation was set to 340 MW, the rated capacity of the New Colgate Powerhouse. Maximum hourly ancillary services was set to 60 MW – the default setting determined by the YCWA. Maximum water flow release from Colgate powerhouse was set to 3,430 cfs, which is constrained by the 15-foot diameter penstock leading into the powerhouse. These parameters were held constant for all model runs.

The post processor model is designed to take the available water (under the constraints of the operating regime), and allocate that water in order to optimize for total revenue. The model can also be set to optimize for electricity generation revenue or ancillary services revenue only. For the present analysis, the model was set to optimize for total revenue for all model runs so that full impacts could be examined. One important limitation of the post processor model is that it does not account for water that leaves the system when CAISO "calls-up" AS capacity to actually increase or decrease generation. In other words, water that is used when AS capacity is actually converted into energy generation impacts. This limitation is discussed more in Section 8 (Discussion), but is not expected to dramatically alter any study findings.

Output from the model is in the form of time series data for each of the variables of interest: electricity generation (Megawatt-hours (MWh)), energy revenue (dollars), provision of capacity for three ancillary services (MW), and revenue from ancillary services (dollars) for each hour of the input historical water data record. Output is also segregated into peak, partial peak, off-peak, and super off-peak hours – however no analysis was done on these variables. The resulting model output data were exported to Microsoft Excel for analysis. Modeled electric generation or AS provision could then simply be expressed as a sum across the hours, days, months, or years of interest. Revenue is calculated as the generation (or AS provision) for a specific hour, multiplied by the price for that hour. These results can also be summed to examine hours, days, months, or years for analysis.

Three hydropower operations regimes were modeled and examined: The YCWA's Final License Application (FLA), the Base Case (recent operations) regime, and the environmentally protective operations regime developed by resource agencies and NGOs. Because the licensee is proposing an operational departure from Base Case in their FLA, the majority of analysis was devoted to comparing the impacts of the environmental operation regime against the FLA, rather than Base Case. The flow regimes were compared by evaluating average and total generation, AS provision, and revenues across the 39 years of water data input in the model. Findings are summarized in Section 4.

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*3.2. Methods to Estimate GHG Impacts of Reduced Hydropower Generation*

Based on the findings of Davis and Hausman (2015) described in Section 5, I assume that all reduced hydropower generation shift to natural gas generators in California. Figure 5.1 shows that a more efficient natural gas combined cycle (NGCC) generators would likely be the marginal generator during the lower demand hours, while combustion turbines and boilers (both also fueled by natural gas) would be marginal during higher demand hours (Davis & Hausman, 2015). I use emissions factor estimates for the more efficient NGCC generators in California (Loyer & Alvarado, 2012) to estimate the increase in greenhouse gas (GHG) emissions due to reduced hydropower generation from the environmental operating regime on the YRDP. Using exclusively the emissions factors for NGCC generators makes this a conservative estimate, since some reduced hydro generation will likely be shifted to the less efficient, higher emitting combustion turbines or boilers. Findings of this analysis are summarized in Section 5.

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### *3.3. Methods to Analyze Climate Change Impacts on Hydropower Generation*

The objective of this analysis is to understand how future climate warming scenarios will affect hydrology in California's western Sierra Nevada, and thereby impact hydropower generation, AS provision, and the relative cost of providing environmentally protective flows. In order to conduct this analysis, I utilize the forecast climate change induced WYT changes from Null and Viers (2013), to calculate the frequency of WYTs under climate warming through 2050 and 2099. The relative frequency of each WYT is compared to the historical water record of the Yuba River watershed (these historical water data were provided via the operations models that were used as inputs to the YRDP generation post-processor model). Although the year 2099 is beyond the timeframe of the present YRDP relicense, limiting the analysis to only examine change through 2050 would only account for 34 years of operation. Longer term analysis is also relevant for long term planning of California's hydropower infrastructure.

Null and Viers conducted their WYT analysis under two different emissions pathways from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios: B1 and A2. The B1 scenario assumes more aggressive reductions in future GHG emissions than the A2 sceanrio. According to the IPCC, the best estimate for end-of-century temperature change under the B1 scenario is +1.8ºC, while the best estimate for end-of-century temperature change under the A2 scenario is +3.4ºC (IPCC, 2007). These two scenarios can be seen as bounding cases for the present analysis. However, the B1 emissions pathway is seen as unrealistically low, and most policy-oriented cost-benefit analysis today uses the A2 scenario as a more realistic emissions pathway.

I first calculate average energy generation, AS provision, and revenues for each WYT under historical (observed) conditions. I account for changes in the relative frequency of each water year type under the two emissions pathways by applying a "weighting" coefficient to each averaged WYT variable (generation, AS, and revenue) to generate a weighted average. The weighting coefficient reflects the increased or decreased frequency of that WYT occurring in each time step (through 2050 and through 2099) and under each of two emissions pathways. This weighted average was summed across all WYTs to generate an average of total generation, AS, or revenue across all WYTs. This average value (for each time step and emissions pathway) was compared to the historical (observed) average to determine the impact of climate change on generation, AS, and revenue. The equation for annual average revenue, generation, or AS under a specific emissions scenario is shown below in Equation 1.

$$\bar{X}_{\varepsilon t} = \sum_{W=1}^{5} \bar{X}_{obs} * F_{W,\varepsilon t} \tag{1}$$

Where:

| | |
|---|---|
| $\varepsilon$ | represents a specific emissions scenario (i.e. A2 or B1) |
| $t$ | represents a specific time interval (historical, 2001-2050, 2051-2099) |
| $\bar{X}_{\varepsilon t}$ | is annual average (revenue, generation, or AS) for emissions scenario $\varepsilon$ and time period *t*, |
| $\bar{X}_{obs}$ | is historical (observed) average annual revenue, |
| $W$ | represents a specific Water Year Type (WYT) from 1 (Wet) to 5 (Critical Dry), and |
| $F_{W,\varepsilon t}$ | is the frequency (%) of WYT (*W*) occurring under emission scenario $\varepsilon$ and time period *t*. |

Findings of this analysis are summarized in Section 7.

## 4. Generation and Revenue Impacts of Environmental Regime

### *4.1. Background*

A significant number of studies have previously examined the impacts of environmental flow regimes on hydropower generation and revenue. Despite being based on advanced optimization models, many of these studies overlook or undervalue the ancillary services market, which can be a significant source of revenue for some hydropower projects. The YCWA estimates that the combined value of ancillary services products increase YRDP annual revenue by 24% on average compared to base generation (YCWA, 2013).

Guisández, et al., for example, in their 2013 article in *Energy Policy,* find that environmental constraints imposed on hydropower operations reduce operational flexibility, and therefore revenue. The authors use a revenue-driven optimization model and find that revenue losses increase quadratically as a function of reduced maximum ramping rates, and almost linearly as a function of minimum environmental flows (Guisández, et al., 2013). However this study mentions nothing on impacts to AS provision or revenue.

Similarly, Rheinheimer et al. (2013) used a linear programming model to estimate the costs of environmental flows on another hydropower project in the Upper Yuba River watershed – the Yuba Bear Drum Spaulding project. This paper was particularly interesting as it modeled not only the costs of environmental flows on generation and revenue, but also how those costs will change under modeled climate warming of 2º, 4º, and 6º C through the end of the 21st century. The authors found modest annual revenue losses of 2-3% under most conditions, and still less than 7% even under the most environmentally protective flow regimes examined. Revenue losses were highest under longer-term, higher warming scenarios (Rheinheimer et al., 2013). The authors also point out the importance of more detailed cost benefit analysis of environmental flow regimes during the FERC relicensing process, particularly with respect to modeling for climate change impacts. However, this study similarly ignored impacts on AS provision and revenue.

One study does demonstrate an opposite finding from the typical result of reduced hydropower generation under environmental constraints. Modeling by Niu and Insley (2013) showed although profits may be reduced by such environmental constraints by 2 – 8%, the actual amount of energy generated in a 24-hour period may increase. The authors explain: “in response to the ramping constraints, operators increase power production in off-peak periods while at the same time attempting to maintain production as much as possible in on-peak periods" (Niu & Insley, 2013, p. 40). The authors go on to suggest that such an increase in hydro generation may offset emissions from fossil generation, resulting in an added environmental benefit in addition to the benefits to aquatic ecosystems below the dam (I do similar analysis in Section 5 of this paper, but with *reduced* hydro generation). The authors are also quick to point out that this result is case specific and not generalizable. Nonetheless, this finding does lend credence to the need for detailed, rigorous cost-benefit analysis of environmental flow regimes for every individual hydropower project when making management decisions.

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*4.2. Impacts on Electricity Generation & AS Provision:*

After running the YRDP hydropower generation post-processor under the FLA and the environmental operating regimes, I calculated an average of annual energy generation (TWh) from Colgate powerhouse and provision of regulation down, regulation up, and spinning reserve (TW-h) for each proposal[2]. The environmental operating regime reduced average energy generation by 6.1% (about 74 GWh annually) compared to the FLA. However, taken in sum, the provision of ancillary services increased by 1.9% under the environmental regime. Specifically, regulation down decreased by 3.5%, while regulation up and spinning reserve increased by 3.2% and 3.1%, respectively. This surprising result suggests that the hydropower operator will rely on these upward ancillary services to mitigate revenue losses when generation is reduced under the environmental operating regime. The annual average energy and capacity outputs for each category are summarized in table 4.1, below.

*Table 4.1: Average annual energy generation and AS provision under FLA and Envi. Proposal*

| | | | | | Colgate Generation | Ancillary Services |
|---|---|---|---|---|---|---|
| ANNUAL AVERAGE: | Colgate Gen (TWh) | Reg Down (TW-h) | Reg Up (TW-h) | Spin (TW-h) | Total Energy (TWh) | Total Capacity (TW-h) |
| FLA | 1.21 | 0.33 | 0.34 | 1.19 | 1.21 | 1.87 |
| Envi | 1.14 | 0.32 | 0.35 | 1.23 | 1.14 | 1.90 |
| % Δ from FLA | -6.1% | -3.5% | 3.2% | 3.1% | **-6.1%** | **1.9%** |

- - -

[2] TW-h of AS represents the sum of the hourly amounts of capacity (MW) that was reserved for AS in each year.

*4.3: Impacts on Revenues from Electricity Generation & AS Provision:*

I similarly calculated an annual average of revenue from Colgate generation and capacity bid into regulation up, regulation down, and spinning reserve under the FLA and the environmental operating regime. The pattern of impacts of the environmental regime was similar to that of generation and AS provision in section 4.1 – average revenues were decreased for energy generation and regulation down, but increased for regulation up and spinning reserve. In sum, average total ancillary services revenues increased by 3.6%, but total average revenue decreased by 3.5%. The annual average revenues are summarized in table 4.2, below.

*Table 4.2: Average annual revenues ($Million / yr) under FLA and Envi. Proposal*

| ANNUAL AVERAGE: | Colgate Gen | Reg Down | Reg Up | Spin | Total AS | **Average Revenue** |
|---|---|---|---|---|---|---|
| FLA | $40.2 | $1.74 | $1.88 | $4.23 | $7.85 | $48.1 |
| Envi | $38.2 | $1.67 | $1.97 | $4.48 | $8.13 | $46.3 |
| % Δ from FLA | -4.9% | -3.9% | 5.2% | 6.0% | 3.6% | **-3.5%** |

Overall, AS provide about 16.3% of total average revenue under the FLA, and about 17.5% of total average revenue under the environmental regime.

It is important here to reiterate that one of the primary motivations of this research is that generation and revenue analyses conducted by licenses during the FERC relicensing process often homogenize generation and revenue impacts of environmental flow regimes into a single number, reduced annual generation, which is used as a proxy for overall impacts. In the case of the YRDP, we can see that the actual impacts are much more nuanced. While annual generation is reduced by 6.1% on average, revenues from energy generation are only reduced 4.9%. Thus, there is not a direct linear relationship between energy generation and revenue. This suggests that the reduced energy generation occurs during hours when energy prices are lower, on average, and water is reserved for hydro generation during more valuable hours. More importantly, the *total* annual revenue is reduced by only 3.5%, on average, because revenues from AS sales increase overall (by 3.6%) under the environmental regime. While it may not always be the case that AS sales increase with more environmentally protective flow regimes, this finding suggests that leaving AS out of an analysis of costs and benefits of hydropower operating regimes may be a significant oversight. Using reduced energy generation as a proxy for revenue losses is oversimplified, inaccurate, and misleading.

## 5. Greenhouse Gas Impacts of Reduced Hydropower Generation

### *5.1. Background*

In section 4, I showed that the environmental operating regime would reduce annual energy generation by 6.1% on average. But reduced generation from one merchant generator in California's electricity market does not mean that consumers will simply have to use less electricity; rather, that reduced generation is met by an increase in the generation of the marginal generator. The marginal generator is the last unit (highest bid) that is needed to meet demand in the supply curve of generators bidding into the California Independent System Operator (CAISO) market. In California, the marginal generator is very likely to be a natural gas fired generator (Davis & Hausman, 2015). Therefore, any reduction in hydropower output is likely to result in an increase in GHG emissions. An attempt to quantify this impact may add depth and nuance to a discussion of the costs and benefits of different hydropower operations schemes. Such impacts have rarely been examined in the context of hydropower and environmental flow regimes.

The majority of the literature related to hydropower and GHG emissions are analyses of emissions from hydropower reservoirs and/or life-cycle assessments of GHG emissions associated with construction or dams and reservoir filling (e.g., Barros et al., 2011; Dones, et al., 2003; Soumis et al., 2004). This type of analysis is important to understanding the full range of environmental and social impacts from hydropower, but is outside the scope of the present work.

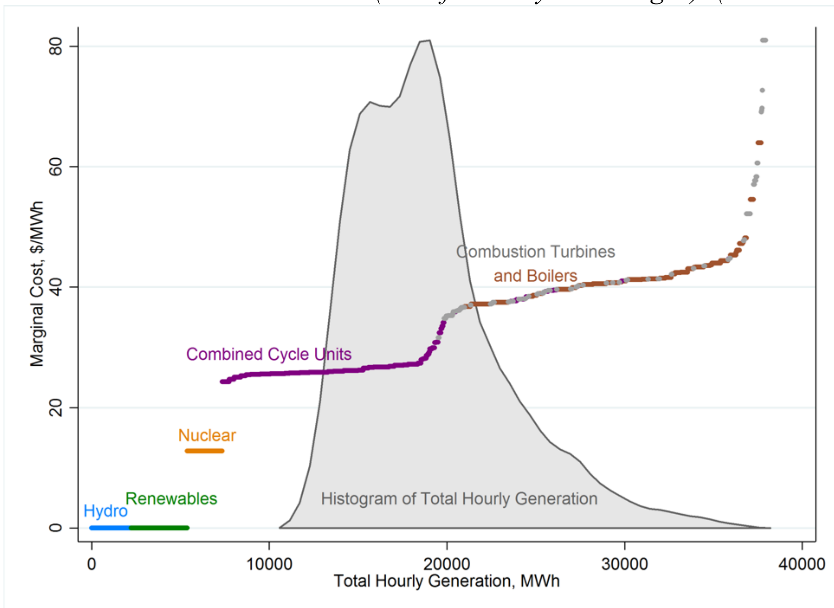
Niu and Insley (2013) did estimate the emissions impact of changes in hydropower generation shifting demand for fossil fuel generation, however their results were anomalous in that they found an *increase* in hydropower generation under environmental constraints. This was because operators increased generation in off-peak hours to make up for lost revenue due to ramping rate restrictions limiting on-peak generation (their hypothetical hydropower system was less water-constrained). Their study, therefore, estimated a *reduction* in GHG emissions, and accounted for this as a separate benefit in addition to the benefits to the aquatic ecosystems downstream of the dam due to the environmental operating constraints.

The Pacific Institute did a similar analysis for reduced hydropower generation during California's 2012-2014 drought. This research found that burning natural gas to compensate for limited hydropower generation increased carbon dioxide emissions by 14 million tons over the three drought years examined. This represented an eight-percent increase in emissions of carbon dioxide from California power plants (Gleick, 2015). Although this study was examining impacts of reduced hydropower generation due to drought, the methods are largely transferrable to the present study of reduced hydropower generation due to environmental operating constraints.

Other papers have examined GHG effects of unexpected reductions from other sources of electricity like wind or nuclear. One such study developed a simplified power system model to estimate the GHG emissions from fossil-fired generators used to provide power when wind farm output drops unexpectedly. To protect against this uncertainty, some conventional power plants are left idling online, consuming fuel and thereby emitting GHGs. However, the author finds the total GHG impact to back-up large-scale wind power to be quite modest (Fripp, 2011). This study differs from the present study due to the focus on operating reserves and unexpected reductions in generation, but it is nonetheless useful as an example of electricity market shifts from carbon-free to fossil-fired generation.

Finally, and perhaps most useful to the present analysis, is a study conducted by researchers at the Energy Institute at the Haas School of Business, which analyzes the market and environmental impacts of the abrupt closure of the San Onofre Nuclear Generating Station (SONGS) in California in 2012. The authors plotted the marginal cost curve and total generation histogram for California in 2012 (see Figure 5.1), and show that lost generation from SONGS was met primarily by increased in-state natural gas generation (Davis & Hausman, 2015). They find that this shift toward natural gas increased carbon dioxide emissions by 9 million tons in the first twelve months following the closure of SONGS (Davis & Hausman, 2015). Based on this analysis, one can confidently assume that reduced hydropower generation in California will be shifted to some form of natural gas generation in the short run.

*Figure 5.1:* *Marginal cost curve and total generation for California in 2012. In most hours, the marginal generating unit is a combined cycle natural gas unit. In high demand hours, however, the marginal unit is typically either a combustion turbine or a boiler (both fueled by natural gas). (Davis & Hausman, 2015)*




I will also point out that the actual increase in GHG emissions in California is dependent, to a large extent, on the nature of California's Carbon Cap and Trade mechanism, established by the California Global Warming Solutions Act (Assembly Bill 32). If the cap on carbon emissions is binding, the reduction in hydropower generation will not result in an increase in statewide GHG emissions, but would rather result in a change in the cost of GHG permits with resulting changes in wholesale and retail electricity prices. However, the sharp drop in permit prices and continued low price since 2012 suggests an over-allocation of permits (California Carbon Dashboard, 2016). It is therefore likely that reduced hydropower generation will, indeed, result in increased GHG emissions in California at this point in time. However, merchant natural gas generators will be required to acquire permits for the additional tons of carbon emitted with increasing generation. I estimate this cost to natural gas generators below in section 5.4.

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## *5.2. Impacts of Reduced YRDP Generation on Greenhouse Gas Emissions:*

As described in Section 3.1, the environmental operating regime reduced annual hydropower generation by approximately 74,000 MWh, on average. Following the methods of Davis and Hausman (2015) described above, this reduced generation from hydropower will likely be met with increased generation from natural gas generators in California. As Figure 5.1

shows, the more efficient natural gas combined cycle (NGCC) generators would likely be on the margin during the lower demand hours, while combustion turbines and boilers (both also fueled by natural gas) would be marginal during higher demand hours (Davis & Hausman, 2015).

Using emissions factor estimates for natural gas generators in California (Loyer & Alvarado, 2012), I estimate the increase in emissions of Carbon Dioxide ($CO_2$) and four criteria pollutants due to reduced hydropower generation from the environmental operating regime on the YRDP. I estimate that $CO_2$ emissions will increase by about 27,000 metric tons per year, on average, under the environmental hydropower operations regime. The criteria pollutants examined($NO_x$ , $SO_x$, CO, and PM 2.5) increase very modestly (0.4 – 3.3 tons). Estimates of the additional GHG and criteria pollutant emissions are summarized in Table 5.1.

*Table 5.1: GHG and criteria pollutant emissions impacts of reduced hydropower generation*

| Average Reduction in Generation (FLA - Envi): 74,000 MWh / year | | | |
|---|---|---|---|
| Pollutant | Emission Factor (lbs / MWh) | Emission Factor (Tonnes / MWh) | Addl. Emissions (Tonnes / Year) |
| $CO_2$ | 810 | 0.37 | 27,000 |
| $NO_x$ | 0.07 | 0.000032 | 2.4 |
| $SO_x$ | 0.01 | 0.000005 | 0.4 |
| CO | 0.1 | 0.000045 | 3.3 |
| PM 2.5 | 0.03 | 0.000014 | 1.0 |

*Emissions factors from Loyer and Alvarado, 2012*

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*5.3. Social Cost of $CO_2$ of Greenhouse Gas Emissions Due to Reduced YRDP Generation:*

The Social Cost of Carbon Dioxide (SCC) is an estimate of the global economic damages associated with a one-tonne increase in $CO_2$ emissions in a given year (EPA, 2015). It is meant to encapsulate damages to agricultural productivity, human health, property, energy systems costs, and heating/air-conditioning costs. This value can also be conceptualized as the economic benefit of a one-tonne reduction of $CO_2$ (EPA, 2015).

Using the Environmental Protection Agency's central estimate for the SCC, I quantify the global social cost of these increased CO2 emissions due to reduced hydropower generation under the environmental operating regime.

The concept of the SCC has generated some controversy, and is may not account for all damages of climate change. The IPCC Fifth Assessment report notes a number of impacts that are omitted from the SCC, which would likely increase the SCC damage values (EPA, 2015). Nonetheless, the SCC gives us some idea of global social costs of an additional tonne of CO2 in the atmosphere. It is important to reiterate that the SCC is an estimate of *global* costs, whereas the revenue impacts examined in Section 4 are exclusive to the YCWA. The environmental and social benefits of the environmentally protective operating regime are likewise local benefits.

For the year 2016, the EPA estimates that an additional tonne of CO2 will result in a global cost of $37 (EPA, 2015). Under this assumption, the increased emissions examined here would result in an annual social cost of over $1 million, shown in Table 4.2.

| Reduced Generation (MWh/year) | Tonnes $CO_2$ per MWh, NGCC | Addl. Tonnes/Year | Social Cost of $CO_2$ [3] (\$/tonne $CO_2$) | **Annual Social Cost of $CO_2$ (\$ Million/yr)** |
|---|---|---|---|---|
| 74,000 | 0.37 | 27,000 | $37 | **$1.01** |

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<u>*5.4. Impacts of Reduced YRDP Generation on California Electricity Market:*</u>

Davis and Housman (2015) find that the weighted average marginal cost of natural gas generation in California is about $29 per MWh. Under the assumption that all reduced hydropower generation is met with increased natural gas generation, I can estimate that the reduced hydropower generation under the environmental regime would increase statewide electricity costs by about $2.1 million.

However, there is an another layer to this story: the merchant natural gas generators that increase output in order to supplement reduced hydropower generation would be required to purchase $CO_2$ permits under the California Cap and Trade market. In the most recent California $CO_2$ permit auction, the median permit price was \$12.73 per tonne of $CO_2$ (CARB, 2016). Given an average emissions factor of 0.37 tonnes $CO_2$ per MWh for NGCC, the permit price results in an additional cost of \$4.71 per MWh of NGCC generation. This permit price would be internalized into the day-ahead market bids of these generators. Therefore, the total weighted average marginal cost of natural gas generation could be estimated at about \$34 per MWh.

[3] SCC value retrieved from EPA (2015).

Applying this value to the reduced YRDP hydropower generation under the environmental regime, this would result in an increase in statewide electricity costs of about $2.5 million.

According to CAISO, the total estimated wholesale cost of electricity in 2014 was $12.1 billion (CAISO, 2015). The increase in electricity costs due to the YRDP environmental regime, therefore, represents a 0.02% increase in statewide electricity costs.

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## 6. Hydropower Generation and Revenue Impacts by Water Year Type

*6.1. Definition and Importance of Water Year Type (WYT)*

The "water year" in California runs from October 1st to September 30th of the following year. Water managers and hydrologists classify precipitation, moisture, and complex hydrology into simplified classification systems and indices in order to have a simple, numerical metric that can be used for water allocation and decision making (Null & Viers, 2013). The estimated water resource is categorized into types, such as "wet", "dry", or "normal" compared to historical averages. In California, the WYT classification is used to inform allocation decisions for water supply, environmental protection, reservoir storage, and hydroelectric generation (Null & Viers, 2013). It is no surprise that hydropower projects generate less electricity when less water is available. Hydropower currently generates 9% to 30% of California's electricity demand, depending on hydrological conditions (Madani & Lund, 2010). On average, hydropower generated 18% of California's electricity from 1983-2013, but has accounted for less than 12% during the recent 2012-2015 drought (Gleick, 2015).

Because hydropower output can vary so dramatically across different water year types, and because environmental health, water resource decision making, and WYTs are inextricably linked, it is important to understand how hydropower generation and revenues vary by WYT – particularly in the context of evaluating the impacts of environmentally protective flow regimes.

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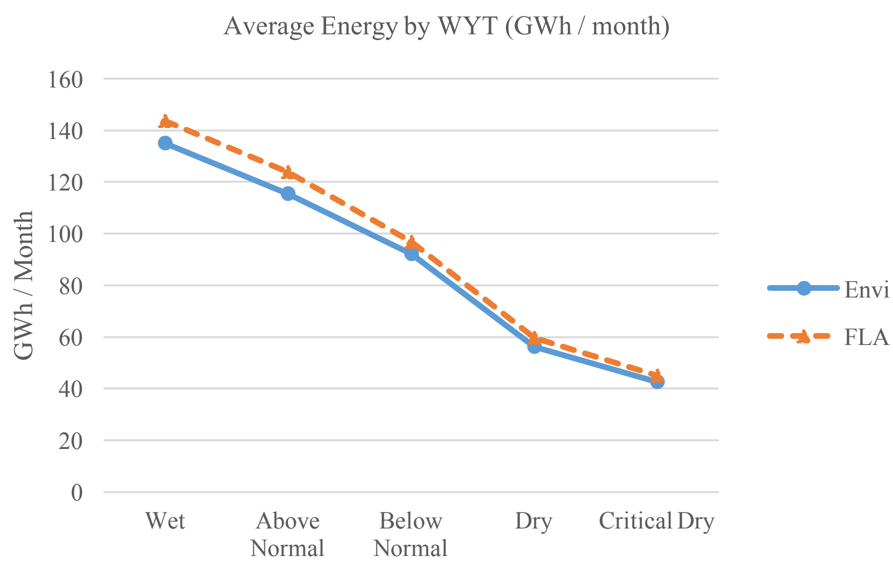
*6.2. Impacts of Environmental Operations on Generation and AS by WYT:*

Unsurprisingly, this analysis showed a significant reduction in hydropower generation in drier years. The magnitude of this change, however, is remarkable: the YRDP is projected to generate over 68% less energy in "critical dry" years compared to wet years (this is true for both the environmental regime and the FLA). The project generates 58% less energy in "dry" years, 32% less energy in "below normal" years, and 14% less energy in "above normal" years compared to "wet" years.

A more interesting finding is that the average reduction in energy generation due to environmental operating regimes is not consistent across water year types. Under the environmental regime, the YRDP generates 6.1% less energy in wet years, 6.8% less in above normal, 4.9% less in below normal, 6.1% less in dry, and 5.5% less in critical dry years. There is not a clear trend that impacts are reduced or increased disproportionately in drier or wetter conditions. These findings are summarized in Figure 6.2-1.

*Figure 6.2-1. Average Monthly Hydropower Generation by WYT*




Turning to ancillary services, there is another interesting trend: the YRDP's provision of regulation up and spinning reserve increases in drier years. Regulation down, on the other hand, decreases. I interpret that this is due to the Colgate Powerhouse operating at a lower capacity during drier years, which leaves more room for upward regulating services. The results suggest that the YRDP may bid 70% more capacity into regulation up in critical dry years compared to wet years, and 60% more into spinning reserve. Interestingly, the capacity bid into regulation down decreases by only 45% in critical dry years compared to wet years.

Similar to the findings from generation by WYT, the impacts of environmental operations on AS compared to the FLA are not consistent across WYTs. In regulation up and spinning reserve, the environmental regime initially provides nearly 8% more capacity during wet years, but the difference collapses near zero for dry and critically dry years. This is because the low generation levels during these driest years frees up capacity (headroom) for AS, even for the FLA. Regulation down sees the opposite trend: the environmental regime provides 2.5% less capacity during wet years but decreases to 7.4% less capacity during critical dry years. These findings are summarized in Figures 6.2-2, 6.2-3, and 6.2-4.

*Figure 6.2-2. Average Hourly Regulation Up by WYT*

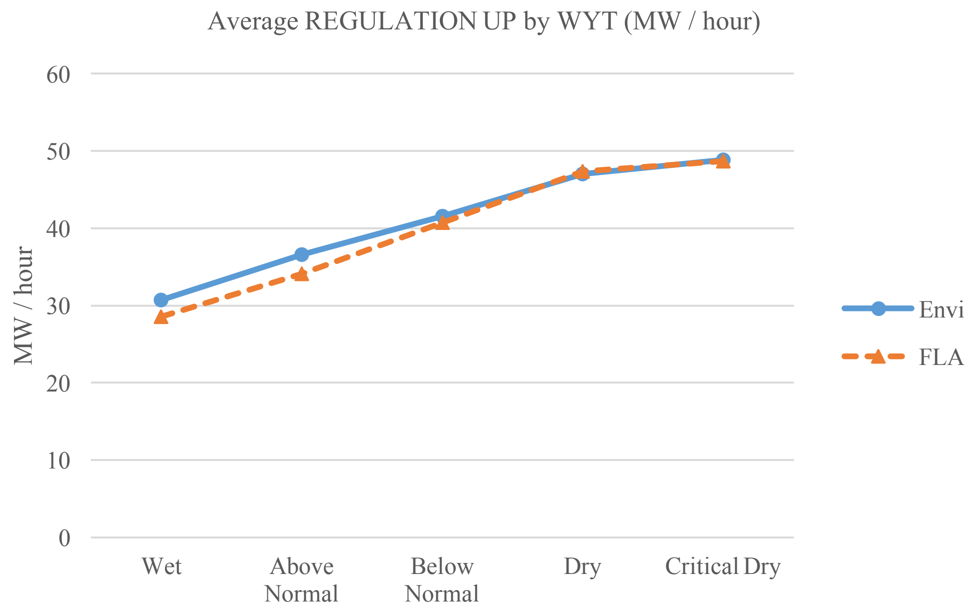



*Figure 6.2-3. Average Hourly Regulation Down by WYT*

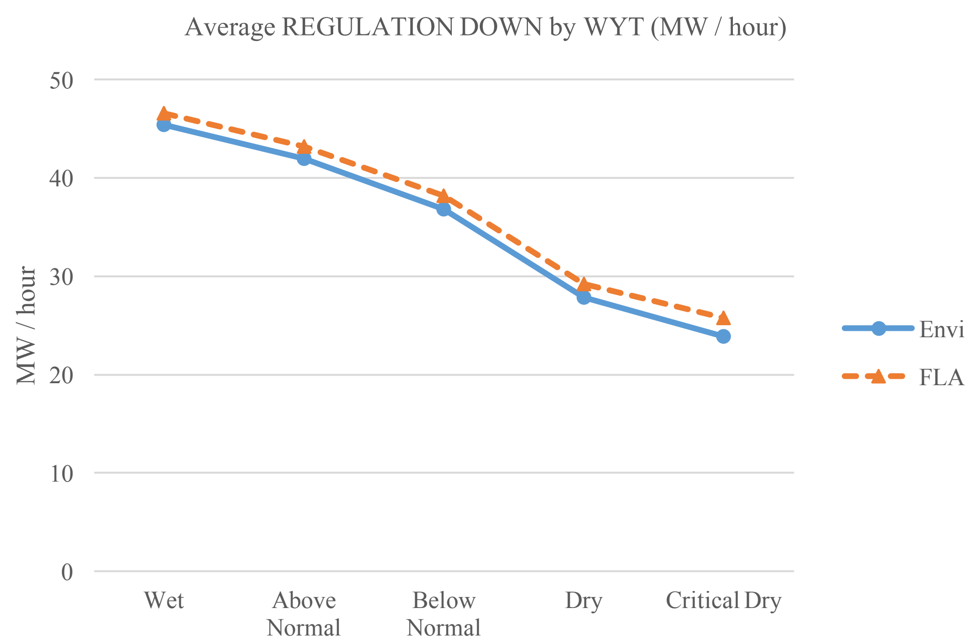
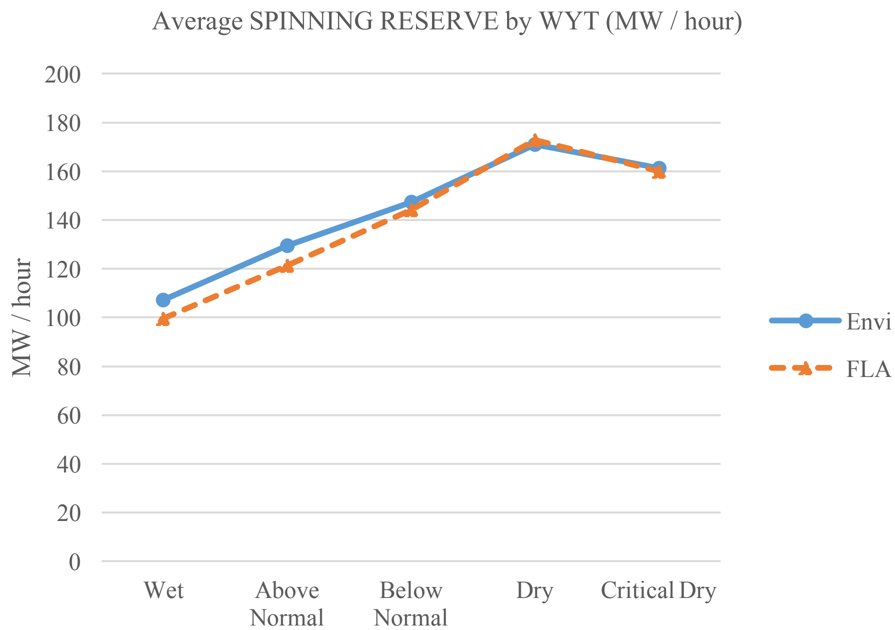


*Figure 6.2-4. Average Hourly Spinning Reserve by WYT*

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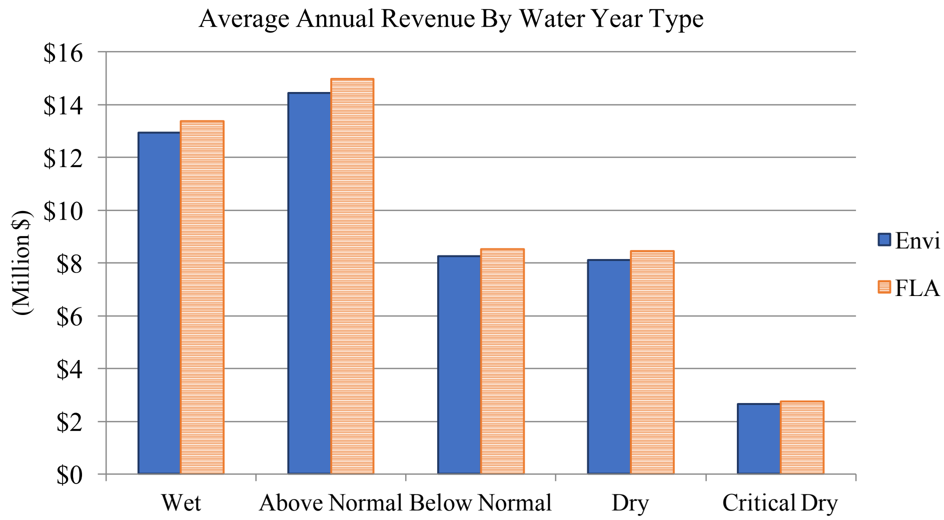
## *6.3. Impacts of Environmental Operations on Revenue by WYT:*

Overall, it is clear that the majority of YRDP revenue is generated in the wettest years. In each of the four hydropower operating regimes examined, the wettest two water year types ("Wet" and "Above Normal") accounted for 59% of total hydropower revenues. By comparison, only 6% of total revenue comes from the two driest water year types. In general, the negative impacts on electricity generation and revenue due to environmental flow regimes on the YRDP are more pronounced during drier years, and less significant during wetter years.

In comparing revenues under the environmental regime and the FLA across the five WYTs, the environmental regime reduces total annual revenue by 3.2% to 4.2% with no clear trend from wet to dry years. These negative revenue impacts are buffered by the increased revenue from ancillary services under the environmental flow regime, but that difference collapses in the driest years (as shown in section 6.2).

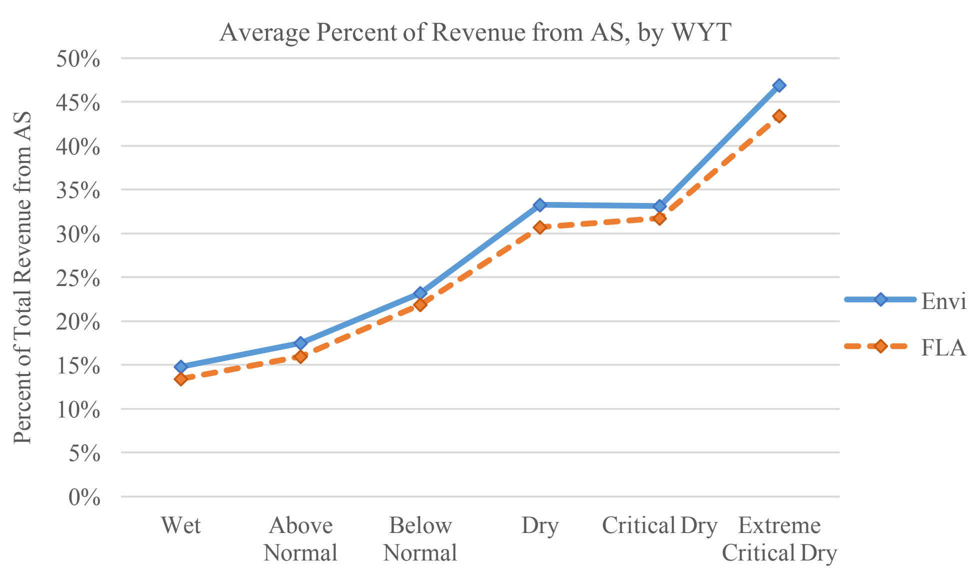
It is also important to note that the variation in revenue across WYTs is much larger than any impacts of the environmental regime versus the FLA. While the environmental regime reduces average revenue by 3-4%, the variation in revenue from "Wet" to "Critically Dry" years is nearly 80%. Even "Wet" to "Above Normal" years vary by 12%. See Figure 6.3-1.

*Figure 6.3-1. Average Annual Revenue by WYT*




Another important conclusion from these data is that the percentage of total project revenue coming from ancillary services appears to be inversely correlated with water availability. In other words, **in drier years, ancillary services provide a greater portion of the project revenue.** For example: during the wettest years, ancillary services provide 10-11% of total revenue. But during extreme critical dry years, ancillary services provide up to 40% of total revenue. Furthermore, ancillary services revenues provide a greater portion of total revenues in the environmental flow regimes compared to the FLA and Base Case regimes across all water year types. These findings are shown in Figure 6.3-2.

*Figure 6.3-2. Average AS Percent of Total Revenue by WYT*



## 7. Impacts of Climate Change on YRDP Generation, Revenue, and Operations

### *7.1. Background of Climate Change Impacts on Hydropower*

Studies of the impact of climate change in California consistently indicate that air temperature will increase and precipitation will decrease (Franco et al., 2011). Additional research has suggested that climate warming will increase both the frequency and the severity of drought in California (IPCC, 2013; Diffenbaugh, et al., 2015). Even when precipitation rates are "normal" or above, it is expected that more winter precipitation will fall as rain, rather than snow, higher temperatures will shift spring runoff earlier in the year, the intensity of peak flow will be reduced, and winter runoff will be increased (Guegan et al., 2012). Some of these impacts, such as a shift toward earlier streamflows, have already been measured by researchers (Maurer et al., 2007). Taken together, **it is clear that these changes will alter the historical patterns of snowpack and runoff that California's high-elevation hydropower system relies on** (Guegan, et al., 2012).

California's hydropower system is considered an asset for mitigating climate change and enabling integration of other renewables, but is also vulnerable to climate change (Viers, 2011). Despite these significant hydrological changes being evident on a decadal time-scale, the Federal Energy Regulatory Commission (FERC), which is responsible for all non-federal hydropower licenses, does not currently accept any climate change analyses in their process of hydropower relicensing decision-making (Viers, 2011).

Climate change is important to examine in the context of hydropower not only because it will affect electricity generation and revenues, but also because it will affect the full range of ecosystem services already impacted by hydropower systems. Hydrologic changes from a warmer climate are likely to increase conflicts between hydropower generation, water delivery, ecosystem support, flood control, fishing, and whitewater recreation (Ligare et al., 2012).

Numerous studies have estimated the impact of climate change on runoff in Sierra watersheds (Null et al., 2010; Null & Viers, 2013; Stewart et al., 2005). These studies suggest that peak runoff is expected to shift 10-30 days earlier compared to 1948-2002, and total runoff is expected to decline with increased warming (Stewart et. al, 2005). Moreover, we are likely to see a shift toward more "Dry" and "Critically Dry" water year types (WYT) as classified by the California Department of Water Resources (Null & Viers, 2013). Nonetheless, the net effects of climate warming on total runoff volumes remain unclear (Hanak & Lund, 2012). What is clear is that we have entered an era of hydrologic non-stationarity with respect to water resources in California (Milly et. al, 2008).

Other studies have modeled the effect of this changing hydrology on Sierra hydropower generation and revenue (Rheinheimer et al., 2013; Guegan et al., 2012; Rheinheimer et al., 2015; Madani & Lund, 2010; Medellin-Azuara et al., 2008). Each of these studies has demonstrated a reduction in Sierra hydropower generation due to climate warming, with severity depending on the degree of warming. However, this effect is not uniform across the Sierra region, nor across different warming scenarios (Guegan et al., 2012). In general, previous modeling suggests that the effects of reduced total runoff due to decreased precipitation is more impactful to hydropower than seasonal shifts in streamflow timing (Hanak & Lund, 2012).

Although some of these models do estimate the effect on hydropower revenues, they do so at a relatively coarse scale – accounting only for *energy* sales, and not the grid-regulating ancillary services markets that are an important source of revenue for many Sierra hydropower projects. This section will attempt to quantify the impact of climate-induced hydrologic change on: (1) total energy generation, (2) provision of ancillary services, (3) project revenue, and (4) the relative cost of providing environmentally protective flows downstream of the three dams under different warming scenarios.

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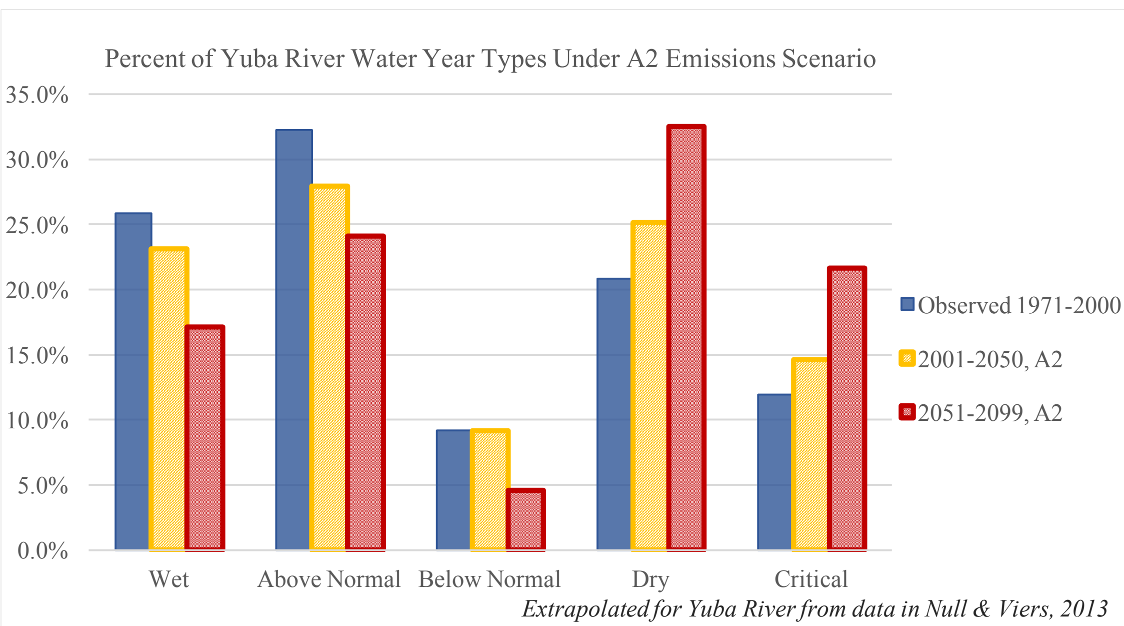
### *7.2. Change in Frequency of Water Year Types Due to Climate Warming*

In a 2013 paper, Null and Viers model streamflows in western Sierra Nevada rivers, and show that the frequency of water year types changes significantly with climate change. The authors model flows under two emissions pathways defined by the Intergovernmental Panel on Climate Change (IPCC), Special Report on Emissions Scenarios (SRES) – the A2 and B1 scenarios. The B1 scenario assumes more aggressive reductions in future GHG emissions than the A2 sceanrio. As a result, according to the IPCC, the best estimate for end-of-century temperature change under the B1 scenario is +1.8ºC, while the best estimate for end-of-century temperature change under the A2 scenario is +3.4ºC (IPCC, 2007). These two scenarios can be seen as bounding cases, to some extent. However, the B1 emissions pathway is seen as unrealistically low, and most policy-oriented cost-benefit analysis today uses the A2 scenario as a more realistic emissions pathway.

Overall, Null and Viers show a clear shift toward a higher frequency of dry and critically dry years compared to the observed frequencies in the historical record. Projecting the hydrologic change for the WYT index encompassing the Yuba river watershed under the A2 emissions pathway for the first half of this century (through 2050), the authors find a 2.7% increase in "critically dry" years and a 4.3% increase in "dry" years compared to the historical record. These changes coincide with a 2.7% decrease in "above normal" and a 4.3% decrease in "wet" years (Null & Viers, 2013). Forecasting the same changes under the A2 scenario through the end of the century (through 2099), the authors find a 9.7% increase in critically dry years, an 11.7% increase in "dry" years, a 4.6% decrease in "below normal" years, an 8.1% decrease in "above normal" years, and an 8.7% decrease in "wet" years (Null & Viers, 2013).

Utilizing the modeled WYT changes from Null and Viers, I calculate the frequency of WYTs under A2 and B1 emissions pathways through 2050 and 2099, compared to the historical water record of the Yuba River watershed. These historical data were provided via the operations models that were used as inputs to the YRDP generation post-processor model, described in Section 3. Figure 7.2 illustrates the shift from historical WYTs (solid blue) toward more dry and critical dry year types by 2050 (striped yellow), with the trend growing more severe through 2099 (checkered red).

*Figure 7.2. Frequency of Yuba River WYTs Projected Through 2050 & 2099 for A2 Emissions*

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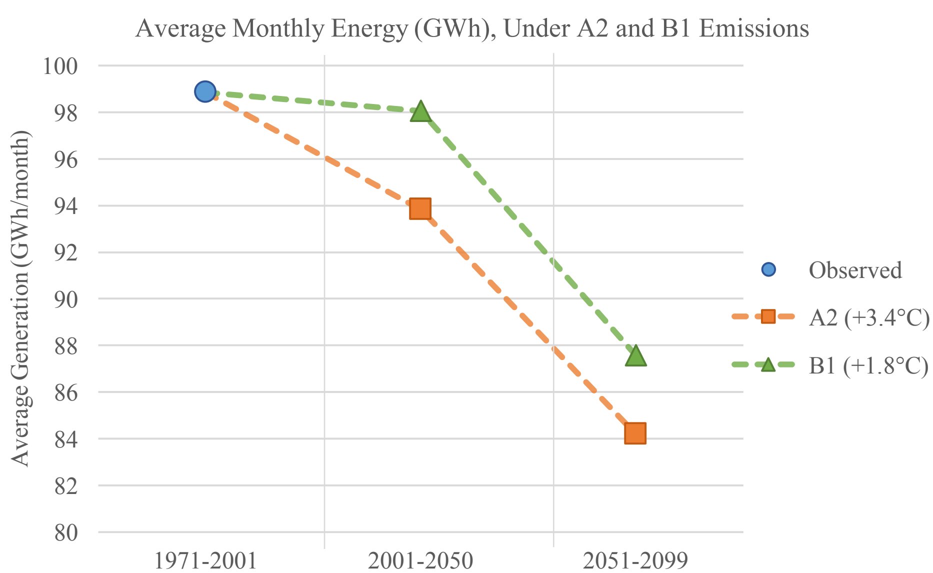
*7.3. Impact of Climate Change on Electricity Generation and Provision of AS*

To determine the effect of climate change on energy generation and provision of ancillary services, I first calculated the average electricity generation (GWh / year) and AS provision (MW-h) for each WYT. I account for changes in the relative frequency of each water year type under the two emissions pathways by applying a weighting coefficient to each averaged WYT variable (generation, AS, and revenue) to generate a weighted average. The weighting coefficient reflects the increased or decreased frequency of that WYT occurring in each time period (2001-2050 and 2051-2099) and under each of two emissions pathways. This weighted average was summed across all WYTs to generate an average of total generation, AS, or revenue across all WYTs. This average value (for each time step and emissions pathway) was compared to the historical average to determine the impact of climate change on generation, AS, and revenue.

Although I modeled the climate change impacts to generation, AS, and revenue for both the FLA and the environmental regime, I found no remarkable difference in the percent change experienced by each regime in all cases (this difference was less than 1% in all WYTs). Therefore, in an effort to not obfuscate overall trends and findings, the analysis and figures presented are for only the environmental operating regime.

Under these assumptions, there is a clear downward trend in YRDP hydropower generation under climate warming. I find that average monthly generation will decrease by 1-5% by 2050 and 11-15% by 2099. These findings are summarized in Figure 7.3-1.

*Figure 7.3-1. Average Monthly Generation Under Climate Scenarios*



Ancillary services provision under climate warming is expected to increase for regulation up and spinning reserve, and decrease for regulation down. This finding makes intuitive sense: because average generation is reduced, there is more headroom for the powerhouse to provide upward regulating AS, and less room to provide downward regulation. AS findings are summarized in Figures 7.3-2 and 7.3-3.

*Figure 7.3-2. Average Regulation Up and Down Provision Under Climate Scenarios*

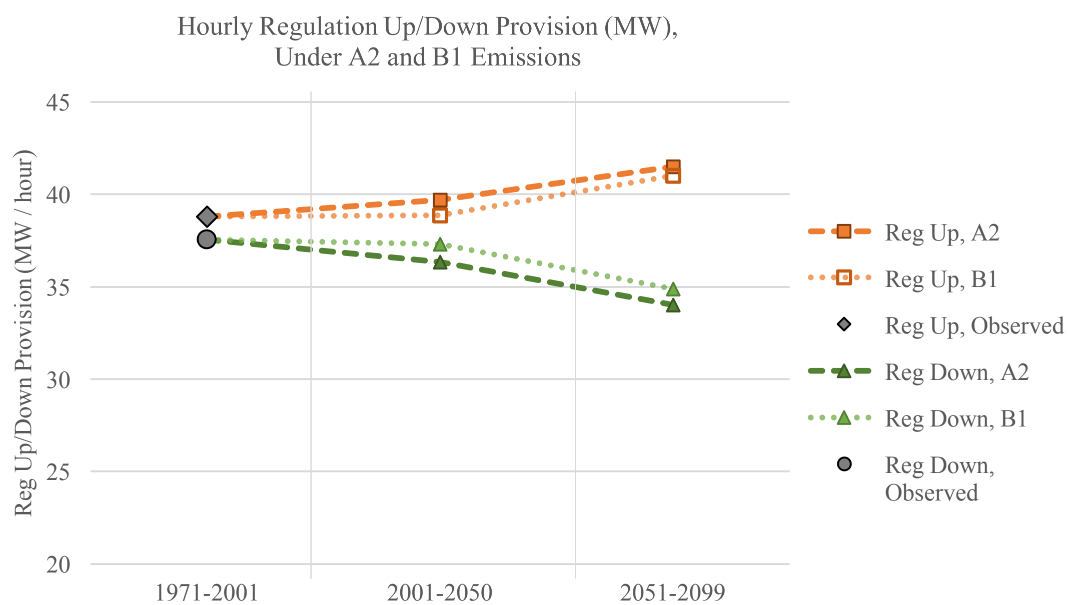
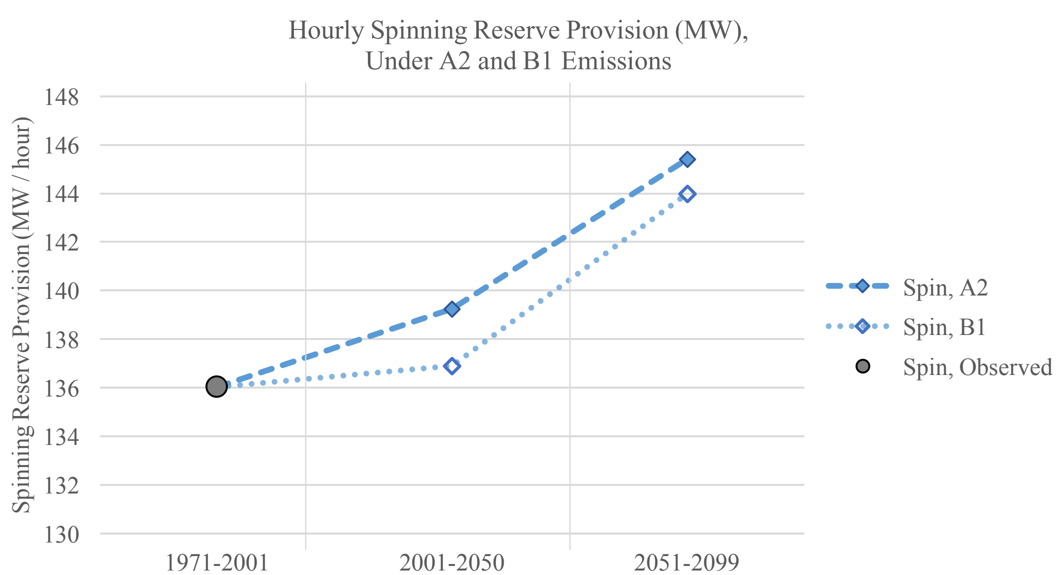



*Figure 7.3-3. Average Spinning Reserve Provision Under Climate Scenarios*

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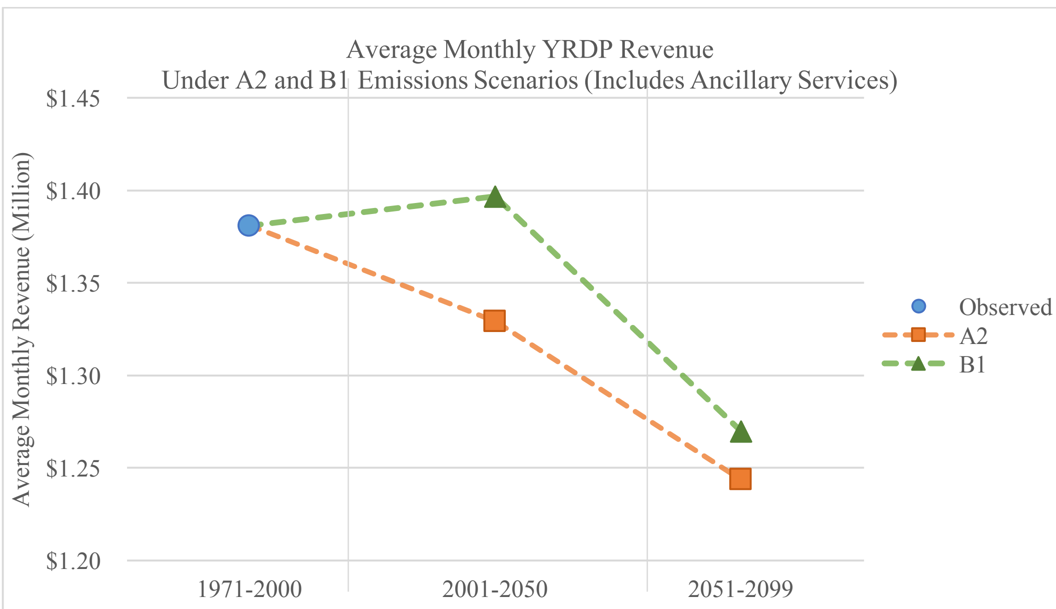
*7.4. Climate Change Impact on YRDP Revenues*

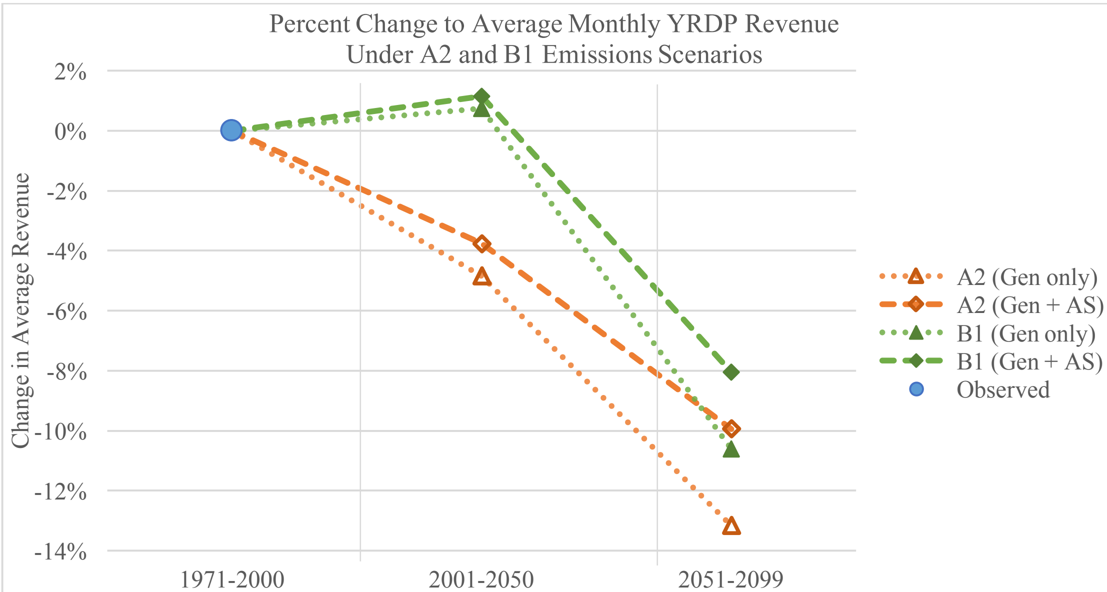
Similar to the trend in hydropower generation, there is a clear downward trend in YRDP revenues under climate warming scenarios. Strangely, the B1 scenario shows near term warming (through 2050) may actually *increase* average monthly YRDP revenue, but the A2 scenario for the same time period shows a 4% decrease in revenue. This seemingly anomalous result is due to the fact that according to Null and Viers (2013), "Wet" years actually increase by 2% and "Critical Dry" years decrease by 1.7% through 2050 under the B1 scenario. This is in contrast to the general trend of a shift toward drier years. Looking at longer term warming (through 2099), there is no disagreement; the B1 scenario implies an 8% decrease in average revenue, while the A2 scenario implies a 10% decrease. These findings are summarized in Figure 7.4-1.

*Figure 7.4-1. Average Monthly YRDP Revenue Under Climate Scenarios*




However, the downward trend shown in Figure 7.4-1 homogenizes revenues from electricity generation and AS into one value. In fact, overall AS revenues increase under climate warming, and may act as a buffer to future revenue losses due to climate change. It is reasonable, therefore, to consider that AS markets may become an increasingly attractive and important revenue stream for hydropower operators under future climate change. This buffering effect of ancillary services is shown in Figure 7.4-2.

*Figure 7.4-2. Percent Change in Average Monthly YRDP Revenue Under Climate Scenarios, with and without Ancillary Services Revenues*




These findings demonstrate significant implications of climate change on YRDP generation and revenue. These findings have a number of important management and policy implications that should be considered:

(1) Reduced YRDP generation due to climate change may result in increased GHG emissions, similar to the effect demonstrated in Section 5. (2) Reduced generation due to climate change may also affect the ability of hydropower projects to enable grid integration of variable renewable energy like wind and solar. (3) Reduced revenue under climate warming will make it harder and harder for hydropower operators to sacrifice water for environmentally protective flows that could otherwise be used to generate electricity and bolster revenues. FERC's hydropower compliance director Dr. Jennifer Hill demonstrated this possibility by showing increased compliance variances due to the California drought (Hill, 2016). Increased compliance variances would result in lower flows and higher ramping rates – reducing environmental quality and survival rates of aquatic species downstream of dams. (4) AS markets for regulation up and spinning reserve may become an increasingly attractive and important revenue stream for hydropower operators under future climate change, since reduced average generation provides more headroom for these upward regulating services.

Future work should also account for changes in *timing* of streamflow, and other potential hydrological impacts of climate change that are not factored in this simple analysis.

## 8. Discussion

The federal hydropower relicensing process occurs only once every 30-50 years, providing a rare opportunity for FERC, the hydropower operator, environmental groups, state and federal resource agencies, and other stakeholders to re-examine hydropower operations and optimize for economic, environmental, and social benefit. This paper has analyzed impacts and benefits that are not normally considered in the relicensing process, and the results suggest that typical cost-benefit analyses conducted for FERC relicensing negotiations often neglect many trade-offs of changes to hydropower flow regimes. The results presented in this paper emphasize the need for deeper, more thorough analysis of trade-offs.

The optimization model used for the analysis in this study has some limitations. First, the model was constructed specifically for the YRDP. Because no two hydropower systems are exactly alike, this means that the specific results of this study cannot be directly transferred to other hydropower relicensing negotiations. Second, the model does not account for water that leaves (or remains in) the system when CAISO "calls-up" AS capacity to actually increase or decrease generation. For example, if Regulation Up is taken by CAISO, the project must send more water through the powerhouse to increase generation. Likewise, if Regulation Down is taken by CAISO, the YRDP reduces the amount of water sent to the powerhouse. The model has no way to account for this effect. However, for the present analysis this limitation is acceptable because: (1) The provision of Regulation Up and Regulation Down are roughly balanced. If these services are called-up by CAISO at equivalent rates (there is no reason to suggest otherwise), they will be energy neutral. Therefore, there will be no impact on water in the system. (2) Spinning reserve is taken only in contingency events, such as when another large power plant trips offline (CAISO, 2009). This occurs so infrequently it can be considered negligible. Although the model could be improved to better account for water use for AS, the findings of energy and AS provision under different scenarios would not be greatly affected.

The environmental operating regime would provide a wide range of local environmental and social benefits that were not quantified or valued in this paper. This is, in part, because there are currently no suitable monetary measures to quantify the ecosystem or social benefits of environmentally protective hydropower operations (Niu & Insley, 2013). But our inability to quantify these benefits does not mean that they are small or unimportant. In Section 2, I presented some of the environmental and social impacts of hydropower, and discussed how these impacts could be alleviated through environmentally protective operations. These environmental and social benefits should not be undervalued, even if they cannot be compared “dollar for dollar” with reduced hydropower revenues.

Some analysis of generation and revenue impacts of different hydropower operating proposals are standard in the relicensing process. However, these analyses are typically very coarse – and often homogenize generation and revenue impacts into a single number. The analysis in this paper includes more detail from the complex California electricity market – most notably including revenues from ancillary services (AS). The present analysis showed that AS revenues may increase under the environmental regime. While it may not always be the case that AS sales increase with more environmentally protective flow regimes, leaving AS out of an analysis of costs and benefits of hydropower operating regimes may be a significant oversight. Moreover, using reduced energy generation as a proxy for revenue losses is inaccurate and misleading: while the environmental regime reduced average energy generation by 6.1%, average revenue was reduced by only 3.5%. Future generation and revenue analyses in relicensing negotiations should follow similar methods.

Different hydropower operating conditions have distinct local, regional, and global environmental and social trade-offs that are not adequately examined in the hydropower relicensing process. Local impacts include changes to generation and revenue, environmental impacts, cultural impacts, and recreational impacts. Regional and global impacts include the effects of different hydropower operations on statewide GHG emissions and electricity costs. This analysis shows that the environmental regime would reduce YRDP generation, which would result in more natural gas electricity generation, increasing statewide electricity costs by about 0.02% annually. Increased natural gas generation would result in an increase of $CO_2$ emissions of about 27,000 tonnes annually, and a global social cost of about $1 million per year. While the local impacts are negotiated in depth in hydropower relicensing, regional and global impacts are not.

Atmospheric scientists and hydrologists have suggested that California’s hydrology is changing on a decadal time scale – a much shorter timeframe than a 50-year hydropower operating license sought by the YCWA in this case study. Nonetheless, climate change impacts are not currently examined by any agency or stakeholder during the relicensing process. This analysis has demonstrated that climate change has the potential to significantly reduce hydropower generation and revenue – and that the impact of climate change on generation is likely much larger than the impact of implementing the environmental flow proposal. This has a number of important management and policy implications that should be considered, including: (1) Reduced YRDP generation due to climate change may result in increased GHG emissions, similar to the effect demonstrated in Section 5. (2) Reduced generation due to climate change may also affect the ability of hydropower projects to enable grid integration of variable renewable energy like wind and solar. (3) Reduced revenue under climate warming will make it harder for hydropower operators to sacrifice water for environmentally protective flows that could otherwise be used to generate electricity and bolster revenues. This may increase license compliance variances, resulting in lower flows, higher ramping rates, and therefore reduced environmental quality and survival rates of aquatic species downstream of dams. (4) AS markets for regulation up and spinning reserve may become an increasingly attractive and important revenue stream for hydropower operators under future climatic change.

The potential impacts of climate change lend credence to the argument for a more adaptive style management of hydropower projects. Hydropower operators and water resource managers like certainty – but water resource management in California has never operated under the luxury of certainty. Climate change introduces a new degree of uncertainty in water management, but attempts to understand how climate will impact WYT probability, streamflows, and timing of flows will buffer against that uncertainty. Viers (2011, p. 660) summarized the need to adapt the relicensing process to a changing climate: "Some adaptation will be necessary given the magnitude of anticipated change. The current approach by FERC, however, is likely to result in *reactive* adaptation with near-term, single actor solutions held in the private domain. The public trust would be better served by *anticipatory* adaptation with mid- to long-term, multiple actor solutions held in the public domain." Such adaptive management will be essential to ensure the multiple beneficial public uses and ecosystem services of managed river systems.

Although the specific findings cannot be transferred directly to other hydropower projects undergoing relicensing, the methods and process followed in these analyses are highly replicable. Future relicensing analyses should account for AS revenues, examine impacts by WYT, consider broader regional and global impacts of operating conditions, and analyze the impact of climate change on hydropower operations. The methods utilized in this study are an example of how such analyses could be done.

## 9. Conclusion

Large hydropower systems incur various impacts on society and the environment – but the manner in which these systems are operated can determine the severity of these impacts. The federal hydropower relicensing process – which occurs only once every 30-50 years – examines a number of potential impacts, but disregards others. This paper has identified some of the important tradeoffs that should be examined more carefully in future relicensing proceedings. These include higher-resolution analysis of impacts on hydropower generation and revenue, the greenhouse gas impacts of a change in demand for fossil fuel generation, and the impact of climate change on hydropower generation, revenues, and ability to provide environmentally protective flows.

For the case of the YRDP, this study found that the environmental operating regime reduces average hydropower generation by 6.1% and average revenue by 3.5% compared to the FLA. The impact on generation should not be used interchangeably with the impact on revenue in relicensing negotiations. Using reduced energy generation as a proxy for revenue losses is over-simplified, inaccurate, and misleading. The environmental regime increased average ancillary services provision (1.9%) and revenue (3.6%) compared to the FLA. This is because the reduced average energy generation under the environmental regime leaves more headroom in the powerhouse for upward capacity provision. While it may not always be the case that AS sales increase with more environmentally protective flow regimes, this finding suggests that leaving AS out of an analysis of costs and benefits of hydropower operating regimes may be a significant oversight.

The potential greenhouse gas impacts of different operating regimes are rarely quantified in the relicensing process. This study showed that in California, reduced hydropower generation under the environmental regime leads to an increase to natural gas generation, increasing GHG and other criteria pollutant emissions. For the YRDP, this would result in about 27,000 additional tonnes of $CO_2$ annually, with a global social cost of about $1 million per year. The increase in natural gas generation will also impact electricity markets, to some degree, due to an increase in the marginal cost of generation. This study showed, however, that for the YRDP this effect represented only 0.02% of the total wholesale electricity costs in the California electricity market. These global and regional impacts should be examined in order to understand the full range of social and environmental costs and benefits of different operating proposals under negotiation during the relicensing process, but they can be very difficult to compare against the local costs and benefits of different operating proposals.

Climate change is projected to increase the frequency of dry and critically dry years in California, resulting in reduced hydropower generation and revenue. For the YRDP, a simple analysis suggests that average generation may decrease by up to 5%, and average revenue may decrease by up to 4% by 2050. These losses are exacerbated looking further to the future. An increase in AS provision and revenue under climate scenarios buffer the revenue losses to some extent, suggesting that AS markets may become an increasingly attractive and important revenue stream for hydropower operators under future climate change. A more robust analysis of climate impacts on hydropower should consider not only the trend toward dry years, but also changes in timing, magnitude, and duration of streamflows under future climate change, which were not considered here. In sum, these findings emphasize the need for hydropower analyses to consider the effects of operations on generation, revenue, downstream ecology, and society within a non-stationary hydroclimate.

Future research should also examine the value of hydropower generation and AS under increasing penetration of variable renewable energy like wind and solar. This study used average prices for 2010-2012, but these prices may not be representative of energy and AS prices within the time frame of a 50-year license. For example, increased penetration of variable renewables may increase the need for flexible generation and grid regulation, which could increase the value of hydropower in the market. CAISO is soon to unveil a new "flexible ramping product" to the market which may add considerable value to hydropower (CAISO, 2016). On the other hand, increased deployment of battery electric storage and demand response may supply much of this grid regulation, which could potentially decrease AS prices. A reliable forecast for AS prices would be especially useful for this analysis given the increase in AS provision under the environmental regime. However, an initial sensitivity analysis showed relatively little overall effect on revenue impacts, even after increasing AS prices by 25%.

It is likely too late for this study to affect the relicensing negotiations of the YRDP, which are currently well underway. However, FERC and other stakeholders should be encouraged to conduct similar analyses to the type shown here. The analyses performed here produced important findings and present a methodology that could be followed in other hydropower analyses. Better data will support better management decisions, and lead to greater transparency and fairness in the relicensing process. Improving data, transparency, and process fairness will result in more optimal social, environmental, and economic outcomes while reducing social conflict.

In her New York Times Op-Ed, Senator Murkowski advocated for changes to streamline the FERC relicensing process. Many groups argue, however, that “streamlining” the process is synonymous with “short-cutting” the process. While the process may not be entirely “broken,” as Senator Murkowski suggests, there is room for improvement – both in efficiency and in quality. FERC should ensure that any legislative action to streamline the relicensing process does not come at a cost to the depth, quality, and transparency of analyses undertaken. Other relicensing participants, such as resource agencies and environmental and social NGOs, should continue to push for greater depth, quality, and resolution in relicensing studies – but should do so without creating unnecessary road-blocks and barriers that increase conflict and worsen outcomes overall. This study provides some guidance on how such analyses could be conducted and considered.

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