Examining the Net Revenue and Downstream Flow Impact Trade-Offs for a Network of Cascading, Small-Scale Hydropower Facilities

Preprint

Michael Craig,[1] Jin Zhao,[2] Gia Schneider,[2]
Abe Schneider,[2] Sterling Watson,[2] and Greg Stark[3]

1 University of Michigan
2 Natel Energy
3 National Renewable Energy Laboratory

Presented at Hydrovision International
Portland, Oregon
July 23–25, 2019

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Conference Paper
NREL/CP-5000-74274
May 2020

Contract No. DE-AC36-08GO28308

Examining the Net Revenue and Downstream Flow Impact Trade-Offs for a Network of Cascading, Small-Scale Hydropower Facilities

Preprint

Michael Craig,[1] Jin Zhao,[2] Gia Schneider,[2]
Abe Schneider,[2] Sterling Watson,[2] and Greg Stark[3]

1 University of Michigan
2 Natel Energy
3 National Renewable Energy Laboratory

Suggested Citation
Craig, Michael, Jin Zhao, Gia Schneider, Abe Schneider, Sterling Watson, and Greg Stark. 2020. *Examining the Net Revenue and Downstream Flow Impact Trade-Offs for a Network of Cascading, Small-Scale Hydropower Facilities: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-74274. https://www.nrel.gov/docs/fy20osti/74274.pdf.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5000-74274
May 2020

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Examining the Net Revenue and Downstream Flow Impact Trade-Offs for a Network of Cascading, Small-Scale Hydropower Facilities

Michael Craig[1], Jin Zhao[2], Gia Schneider[2], Abe Schneider[2], Sterling Watson[2], and Greg Stark[3,4]

Abstract

Introduction

One of the challenges associated with conventional, large-scale hydropower (> 50 MW) is the local environmental impact on stream flows and water quality, and investigating how small-scale hydropower (< 10 MW) might help mitigate these consequences was the inspiration for the research presented here. We examined how the co-optimization of the operation of a 36-station array of cascading small hydro facilities would perform economically while ensuring minimal impact to river flows. This work was conducted by the National Renewable Energy Laboratory and Natel Energy, as a part the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy's Small Business Voucher program.[5]

Background

Concerns about how water impoundment and the large fluctuation in downstream flows affects the quality of river systems has been an ongoing concern for a number of years (Kern et al. 2012, Jager and Bevelhimer 2007). Earlier work examined whether dams could be operated so that they mimicked natural stream flows by changing their operations from load following to run of river. Kern et al. (2012) investigated how varying the operational paradigm for a single, large hydropower plant located in PJM's operational area would affect that facility's net revenues. They found that by switching from a load-following to a run-of-river approach would reduce annual revenues by up to 15%. Similarly, Jager and Bevelhimer (2007) performed a retrospective analysis of hydropower facilities that had changed from peaking to run-of-river operations, and they found that most facilities had reduced generation efficiency; however, they did not quantify how these changes affected revenues. Common to both studies is that plant operations were examined in isolation, that is, separate from other river operations (e.g., cascading plants were not considered).

---

[1] University of Michigan School for Environment and Sustainability, 440 Church Street, Ann Arbor, MI 48109 (Michael performed this research while at the National Renewable Energy Laboratory)

[2] Natel Energy, 2401 Monarch Street, Alameda, CA 94501

[3] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401

[4] Corresponding author: Greg.Stark@nrel.gov

[5] EERE's Small Business Vouchers (SBV) program opens the national labs to qualified clean energy small businesses by making the contracting process simple, lab practices transparent, and access to the labs' unique facilities affordable. Most importantly, SBV gives U.S. clean energy small businesses an incredible competitive advantage in the global marketplace and increases national lab awareness of the challenges small businesses face in the energy sector (please see https://www.energy.gov/eere/technology-to-market/small-business-vouchers for more information).

The current work builds on the previously mentioned efforts and investigates whether a series of cascading, small, low-head hydropower plants can be operated in a manner to minimize the impacts to water quality while not significantly reducing operational revenue (with downstream flows serving as a proxy for water quality).

Test System

The system under study comprises 36 small-scale hydropower facilities designed by Natel Energy (2018). Each facility used one of two hydroEngine linear Pelton impulse turbines, with the choice being dependent on the head available for the given facility (see Table 1).

Table 1. hydroEngine Types and Capabilities

hydroEngine type	Number of facilities	Average power (min–max) at maximum head height [MW]
1	32	1.0 (0.93–1.06)
2	4	0.5 (0.46–0.51)

The linear Pelton design provides excellent rangeability, and the power output of the units can increase from zero to maximin capacity (and vice versa) within a matter of minutes. Additional information about the hydroEngine turbines can be found at Natel Energy's website (Natel Energy 2018).

Each turbine was coupled to a 2-meter-deep forebay, and the storage volumes of the forebays ranged from 0.02 to 0.77 MWh of stored energy (700-49,000 m^3). The units were deployed in a cascading manner, with upstream units feeding the reservoir of units downstream. When summed across all 36 facilities, the stored energy equates to 8.82 MWh, with a nameplate capacity of 33.5 MW. Accounting for downstream generation, the stored energy ranges between 0.59 and 5.98 MWh for each station (the amount of storage varies with both reservoir size and a facility's position in the cascade) and 87 MWh across all facilities.

For purposes of the study, historic flow information from the U.S. Geological Survey's Goodyear Bar gaging station on the Yuba River, located in Sierra County in Northeastern California, was used (U.S. Geological Survey 2018). The 36 generating stations were deployed in a cascading manner and located over a 36-km stretch of the river upstream of Goodyear Bar, with the traversal times between facilities ranging between 0.10 and 1.90 hours, respectively. Fifteen-minute flow data were used, and facility-specific flows (i.e., upstream flows at each generating station) were calculated based on a ratio of each facility's drainage area and the Goodyear Bar drainage area. To ensure robustness in the results, data for dry (2015), typical (2016), and wet (2017) years were used.

Additional information about the test system can be found in Craig et al. (2019).

Analytical Approach

In order to characterize how constraining downstream flows affects generator revenue, we used a multi-integer linear programming model that optimized the net revenue subject to operating and environmental constraints. These constraints limited downstream flow impacts and represented machine performance characteristics, cascading flows between facilities, minimum flow requirements, and nonlinear power generation and reservoir volume relationships. The nonlinear aspects of the problem were simplified by using piecewise linear approximations (e.g., the head to available power relationship for each facility was modeled as a two-piece linear approximation).

Net revenue consisted of energy and ancillary service revenues, including mileage payments, minus variable operation and maintenance costs (California Independent System Operator [CAISO] 2016). We used a price-taker approach given the test system's small size (33.5 MW) relative to the amount of generation in CAISO's footprint (CAISO has over 50,000 MW of capacity). Net revenue optimizations relied on historic price data from CAISO's northern zone (NP15), and both day-ahead unit commitment and hourly dispatch optimizations were performed for all three study years (CAISO 2017).

To capture the water transversal times (up to 15 hours from the first to last facility), we ran the model with a 15-hour window plus 2-hour look-ahead period.

Table 2. Characteristics That Drove Model Design

Motivating Technology Characteristic or Desired Feature	Model Design Implication
Combined capacity of Natel's turbines are small relative to total system capacity	Model maximizes net revenues of turbines assuming they are price takers
Natel cares about profitability and environmental impacts	Model constrains operations to minimize streamflow impacts
Natel plans initial deployment within CAISO's footprint	Model optimizes operations across energy and multiple ancillary service markets
Natel plans to deploy 36 turbines in sequence along one river	Model captures impacts of upstream turbines on downstream turbines
Low-head turbines have nonlinear stored water volume and generation functions	Model uses piecewise linear approximations for stored volume and generation
Natel may deploy technology in other regions	Model's flexibility permits its application to estimate revenues in other systems

The primary factors that drove the model design are summarized in Table 2, and a schematic of the resulting model is shown in Figure 1. Note that the model was constructed so that it would be easy to adapt for other study types (e.g., in related work, we performed studies that examined how variable operation and maintenance [VO&M] costs impacted net revenues) as well as study areas (the model was designed so that market products are easy to configure, and the market product price streams are read from csv files).

Additional information about the analytical approach and the resulting model can be found in Craig et al. (2019).

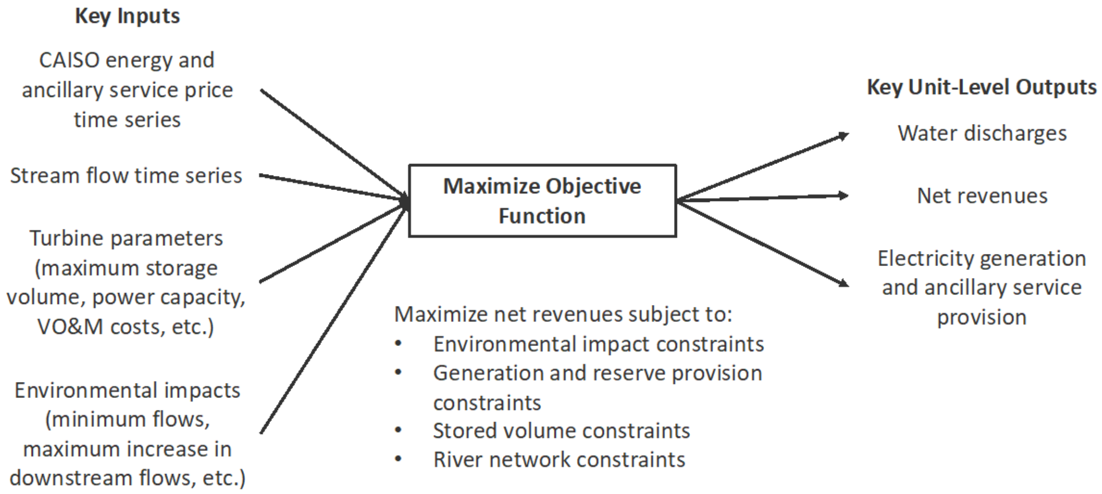

Figure 1. Profit maximization model

Results

Two types of scenarios were performed: one that investigated how limiting downstream flows would impact plant revenues, and another that examined role reservoir size on net revenues.

The nominal annual electricity generation and net revenues for the dry, typical, and wet years are shown in Table 3.

Table 3. Annual Generation and Net Revenue for the Combined Facilities

Year (conditions)	Annual Generation (GWh)	Annual Net Revenue (thousands $)
2015 (dry)	55	500
2016 (typical)	93	900
2017 (wet)	142	2,200

These values can be used to provide context for how limiting downstream flows affects annual generation and net revenues.

Downstream Flow vs Revenue

The primary study goal was to investigate how limiting downstream flows (i.e., adding additional environmental constraints) would impact the net revenues for the 36-station test system given its cascading configuration.

We investigated a baseline run and three flow-constraint sensitivities, as follows:

None: no downstream flow limitations (traditional load-following operation)

- 1: downstream flows were allowed to increase (decrease) by up to 100% of nominal
- 0.5: downstream flows were allowed to increase (decrease) by up to 50% of nominal
- 0.05: downstream flows were allowed to increase (decrease) by up to 5% of nominal.

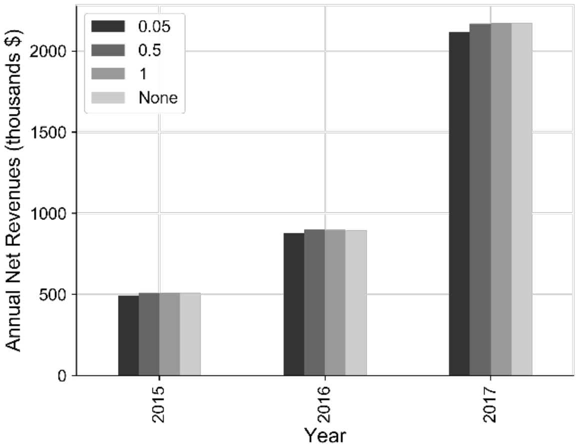

Figure 2. Annual net revenue as a function of flow constraint

We performed optimizations for all 3 years to help ensure robustness across dry (2105), nominal (2016), and wet (2017) years, and assessed the impacts on both generation and net revenues.

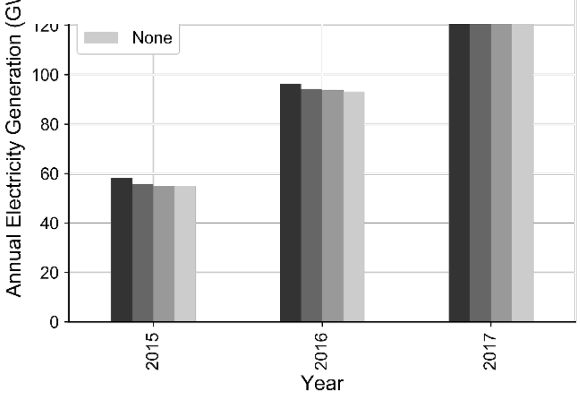

Figure 3. Annual generation as a function of flow constraint

Figure 2 illustrates how the downstream flow constraints affect annual profits. As can be observed, it is difficult to visually distinguish any change in net revenues except in the case where the downstream flows are limited to ±5% of the nominal flow. Even in the most restrictive case, the revenues are only reduced by 4%, which is a number within the optimality gap of the models, and so we cannot say definitively that the revenues actually decrease, even under the most restrictive flow limitation.

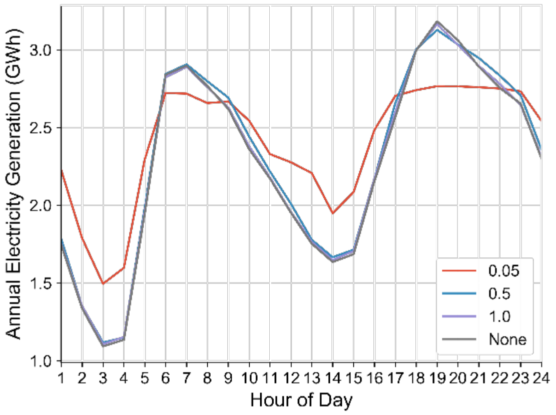

Figure 4. Changes in annual net revenues for a dry year (2015)

Contrary to the impacts on net revenues, annual generation increases when flow constraints are imposed, increasing power generation by up to 6% across the 3 study years. The reason for this is that the flow constraints shift some of the generation from peak to off-peak hours, flattening each generation facility's daily generation profiles (see Figure 4 for an example of how the peaks are shaved and the valleys filled as the downstream flow limits increase). The shift in generation from peak to nonpeak hours also reduces the use of storage reservoirs (the reservoirs are full more of the time, and, consequently, the generators operate at higher head, thereby producing more energy per volume of water).

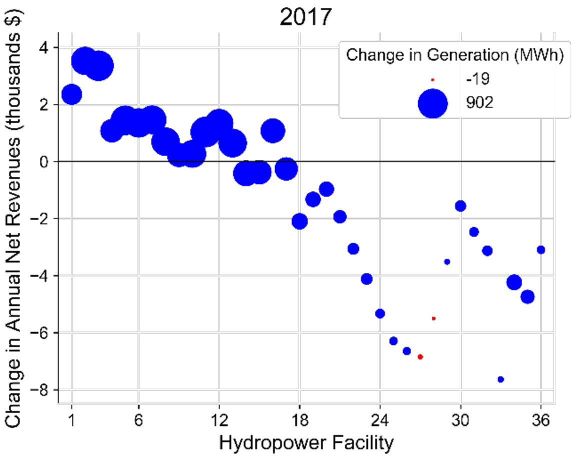

Figure 5. Changes in annual net revenues for a wet year (2017) when downstream flows are limited to ±5% of nominal

Also of interest is how the generation patterns at the individual facilities shift with changes in the downstream flow constraints. Although the combined net revenue for the 36 facilities decreased slightly, the revenues of the individual facilities change markedly, with upstream facilities generating more at the expense of the downstream facilities. The combined changes largely cancel, with only a 4% change in net revenues even under the most extreme constraint (the ±5% flow limit). An example of how the output of individual generators is impacted is shown in Figure 5, wherein the generation at the upstream units increases significantly (facility 1 is the unit that is the farthest upstream). The pattern of generation changes across dry (2015), typical (2016), and wet (2017) years is similar, with the largest increase in generation occurring at facility 2 and the largest decrease at facility 27. The relative impacts to the generation at these two facilities is shown in Table 4.

Table 4. Change in Annual Generation when Downstream Flows are Limited to ±5% of Natural Flows

Generation change (MWh)	Dry Year (2015)	Typical Year (2016)	Wet Year (2017)
Largest increase (station 2)	856	956	902
Largest decrease (station 27)	-103	-10	-19

As to why the impact of the flow constraints differs from earlier findings (i.e., the flow constraints had minimal impact on net revenues), we believe that this is a result of our model's ability to optimize all of the degrees of freedom provided by having a large number of small, flexible facilities in close proximity; however, additional research is needed to confirm this hypothesis.

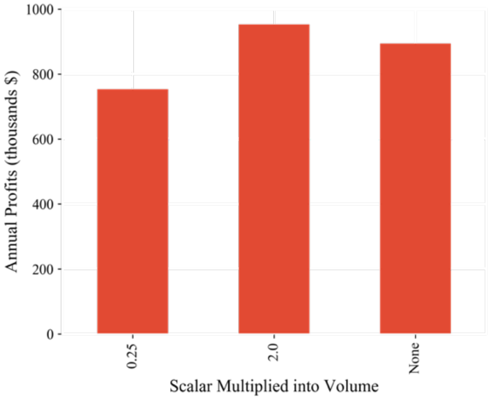

Figure 6. Annual net revenues as a function of reservoir size (typical weather year, 2016)

Reservoir Size

To help ensure that the study results are not an artifact of the small reservoir sizes, we examined how reservoir size would affect revenues (see Figure 6). For a typical year with no downstream flow constraints, doubling the reservoir size at each facility increased net revenues by 7%; whereas, quartering the reservoir size reduced the system's net revenues by 16%. We observed that, although the individual reservoirs are small (each contains between 2 to 45 minutes of storage capacity), they add to the system's net revenue potential.

Conclusion

In this study, we analyzed how constraining the downstream flows of a hypothetical array of 36 cascading, small-scale hydropower facilities would affect net revenues. We built a model for the hypothetical system and examined its operations under typical, dry, and wet conditions. We discovered that limiting the downstream flows to ±50% of the river's natural flows had a negligible impact on net revenues (<1% reduction in net revenues), irrespective of hydrologic conditions, and even when downstream flows were limited to ±5% of the river's natural flows, net revenues were only impacted by 4%. These outcomes are significant in that they demonstrate how an array of small-scale hydropower facilities can be operated so that the facilities have minimal impact on natural stream flows. This work opens several new potential research areas including exploring how using small-scale hydropower can be used for stream restoration and investigating how multifacility optimization can be used to mitigate environmental impacts.

Acknowledgements

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

California Independent System Operator (CAISO), 2016. *Fifth replacement electronic tariff (see https://www.caiso.com/Documents/Section4_RolesAndResponsibilities_asof_Oct1_2016.pdf)*.

CAISO, 2017. Locational Marginal Prices (LMP), node TH_NP15_GEN-APND *OASIS* Online: http://oasis.caiso.com/mrioasis/logon.do?reason=application.baseAction.noSession.

Craig M, Zhao J, Schneider G, Schneider A, Watson S, and Stark G, 2019. Net Revenue and Downstream Flow Impact Trade-Offs for a Network of Small-Scale Hydropower Facilities in California, Envioronmnetal Research Communications. **1** 011001.

Jager H I and Bevelhimer M S, 2007. How Run-of-River Operation Affects Hydropower Generation and Value, *Environ. Manage.* **40** 1004–15.

Kern J D, Characklis G W, Doyle M W, Blumsack S, and Whisnant R B, 2012. Influence of Deregulated Electricity Markets on Hydropower Generation and Downstream Flow Regime, *J. Water Resour. Plan. Manag.* **138** 342–55.

Natel Energy, 2018. (see https://www.natelenergy.com/ and https://www.natelenergy.com/turbines/ for information about the company and its products).

U.S. Geological Survey, 2018. USGS 11413000 N Yuba R Bl Goodyears Bar, CA *usgs.gov.*