FEATURE

Potential Solar Replacement of Hydroelectricity to Reopen Rivers: Maine as a Case Example

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A backhoe begins work June 24, 1999, on removing the 850-foot-long Edwards Dam in Augusta, Maine, built in 1837 and constructed of a cribwork of logs and stone and later capped with concrete. When the dam is breached the water level will drop 10 feet behind the dam. Photo Credit: Kennebec Journal

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Hydroelectricity provides 6% of U.S. electrical power needs, but hydro-dams block migrations of both anadromous and catadromous fishes. Engineered fishways have been built to facilitate fish movements past dams, but many have performed poorly. Dam removal is an effective way of restoring dwindling migratory fish populations by allowing unrestricted pathways to their spawning areas and for the downstream migrations of post-spawning adults and juveniles. However, hydro-dam removals result in a loss of electricity production. For the replacement of energy foregone from a dam removal, various alternative energy installations are now feasible. Here, we present a one-to-one conceptual replacement of hydropower with photovoltaic (PV) outputs for large and small river systems in Maine. We estimate that the equivalent land area needed to replace 14 hydro-dams with PV panels in the Kennebec River watershed—producing an annual mean (±SE) of 1,101.7 ± 37.9 gigawatt-hours—is 950.7 ± 32.8 ha, which is equivalent to 22% of the existing reservoir area. For the Mousam River, three hydro-dams could be replaced with 0.38 ha of PV. Our results indicate that modest land areas are needed to replace hydroelectricity with PV from even heavily dammed rivers, providing a realistic and potentially highly effective conservation policy option for Maine and for elsewhere.

INTRODUCTION

Water-generated energy, either mechanical or hydroelectricity, has long helped shape human civilizations, but at the expense of free-flowing waters. Taming of rivers for these purposes has often been celebrated, with some large hydro-dams considered engineering marvels (Moran et al. 2018). Advocates also cite hydropower's rapid dispatchability and sometimes low electricity costs as an advantage over other energy sources (Johansson et al. 2012). However, many detrimental effects of dams have been identified, most notably the complete blockage or retardation of upriver and downriver movements of diadromous fishes (Limburg and Waldman 2009).

In the United States, there are approximately 85,000 dams in the conterminous 48 states (Lovett 2014). Less than 4% (2,603) of these dams provide hydropower; however, many of America's largest dams were built primarily to generate electricity (USACE 2018). Today, hydroelectricity remains a modest contributor to American electricity needs, with hydro-dams providing about 6%—a share that is declining (Sharma et al. 2018). However, the proportional contribution of hydroelectricity by state varies widely depending on water resources, historical dam construction, and power delivery networks, and ranges from 0% in Delaware, to negligible in Florida and Georgia, to 61% in Oregon and 71% in Washington (EIA 2018).

Engineered fishways are one apparent solution to allowing migratory fishes to move past dams, but the record of this form of mitigation in the example of the U.S. Northeast is poor (Bunt et al. 2012; Noonan et al. 2012; Brown et al. 2013). There is, however, a growing dam removal movement in the USA based in part on the ecological benefits provided, with monitoring of removals usually showing rapid incursions of migratory fishes into previously occluded river reaches, and with subsequent population increases (Lovett 2014; O'Connor et al. 2015). A prime example is removal in 2011 of the Elwha Dam in the state of Washington. Before removal, anadromous species were restricted to spawning in the 7.4 km of river below the dam. Chinook Salmon *Oncorhynchus tshawytscha*, Coho Salmon O. *kisutch*, Chum Salmon *O. keta*, and Pink Salmon *O. gorbuscha*, as well as Pacific lamprey *Lampetra tridentata* are now recolonizing their former habitat upstream of that location, including the reach above the Glines Canyon Dam at river km (rkm) 21.6, which was removed in 2014 (Moser and Paradis 2017; Duda et al. 2020).

Maine has witnessed considerable success in restoring habitat connectivity via dam removal; e.g., in 1999, removal of Edwards Dam on the Kennebec River (Crane 2009) was the first of a hydroelectric dam regulated by the Federal Energy Regulatory Commission (FERC) on the Atlantic Coast. Though the dam generated only 3.5 megawatts of electricity (0.01% of the state's energy output) it had blocked upriver migration of fish from the sea for 162 years. When it was removed, it reopened 27 km of mainstem river. Migratory fish rapidly recolonized the newly available river above the dam, with the federally endangered Shortnose Sturgeon *Acipenser brevirostrum* returning to its historic spawning sites (Wippelhauser et al. 2015). It also allowed access to a major tributary, the Sebasticook River, initiating one dam removal, installation of a fish elevator at another dam, and stocking efforts of Alewife *Alosa pseudoharengus* that ultimately resulted in a combined run size of Alewives and Blueback Herring *A. aestivalis* rising from zero before the Edwards Dam removal to approximately 6 million in 2018 (MDMR 2018). Similarly, elsewhere in Maine, after the removal of the two lowermost dams in the Penobscot River—a part of the larger Penobscot River Restoration Project—significant changes were seen in fish assemblages in its mainstem and tributaries driven by the presence of more anadromous fishes (Day 2012; Watson et al. 2018).

Additional rationale for dam removal can be found in the fact that U.S. hydropower dams are aging, increasingly exceeding their expected lifespans, while being tested on occasion by higher flows consistent with climate change (van Vliet et al. 2016). Long touted for providing clean energy with respect to its lack of apparent air pollution, it is now known that the impounding waters behind dams leads to increased production of the potent greenhouse gas methane from decaying vegetation (Miller et al. 2017). Nonetheless, the contribution of electricity generated from hydro-dams in the United States is in demand. One emerging solution to remediating the environmental and hazardous consequences of hydro-dams, while not sustaining net energy losses, is to replace the energy foregone by removals of hydro-dams with alternative energy sources (Waldman et al. 2019).

Alternatives to hydropower are rapidly ramping to industrial scales. New sources of municipal-level electricity production include solar, i.e., photovoltaics (PV: Figure 1), and wind power, among several other more minor, but promising sources. As a first look at the potential for an alternative energy source to substitute for electricity generation forgone by dam removals, Waldman et al. (2019) estimated the amount of land required for PV arrays to generate the equivalent electricity now provided by hydropower on a state-for-state basis for the conterminous USA. It was found that in summary of these results by state, on the basis of actual total hydropower generation in 2016 (i.e., 274,868 gigawatt-hours/year), 529,885 ha of PVs would be needed to replace the electricity generation of all 2,603 American hydro-dams—an area approximately equal to the land size of Delaware, which corresponds to a much

Figure 1. Aerial view of a 2-megawatt solar farm at Elizabethtown College, Pennsylvania (used with permission).

smaller area currently flooded by reservoirs. Moreover, PVs could replace the total annual energy produced from these dams, while requiring only 13% of their existing reservoir area.

Although Waldman et al. (2019) revealed strong potential for area-efficient replacement of hydropower by PVs, the analysis did not extend below the level of individual states. To examine this concept at a more granular level, we selected watersheds in the state of Maine to conduct comparable simulations. Maine relies heavily on hydroelectricity (proportional contribution 30%), having the third highest number of hydrodams in the United States, 241, behind only California (339) and New York (279). Moreover, major rivers in Maine average more than 5 mainstem dams (Goode 2006), with 76% of the state's hydropower generated from the state's 24 largest dams. However, most dams in the state have less than a 10-megawatt capacity, with a mean of 3 megawatts per dam; 46 dams have less than or equal to a 1-megawatt capacity (NRCM 2003). Maine is also located at high latitude, with only seasonally abundant sunlight, and as such represents a conservative example for PV vs. hydropower tradeoff.

Historical narratives and scientific reports describe large fish runs in Maine's rivers prior to human intervention (Hall et al. 2012). Since the erection of its first dam in 1634, the river landscape of Maine has been severely altered. By the early 1850s, the accessibility of original habitat to its anadromous fish populations was reduced by as much as 95% (Hall et al. 2011). Maine has an extensive diadromous fish fauna that would benefit from dam removals beyond those that have already occurred, e.g., on the Penobscot River (Day 2012; Watson et al. 2018). Catadromous American Eels *Anguilla rostrata* migrate up Maine rivers. Additionally, all anadromous fish species that occur along the U.S. Atlantic Coast have spawning populations in Maine, with the exception of Hickory Shad *A. mediocris*. These include Atlantic Salmon *Salmo salar*, Atlantic Sturgeon *A. oxyrinchus*, Shortnose Sturgeon, Sea Lamprey *Petromyzon marinus*, American Shad *A. sapidissima*, Alewife, Blueback Herring, Rainbow Smelt *Osmerus mordax*, and Striped Bass *Morone saxatilis*, plus facultatively migratory species such as Brook Trout *Salvelinus fontinalis*, White Perch *M. americana*, and Atlantic Tomcod *Migrogadus tomcod*.

To represent a large watershed, we examined the heavily dammed Kennebec River, the longest river entirely within the

Table 1. Dams on the Kennebec River and tributaries and associated physical and electrical generation data (in order, moving upriver from the most downriver dam).

Dams	Rivers	Approximate river km upstream of river mouth	[1]Actual generation mean ±SE (gigawatt-hours/year)	[2]License expiration date	[3]Nameplate capacity (megawatts)	[4]Capacity factor (%)	Required Solar area equivalent (ha)	[5]Existing reservoir area (ha)
Lockwood Hydroelectric	Kennebec	100	32.1 ± 1.2	10/31/36	7.2	48.5	27.7 ± 1.0	32.8
Hydro Kennebec	Kennebec	103	71.5 ± 7.7	09/30/36	15.4	45.3	61.7 ± 6.7	101.2
Shawmut	Kennebec	106	51.4 ± 1.5	01/31/21	8.8	55.5	44.4 ± 1.3	530.1
Weston Hydro	Kennebec	132	81.6 ± 3.6	10/31/36	12.0	68.2	70.4 ± 3.1	376.4
Anson Abenaki	Kennebec	152	134.4 ± 5.4	04/30/54	29.0	42.5	116.0 ± 4.7	282.5
Williams Hydro	Kennebec	173	94.5 ± 2.5	04/30/54	13.0	73.1	81.6 ± 2.1	180.5
Wyman Hydro	Kennebec	187	371.1 ± 13.5	10/31/36	72.0	47.4	320.3 ± 11.6	1311.2
Harris Hydro	Kennebec	233	219.9 ± 12.8	10/31/36	76.4	27.2	189.7 ± 11.0	1516.0
Gardiner	Cobbosseecontee	61	5.3 ± 0.4	04/30/19	1.0	46.5	4.6 ± 0.3	4.9
Messalonskee 5 (Union Gas)	Messalonskee	99	5.3 ± 0.6	06/30/36	1.8	26.4	4.5 ± 0.6	10.1
Messalonskee 3 (Rice Rips)	Messalonskee	110	5.4 ± 0.6	06/30/36	1.6	30.5	4.7 ± 0.6	35.4
Messalonskee 2 (Oakland)	Messalonskee	113	9.4 ± 1.1	06/30/36	2.8	30.0	8.1 ± 0.9	3.9
Benton Falls	Sebasticook	107	15.7 ± 1.0	02/28/34	4.2	34.0	13.6 ± 0.9	33.6
Pittsfield (Burnham)	Sebasticook	133	4.0 ± 0.3	10/31/36	1.1	29.7	3.5 ± 0.3	123.0

[1]Mean production considered from 2010–2016 (Source: EIA 2018)

[2](Source: FERC 2018)

[3](Source: ORNL 2018)

[4]Calculated based on [1] and [3]

[5](Source: U.S. Army Corp of Engineers National Inventory of Dams 2018)

state of Maine. We estimated the land area needed to replace the equivalent amount of foregone hydroelectricity with solar energy on the Kennebec River. Secondly, we estimated the PV area needed to replace hydro-dams on the Mousam River, a much smaller but also heavily dammed watershed in southern Maine.

METHODS

Descriptions of Watersheds and Hydroelectric Facilities

Kennebec River

The Kennebec River watershed occupies 15,200 km^2 in central Maine, running for 270 km from its source at Moosehead Lake at 370 m above sea level to the sea at the city of Bath. The mean flow of the Kennebec River is 258 m^3/s near its mouth. We identified 14 functional hydroelectric dams within the Kennebec River basin (Table 1; Figure 2). Eight dams are on the mainstem Kennebec River, from rkm 100 to 233. Six are on major tributaries, including the Cobbosseecontee (rkm 1), the Messalonskee (rkm 3), and the Sebasticook (rkm 2). Nameplate generation capacity at mainstem dams ranged from 7.2 megawatts at Lockwood Dam to 76.4 megawatts at Harris Dam; actual mean generation (2010–2016) ranged between mean (±SE) of 32.1 ± 1.2 gigawatt-hours/year at Lockwood to 371.1 ± 13.5 gigawatt-hours/year at Wyman Hydro Dam. Among tributaries, nameplate capacity ranged from 1.0 megawatts at Gardiner Dam on the Cobosseecontee River to 4.2 megawatts at Benton Falls Dam on the Sebasticook River. Actual generation (2010–2016) on the tributaries ranged between 4.0 ± 0.3 gigawatt-hours/year at Pittsfield Dam to 15.7 ± 1.0 gigawatt-hours/year at Benton Falls Dam, both on the Sebasticook River.

Mousam River

The Mousam River watershed encompasses 272 km^2 and originates at an elevation of 146 m, and flows 48 km at a mean rate of 5.07 m^3/s until meeting the sea near Kennebunk in southern Maine (USGS 1978). With 11 mainstem barriers, the Mousam is one of the most heavily dammed rivers in the state, of which the 3 lowermost are hydro-dams (Table 2; Figure 2). Nameplate generation capacity at these dams ranged from 0.15 megawatts at Kesslen and Dane Perkins Dams to 0.55 megawatts at Estes Lake Dam; actual generation in 2017 ranged between 0.04 gigawatt-hours/year at Dane Perkins Dam to 0.46 gigawatt-hours/year at Twine Mill Dam.

Data Sourcing and Analysis

The area of photovoltaics required to replace the existing hydropower dams in the Kennebec and Mousam river basins was estimated using databases from U.S. federal agencies. The U.S. Energy Information Agency (EIA) maintains the largest database on commercial energy production in the United States. The actual annual energy production from conventional hydroelectric using hydraulic turbine data for the Kennebec River basin was accessed at the EIA webpage (available: https://bit.ly/2RO6oyM), whereas for the Mousam River, the Maine Hydropower Study (Kleinschmidt 2015), was accessed in July 2018. For our purposes, we averaged the actual production of each hydropower dam for the latest 7 years available (2010–2016; Table 1) for the Kennebec River, but for the Mousam River, due to unavailability of the long-term data, only 2015 data (Table 2) were used. The nameplate capacity of each dam was obtained from the Oak Ridge National Laboratory's National Hydropower Asset Assessment Program's webpage (available: https://bit.ly/33A3W1I). Dates of license expiry were obtained from the FERC webpage (available: https://bit.ly/2Q7t7FE). Capacity factor (the ratio of its actual output over a period of time, to

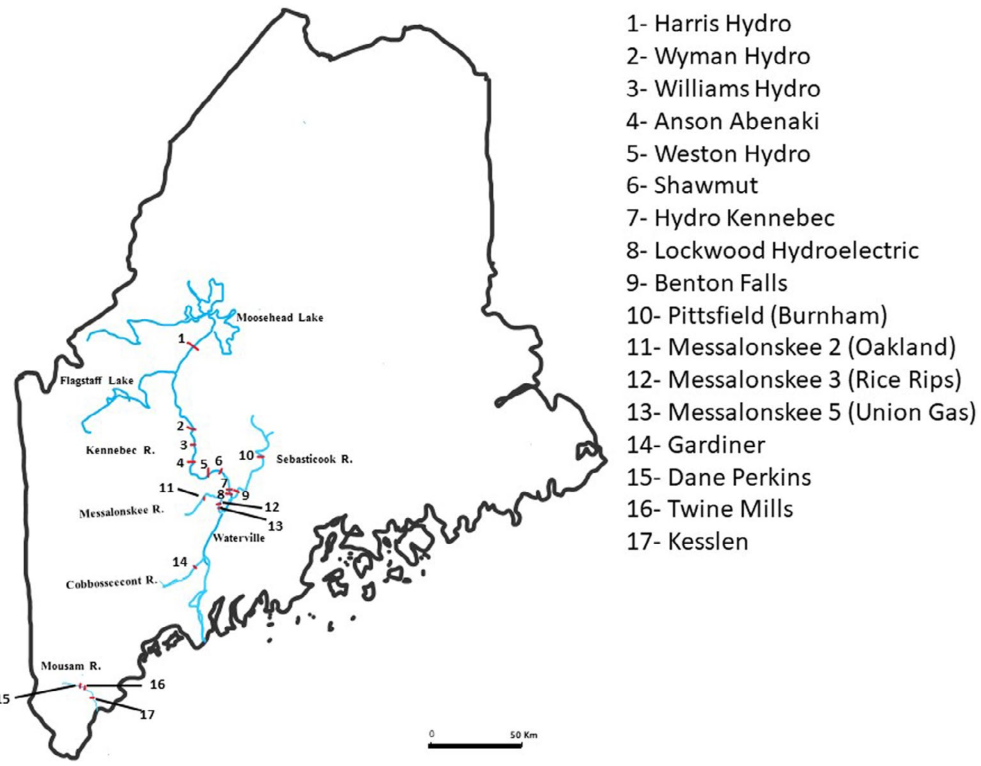

Figure 2. Map of Maine showing the Kennebec River and Mousam River with tributaries and hydro-dams.

its potential output if it were possible for it to operate at full nameplate capacity indefinitely) of each dam was calculated based on the actual annual production and the nameplate capacity. Finally, the existing reservoir area of the dams were obtained from U.S. Army Corp of Engineers National Inventory of Dams (available: https://bit.ly/2RO6WVm).

For the PV cell area estimate, we used PVsyst 6.68 developed by PVsyst SA, Switzerland. This program takes into account geographic location, modules, inverters efficiency, orientation, and inclination of solar panels. We considered a grid-connected PV system for this analysis. Because of their low energy storage loss, grid-connected systems are considered more effective than storage-based systems. We chose Waterville, Maine (44.56°N, −69.59°W; Figure 2) as the solar radiation receiving site. The climatic variables used were obtained from Meteonorm 7.1 (1991–2005) database for Waterville. The monthly details of climatic variables of the area are given in Table 3.

For the optimal output, we simulated PV module to Si-poly YL250-29b YINGLI SOLAR with a plane tilt of 30° and azimuth of 180° to the tangential plane. For the inverter, we chose two TBEA Xi'an electric inverters with 500-kilowatt power with the operating voltage of 450–820 and maximum voltage of 1000 volts. The output was selected at 50 and 60 Hz for local compatibility.

Our calculations show that a total of 4,000 poly crystalline modules, 200 strings in parallel and 20 modules in series are needed to generate 1000 kilowatts of power. The area required for fixing the panels is 6,494 m^2 (~0.7 ha). The annual energy generated by the system was calculated to be 752 megawatt-hours. On a one-to-one basis, 752 megawatt-hours of energy could be generated by photo voltaic modules of 6,494 m^2 (~0.7 ha) and this was the basis of our analysis.

RESULTS AND DISCUSSION

State of Maine

Currently, the 241 hydropower dams in operation in Maine inundate 196,731 ha of land—equivalent to 2.1% of the state area (USACE 2018). The nameplate capacity of hydropower dams in the state is 726 megawatts, with an actual total annual generation in 2016 of 3,733 gigawatt-hours (EIA 2018; USACE 2018). Replacement of Maine's total hydropower generation with PV would require 7,542 ha of area, which is 0.08% of the state's land area (Waldman et al. 2019), or about the total areal footprint of the state capital, Augusta.

The Kennebec River Basin – Current Hydropower vs. Potential Solar Replacement

Based on actual energy production from 2010 to 2016, we estimate that the equivalent land area needed to replace all of the 14 functional hydropower dams in the Kennebec River watershed—producing an average (±SE) of 1,101.7 ± 37.9 gigawatt-hours in a year (~25% of Maine's total energy supply)—is 950.7 ± 32.8 ha (Table 1), which is equivalent to 0.06% of the Kennebec River watershed area or 0.01% of the total land area of Maine. Based on the U.S. Army Corp of Engineers National Inventory of Dams dataset, the current areal extent of the reservoir footprint in the Kennebec River watershed is 4,542 ha. As a conservative estimate, dedicating 22% of the existing reservoir footprint for PV plates alone could generate energy equivalent to the current production

Table 2. Hydroelectric dams on the Mousam River and associated physical and electrical generation data (in order, moving upriver from lowermost dam).

Dams	Approximate river km upstream of river mouth	Actual generation 2015- (gigawatt-hours/year)	Nameplate capacity (megawatts)	Capacity factor (%)	Required solar area equivalent (ha)
Kesslen	6.25	0.23	0.15	17.7	0.12
Twine Mill	12.15	0.46	0.30	17.5	0.24
Dane Perkins	13.00	0.04	0.15	2.8	0.02

Electrical generation data from Harvey (2015), Kleinschmidt (2015), and Kennebunk Light and Power District.

Table 3. Monthly climatic variables in Waterville, Maine.

	Global irradiance (kilowatt-hour/m^2/day)	Irradiance (kilowatt-hour/m^2/day)	Temperature (°Celsius)	Wind velocity (meters per second)
January	1.49	0.59	-7.1	2.89
February	2.37	0.88	-5.2	3.00
March	2.87	1.40	-0.3	3.30
April	4.12	2.22	6.4	3.20
May	4.80	2.89	11.8	2.69
June	5.89	2.72	16.8	2.19
July	5.51	2.83	19.9	1.90
August	4.88	2.45	19.6	1.89
September	3.41	1.96	15.1	2.09
October	2.71	1.23	8.8	2.50
November	1.69	0.78	3.6	2.79
December	1.25	0.72	-3.1	2.80
Year	**3.42**	**1.73**	**7.2**	**2.60**

from the hydro dams and reservoirs. For each dam, the conversion of proportion of the reservoirs to PV panels for equivalent energy production range from 3% (for Pittsfield) to 51% (for Messalonskee 5) to 100% (Gardiner) to 231% (for Messalonskee 2). However, in terms of actual area, for Wyman Hydro and Harris Hydro, the difference between the existing reservoir and required solar footprint is substantial, for example, for Harris Hydro the difference between existing reservoir footprint and required solar PV area is 1,315 ha and for Wyman Hydro the difference is 980 ha, and for the remaining hydro-dams the difference is under 1,251 ha for all dams. (Figure 3).

When attempting to restore anadromous fishes in a river, removal of the dams from the lowermost barrier progressively upriver is likely to provide the most benefit inasmuch as the fish could sequentially recolonize upriver habitat. The Atlantic Salmon population of the Kennebec River is part of the federally endangered Distinct Population Unit for Atlantic Salmon (NMFS and USFWS 2005), but its population was once robust. Foster and Atkins (1867) estimated that at least 68,000 and perhaps as many as 216,000 salmon returned to the Kennebec River annually before 1820. Across the watershed, the Sandy River tributary, entering the mainstem at rkm 147, is recognized as a critically important natural spawning ground and nursery for Atlantic Salmon and is the site of intensive stocking of eggs and fry. However, restoration efforts have not generated a recovery from relic abundances, e.g., in 2018 just 11 adult Atlantic Salmon were trapped at Lockwood Dam and then trucked to the Sandy River. The removal of just the first four dams on the Kennebec River (i.e., Lockwood, Hydro Kennebec, Shawmut and Weston dams) could reopen approximately 135 km of the mainstem Kennebec River while providing unfettered access to the Sandy River. We estimated the land area required for solar energy production to replace those four dams would be 204.2 ± 12.1 ha.

The Mousam River Basin – Current Hydropower vs. Potential Solar Replacement

In comparison to the Kennebec River, the Mousam River is far smaller in all dimensions. The Mousam sustains relic runs of American Shad and Alewives up to Kesslen Dam (J. Waldman, personal observation) but there is no fish passage on Kesslen Dam, the first barrier above tidewater, or on the two others. These three dams have a total nameplate capacity of only 0.6 megawatts (Table 2). Moreover, the capacity factors of those dams are extremely low, ranging in 2015 between 2.8% at Dane Perkins Dam and 17.7% at Kesslen Dam. Actual total generation from all three dams was 0.73 gigawatt-hours in 2017. We estimate that this quantity of electricity could be replaced with 0.38 ha of PV (Table 2).

Implications

Despite the modest generative capacity of solar power in Maine, i.e., 4.5 kilowatt-hours/m^2/day, we found that the land area required for the complete replacement of hydropower dams in the Kennebec and Mousam River watersheds is a small fraction of their reservoir basin footprints (Figure 3). This is at the low end of national solar potential; in the southwestern and southeastern United States, solar generative capacity ranges up to 7 kilowatt-hours/m^2/day (Waldman et al. 2019). Replacement by PV of all Kennebec River hydro-dams would require well less than 1% of its watershed land area. Likewise, for the Mousam River, replacement of the three hydro-dams that would open 13 km of the river to anadromous fish would require only a fraction of 1 ha. In seeking land for this purpose on rivers in Maine and elsewhere, sites for PV arrays could include former reservoir bottom, plus brownfields, abandoned farms and shopping malls, and other underutilized land parcels. Ponds and reservoirs and other water bodies such as canals and waste water treatment plants could be used for floating solar arrays, the shading from which may be useful towards reducing evaporation, algae blooms, and temperature

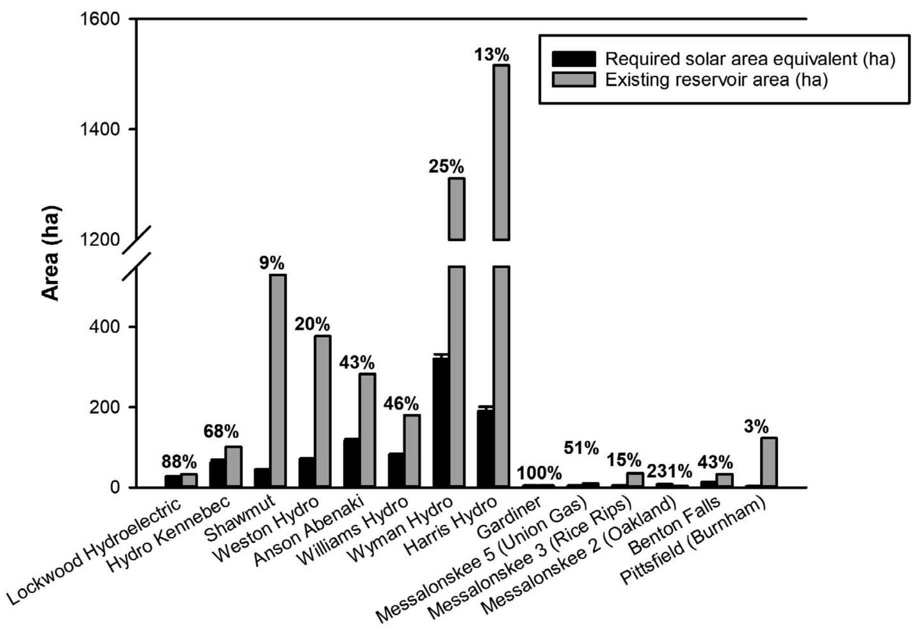

Figure 3. Land area required for photovoltaic panels to generate equivalent electricity as produced by the existing hydro-dams on the Kennebec River expressed as a percentage of the existing reservoir area.

increases (Sahu et al. 2016). Spatial area needed to replace the three dams on the Mousam River is so minimal that PV arrays on industrial or commercial roof tops or on municipal land holdings might suffice; as might energy conservation alone, perhaps by a community-wide effort to help restore their local river. Regardless of the particular site characteristics, location of solar arrays near the removed dams could be desirable so as to tap into the already existing transmission lines for the hydroelectricity.

Dam removal has emerged as an effective tool for reconnecting rivers, alleviating the risks of dam breaching and consequent flooding, and for reversing environmental harm (O'Connor et al. 2015). Among environmental damages, unrestricted migration of diadromous fish for their ecological and economic benefits can be underscored as a primary rationale to the public for freeing rivers from dams that have been impeding the fish's movements. Moreover, removal of dams on large rivers, such as those on the Kennebec would allow for the restoration of potentially larger migratory fish populations, with significant benefits to both riverine and marine fisheries. Removal of dams on small rivers, while not offering the potential for very large migratory fish populations individually, do offer meaningful population recovery possibilities in totality and renewed connectivity within the watershed, while the energy forgone in such removals is minimal. Furthermore, it is likely that for many dams on small rivers, there is not enough total water flow to simultaneously support both highly effective fish ladders and economically viable electricity production.

This exercise, although being a hypothetical endeavor to analyze replacement of hydro energy vis-à-vis PV, proposes a way for ameliorating the environmental harm of hydropower dams. However, due to the land-use changes in increasing solar energy production, there could be accompanying undesirable environmental consequences. Depending on the type and location of the land parcel, the installation of solar panels may interfere with the ecological services provided by that land in terms of carbon sequestration, water discharge, habitat provision for subterranean species, and foraging grounds for birds (Hernandez et al. 2014; Hernandez et al. 2015). Scattered solar panel installations could also decrease terrestrial connectivity. Additionally, PV arrays may lower perceived cultural and recreational aspects of the landscape (Hernandez et al. 2015). On the other hand, dam removal itself may face considerable resistance from some local citizens as the dams offer them active outdoor opportunities (e.g., fishing, boating, etc.) and for some, existing dams and reservoirs represent their heritage as a part of the local landscape. However, dam removal changes the lentic environment to lotic and the outdoor recreational opportunities may be equivalent or even increase.

Despite these potential drawbacks, we believe a balance could be maintained that can lower any negative impacts on terrestrial habitats while keeping the rivers free from barriers. For instance, managing vegetation at PV installations offers potential benefits for pollinators and production of small grazing animals such as goats and rabbits. In fact, agrivoltaics, which combines crop production with PV arrays, indicates higher yields of maize than under full light conditions (Amaducci et al. 2018; Sekiyama and Nagashima 2019). There is also an emerging field of aquavoltaics that combines floating solar arrays on ponds with aquaculture (Pringle et al. 2017).

There are many aspects that could be explored to minimize negative ancillary effects, for example finding onsite or offsite suitable areas for solar panel installations that are already environmentally compromised. Further, beyond solar power alone, its combination with emerging novel and cheaper energy options such as wind power and hydrokinetic turbines together with increased energy usage efficiency should facilitate the feasibility of phasing out more hydro-dams. Ever improving battery storage will also be critical, as will "Smart Grids" that balance energy flow between sources and users (Waldman et al. 2019).

We are unable to provide detailed estimates of the costs of dam removal and of subsequent solar panel installations because they are highly site specific. However, our linear calculations, based on Blachy and Uchida (2017), showed that the total cost of removal of the 14 dams on the Kennebec River would be between US$35.2 million to $60.5 million, and of the 3 dams on the Mousam, $1.6 million to $2.7 million. Additionally, subsequent PV panel installation costs for electrical nameplate capacity equal to the hydropower foregone were approximated using a rate between $2.40 and $3.00 per watt (Barbose et al. 2019). At these levels, we estimate costs of $591.1 million to $738.9 million for the 14 remaining dams in the Kennebec River (total 246.3 megawatts), which includes $104.1 million to $130 million for the 4 lowermost dams on the Kennebec River (total 43.4 megawatts) and $1.4 million to $1.8 million for the 3 Mousam River dams (total 0.6 megawatts). The collective cost of dam removal and subsequent PV installation would range between $626.3 million and $798.9 million in the Kennebec River, whereas for the Mousam River it would range between $3.0 million and $4.5 million.

Given the environmental harm they impose, safety concerns, and the emergence of alternative energy substitutions, now is an apt time to begin to reconsider the future of hydro-dams using novel means. Also, many hydro-dams are nearing FERC license expiry; most on the Kennebec Basin are slated to end in 2036. In 2020, the median ages of the hydro-dams in the Kennebec River and Mousam River watersheds were 97.5 years (mean age: 90 years) and 41 years (mean age: 49 years), respectively. Although many hydro-reservoirs serve additional purposes beyond hydropower, such as for recreation, irrigation, and potable water, there are many positive tradeoffs possible with their restorations to free-flowing rivers. Relicensing hydro-dams under the status quo there or on other large rivers will solidify up to another half century of river blockages.

We believe that PV-for-hydropower substitution is a promising means to break out from the frequently encountered river management pattern in which fish passage sustains only small or relic anadromous fish populations. Analyses at the level of individual watersheds, as we conducted for two rivers in Maine, should provide managers of rivers elsewhere across the United States with a semblance of the areal scale required for replacements of hydropower with PVs.

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