Local, Regional, and Global Trade-Offs of Hydropower Relicensing Decisions

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An Analysis of Electric Generation, Revenue, Electricity Market, Greenhouse Gas Emissions, and Local Environmental Impacts

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Abstract:
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 identifies some of the local, regional, and global trade-offs that should be examined more explicitly in relicensing proceedings. These include higher-resolution analyses of impacts on generation and revenue (including ancillary services) and the potential greenhouse gas impacts of different hydropower operating regimes. Any reduction of low-carbon generation may result in global environmental and social harms if it is replaced by fossil fuel generation. Although rarely quantified in the hydropower relicensing process, this is an important value in understanding the range of costs and benefits of different operating proposals. Using a case study of the Yuba River Development Project, this study finds that an environmentally protective operating regime reduces electric generation by 6.1% but increases ancillary services provision by 1.9% on average. The reduced hydropower generation is replaced by natural gas generation, resulting in an increase in CO_2 emissions with a global social cost of about $1 million annually.

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Contents

Abbreviations:

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
GHG	Greenhouse Gas
GW	Gigawatt
ILP	Integrated Licensing Process
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
TW	Terawatt
WYT	Water Year Type
YRDP	Yuba River Development Project
YCWA	Yuba County Water Agency

1. Introduction

1.1. Motivation and 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). Hydropower is widely valued as an electric generation source that does not contribute to climate-altering emissions like carbon dioxide (Kosnik, 2008), and as such has been accepted as a qualifying renewable energy source for the U.S. Environmental Protection Agency's Clean Power Plan (CPP) (NHA, 2015). 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 revenue (Rheinheimer et. al, 2013, Madani & Lund, 2010).

In the context of hydropower's contribution to climate change mitigation, this reduction in hydropower generation due to local environmentally protective flow regimes may result in an increase in greenhouse gas (GHG) emissions if that reduced generation is replaced with fossil-fuel generation. This shift toward higher marginal cost generation could also affect regional electricity market prices. This presents an interesting conundrum where local environmental and social benefits must be weighed against regional and global environmental and social costs. However, unlike most cost-benefit analyses, examining this conundrum requires the comparison of two essentially non-market valuations: local environmental benefits against global GHG costs.

In this paper, I use a case study of a hydropower project undergoing relicensing to examine the impact of an environmentally protective flow regime on (1) hydropower generation, (2) statewide GHG emissions, and (3) statewide electricity markets. I then calculate the Social

Cost of CO_2 (SCC) of the increased GHG emissions to generate a monetary value that the local environmental and social benefits of environmental hydropower operations can be compared against in cost-benefit analysis.

1.2. Background to Hydropower Relicensing:

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, representing over 54 Gigawatts (GW) of installed capacity and spanning 47 U.S. states. (FERC, 2016). FERC hydropower licenses regulate how non-federal hydropower projects in the U.S. will be constructed, operated, maintained, and decommissioned. 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). 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.

In an effort to identify and resolve stakeholder 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).

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. 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.

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 expires 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 facilities and 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.

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(YCWA, 2016). A subset of these have actively participated in negotiations of the new license and operating requirements of the YRDP.

This 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 operations proposal (known as the Final License Application [FLA]). The environmental coalition's recommendations are centered on 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, with small concessions for minimum required instream flows. 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

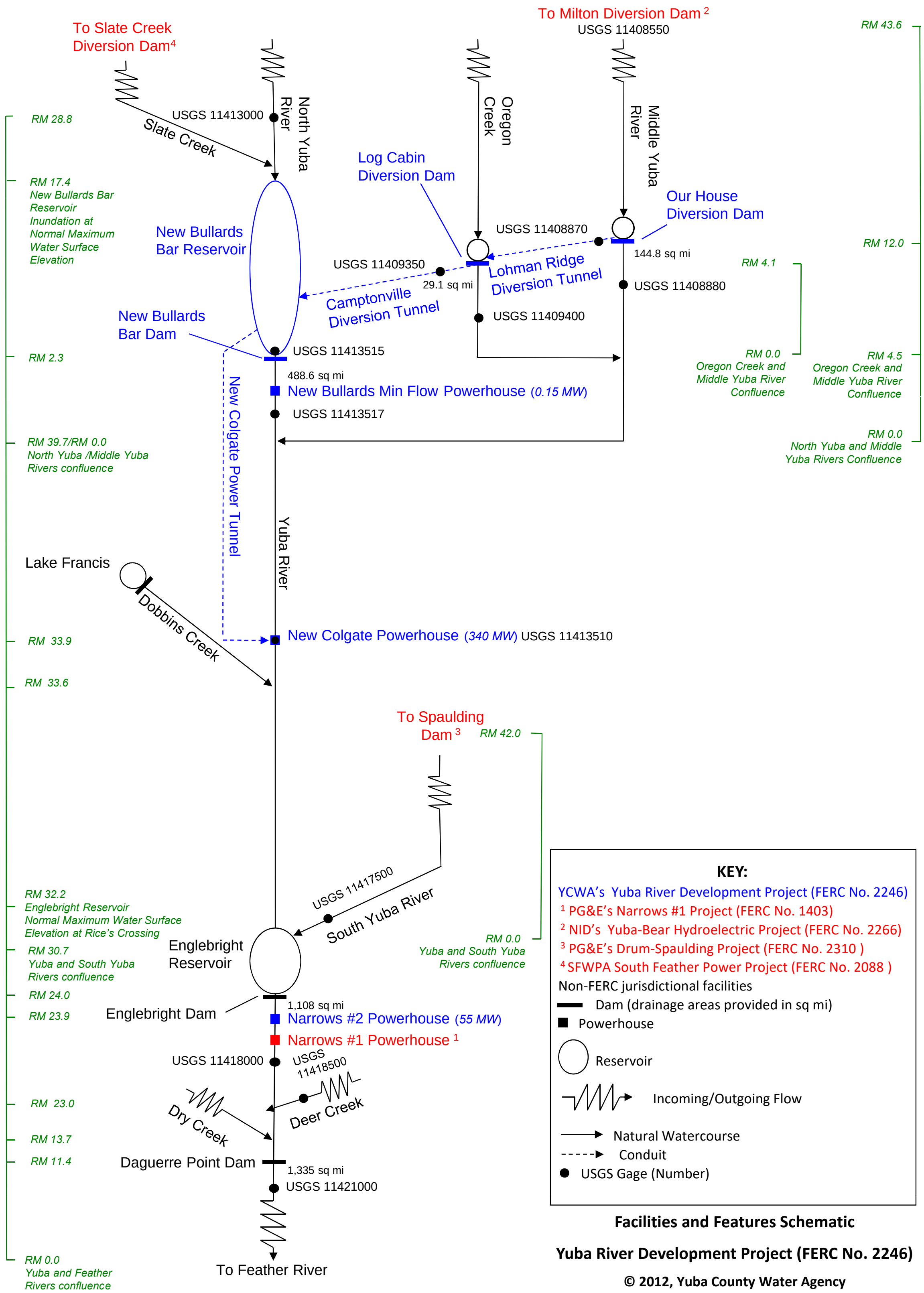
[1] See Poff, et al. (1997). "Flow regime is of central importance in sustaining the ecological integrity of flowing water systems. The five components of the flow regime - magnitude, frequency, duration, timing, and rate of change - influence integrity both directly and indirectly, through their effects on other primary regulators of integrity. Modification of flow thus has cascading effects on the ecological integrity of rivers" (Poff, et al., 1997).

released for flood control. These conditions apply to the North Fork Yuba River below New Bullards Bar 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 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 YCWA's Final License Application (FLA) flow proposal to FERC.

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



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.

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.

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).

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.

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.

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.

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. This assumption can be defended by overlaying the supply curve of electric generators in the CAISO electricity market with the histogram of hourly electric generation, which is shown in Figure 5.1. 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.

4. Generation and Ancillary Services Impacts of Environmental Flow 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.

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.

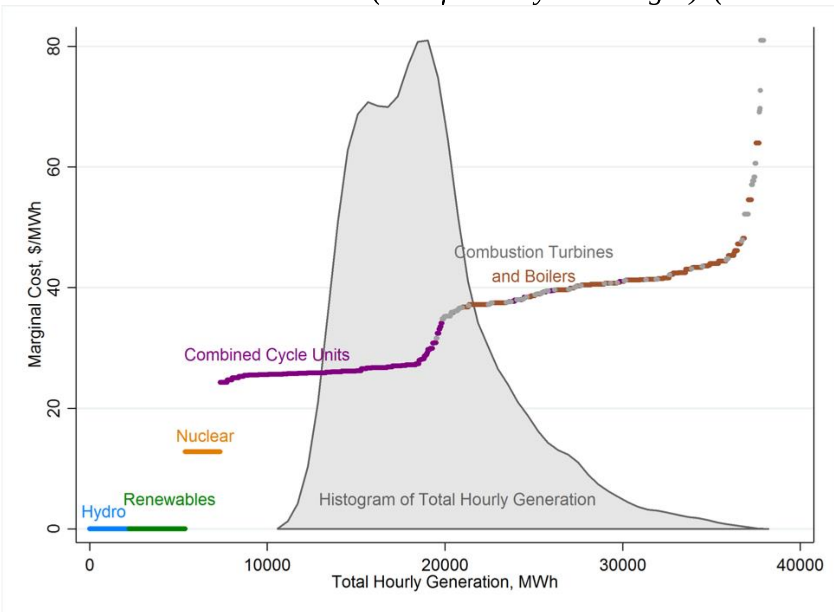
Niu and Insley (2013) did estimate the emissions impact of changes in hydropower generation shifting demand for fossil fuel generation, however their results were anomalous in that they found an *increase* in hydropower generation under environmental constraints. This was because operators increased 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.

<u>Figure 5.1:</u> 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.

<u>5.2. Impacts of Reduced YRDP Generation on Greenhouse Gas Emissions:</u>

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

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**

<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.

6. 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.

7. 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 and the potential greenhouse gas impacts of different hydropower operating regimes. Any reduction of low-carbon generation may result in global environmental and social harms if that generation is shifted to fossil fuel power plants. This is an impact that is not regularly quantified, but should be examined in order to understand the full range of social and environmental costs and benefits of different operating proposals negotiated in hydropower relicensing.

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.

In California, reduced hydropower generation under an environmentally protective operations 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.

As California moves to meet a 50% renewable portfolio standard by 2030, there may be more hours during the year when wind, solar, or other carbon-free electricity is on the margin. It is feasible, therefore, that the GHG impact of environmental flows could reduce as the electric grid decarbonizes. However, with 50% renewable penetration, ramp-rate restrictions on the YRDP will reduce the project's ability to ramp up as variable wind and solar generation declines, leaving fast-ramping natural gas to do so. Therefore, it is not perfectly clear how the impacts described in this paper would change under higher (i.e. 50%) renewables penetration. We can be confident, however, that a 50% renewables penetration would not result in a 50% reduction in the GHG impacts described here, since natural gas will still be marginal during most hours.

Although 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), and such work is outside the scope of this paper. 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). Based on the findings of this analysis, I suggest that this $1 million annual social cost of CO_2 may be weighed (along with reduced annual hydropower revenue) against the non-market value of environmental and ecosystem services gained through environmentally protective flow regimes for the YRDP.

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.

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