Wind energy's bycatch: Offshore wind deployment impacts on hydropower operation and migratory fish

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Wind energy's bycatch: Offshore wind deployment impacts on hydropower operation and migratory fish

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ABSTRACT

Hydropower plays a key role in maintaining grid reliability, but there is uncertainty regarding the ecological implications of using hydropower to balance variability from high penetration of intermittent renewable resources, such as solar and wind. Hydropower can offer advantages at the macro-ecological level (*e.g.,* reduced greenhouse gas emissions), however it may have significant environmental impact on a local level (*e.g.,* increased risk to fish species during migration and breeding periods). Using the New England region as a case study, we use an electricity model to estimate how hydropower operation changes as offshore wind capacity increases at a system level. We then tie alterations in hydropower energy production to local impacts on riverine ecosystems and the lifecycle of migratory fish. We find that increasing offshore wind capacity from 1600 to 10,000 MW more than doubles the average hourly hydropower ramping need and the associated river flowrate during April. This increased flowrate aligns with the migration timing of the lone endangered fish species on the Connecticut River, the shortnose sturgeon. Alternatively, the majority of months in which hydropower operation is most strongly impacted by the addition of offshore wind capacity do not coincide with key fish lifecycle events. Other sustainability benefits, including reduced air pollution and water consumption, can be achieved through deployments of offshore wind. Our results suggest that in order to balance global (*i.e.,* CO_2 mitigation) and local (*i.e.,* fish migration) environmental issues, a portfolio of solutions is needed to address grid integration of renewables.

1. Introduction

Global energy demand rose 2.3% in 2018, and with it, energy-related emissions, demonstrating the urgent need for the development of clean energy solutions [1]. Hydropower is attractive both as a renewable resource and for its ancillary services, providing flexibility and reliability in the integration of variable renewable energy sources such as wind and solar. Worldwide hydropower generation reached 4193 TWh in 2018 and continues to grow rapidly in many countries [2]. Wind and solar are also on the rise, and offshore wind capacity in particular has been growing rapidly, from 3056 MW in 2010 to 28,155 in 2019, an annual growth rate of 91% [3]. Both offshore wind and hydro are important in the global pursuit of decarbonization and environmental sustainability. In this paper we address local environmental impacts at the intersection of these two technologies.

Over the centuries, water resource developments, primarily the construction of dams for irrigated agriculture and hydropower, have resulted in widespread alterations to the natural hydrological regime [4]. The flow regime of a river is central to sustaining biodiversity and ecosystem integrity, and comprises five main components: magnitude, duration, frequency, rate of change, and timing [5]. Changes in flow magnitude, including changes in peak flow, total and mean discharge, baseflow, and hourly flow, are associated with obstructed migration [6,7], along with negative biotic fish responses, including decline in diversity [8], abundance, and demographic parameters [9]. Although economic growth was often used in the past to justify or ignore the adverse ecological impacts of hydropower on riverine ecosystems, careful consideration is needed to assess degradation and identify mitigation strategies, particularly in the face of rapidly changing energy landscapes. Simultaneously, low carbon energy sources are imperative for avoiding broader global environmental destruction as the result of climate damages. For example, Cranmer and Baker [10] estimate that the climate value of offshore wind ranges between $25 billion to $29

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List of abbreviations including units and nomenclature

IUCN	International Union for the Conservation of Nature
WLR	water level regulation
g	gravity in m/s^2
ρ	density of water in kg/m^3
Δh	hydraulic head in m
i	technology or load type
P	average hourly hydropower output in MW
Q	mass flow rate of water through the hydro generators in kg/s
t	time in hours
$V_{i,t}$	the difference in generation (or load) from hour t to hour $t+1$ in MW
$\lvert V_{i,t}\rvert$	absolute ramp in MW
$x_{i,t}$	average power generated by technology i (or the load) in the hour beginning at time t
$F_{j,\tau}$	fixed value per unit of capacity for metric j
$V_{j,\tau}$	variable value per unit of electricity for metric j
$CF_{i\tau}$	capacity factor of technology τ in portfolio i
$x_{ij\tau}$	value of sustainability metric j for technology τ in portfolio i
h	number of hours in a year

trillion depending on assumptions about the cost of the technology, the discount rate, and the severity of climate damages [10]. These global values must be considered alongside impacts on local ecosystems and economies when planning for and regulating energy systems. Understanding local impacts allows communities to assess trade-offs between climate benefits and harmful local environmental impacts. After quantifying these trade-offs, communities will be able to find the most reasonable ways to mitigate externalities.

In this paper, we focus on the impact of increasing offshore wind on the operation of traditional hydropower, which uses dams to store water in a reservoir and then generates electricity by releasing the water through turbines. Hydropower is an important option for providing flexibility to the electric grid due to its fast ramping and large-scale storage capabilities [11]. Previous studies have investigated the value of hydro for supporting offshore wind and find that hydropower allows for an increased share of generation from variable sources [12–14]. Eloranta et al. [15] studied the impacts on fish from the changes in the flow regime induced by hydropower (often called water level regulation (WLR)). Through an empirical study, they found that WLR frequency and magnitude had significant impacts on food availability and fish productivity, which in turn affected brown trout density and condition [15]. While they find a connection between WLR and fish, there is a void of papers connecting energy system changes at the macro level, such as wind energy investments, to WLR or to fish outcomes [15]. Thus, a gap in the literature is a quantitative framework for incorporating mathematical representations of the interactions between fish migration patterns, hydropower variability, and wind energy generation [6].

The key contributions of this paper are two-fold. First, we assess changes in hydropower operation that are associated with the decarbonization of the electricity grid through increased offshore wind energy. Second, we connect these changes to seasonal WLR and consider the impact to life-cycle behavior of fish, assessing the ecological implications resulting from macro-level energy system changes. We use the New England region as a case study in this analysis due to the presence of several diadromous fish species (which refers to fish that migrate between freshwater and the sea) including the federally endangered shortnose sturgeon, and the large number of hydropower dams in the Connecticut River watershed. In New England, hydropower is the most important source of flexibility in the grid; while both hydro and natural gas are often used to balance variability, the region uses a larger proportion of its hydro capacity to accommodate hourly ramping needs [11]. The region also plans to expand offshore wind investments in the coming years. Our work investigates the implications of large offshore wind deployments by combining energy planning and ecological impact assessment. To this end, using an electricity model of the New England power grid, we first quantify changes in hydropower operation as a result of adding offshore wind capacity, and then estimate the timing and magnitude of these fluctuations in terms of discharge in the Connecticut River. We lastly consider how changes in the flow regime may impact the life cycle behavior (*e.g.*, spawning and migration) of diadromous fish species.

The rest of this paper is organized as follows. Section 2 presents the details of the New England region case study, including the hydropower resource and fish species native to the area. Section 3 presents the methods, detailing the electricity model and defining hydropower ramp. Section 4 presents the results. Section 5 contains conclusions of this work.

2. Case study

2.1. Hydropower and wind resource in New England

In New England, the installed capacity of traditional hydropower is 1819 MW, with an annual generation of 7600 GWh. The Connecticut River watershed has the greatest installed hydropower capacity, with 740 MW. In addition, approximately 1000 GWh of Canadian hydropower is imported seasonally from Hydro-Quebec [16,17]. With the construction of a 1200 MW capacity transmission line from Quebec to Maine starting in 2022, Massachusetts plans to purchase an additional 9000 GWh of low-carbon electricity per year from Hydro-Quebec, under a 20-year agreement [18].

Beginning at the Quebec-New Hampshire border the Connecticut River is the longest river in the New England region, flowing through four states and encompassing a watershed of over 11,000 square miles, until it discharges into the Atlantic Ocean. Due to its size, the Connecticut River is one of the most developed river systems in the U.S. Its mainstem has fourteen hydropower projects. Over 1000 smaller dams remain along its tributaries despite decades of conservation efforts to remove aging dams. A map displaying the largest hydroelectric dams on the Connecticut River can be seen in Fig. 1 [19]. We present more detailed data on hydroelectric generation facilities in Appendix C, Table C1.

2.2. Connecticut River water flows and ecosystem

There are dozens of fish species who make their habitat in the Connecticut River Basin Fishway Passage, an ecosystem that includes twelve rivers in the Connecticut River watershed. The nine most commonly observed migratory fish for the year 2018 are displayed in Table 1. All of these species, with the exception of the American eel, are anadromous, meaning that they are born in rivers and then migrate to the ocean to feed and mature, later returning to the freshwater where they were born to spawn [20]. The American eel is catadromous, meaning that it grows in rivers and then returns to the ocean to spawn. Each species plays an important role in the region's ecosystem. For example, the sea lamprey, a parasitic fish that has been responsible for considerable damage to other species in the Great Lakes region [21], is a valuable source of food in the Connecticut River watershed. Additionally, their nesting behavior involves clearing silt from gravel beds, improving the sediment habitat for other spawning species such as trout [22,23]. The shortnose sturgeon population in the Connecticut River declined due to overfishing in the late 19th and early 20th centuries and damming, which restricted their access to habitat [24]. Improvements in fish passage measures have led to an increase in, and population stabilization of, the shortnose sturgeon

Fig. 1. Map of Connecticut River hydroelectric facilities. See Appendix, Section C for tabular data.

Table 1
Migratory fish counts for the Connecticut River watershed for 2018 [25].

Species	Total fish counts
American shad	318,707
Sea lamprey	20,479
American eel	27,505
Alewife	11,308
Blueback herring	5113
Gizzard shad	366
Striped bass	207
Shortnose sturgeon	20
Atlantic salmon	3

population in recent decades (approximately 1600 individuals), but the species is still considered endangered and fishing of them is illegal [22]. Shortnose sturgeon are long-lived, with females reaching up to 60 years of age, and thus population recovery is slow [22].

The presence of hydropower facilities, and associated dams, along the Connecticut River physically hinders the migration of anadromous fish, such as alewives and blueback herring, upstream to spawning grounds or downstream to the ocean. In particular, Hadley Falls, also known as the Holyoke Dam, is the lowermost dam on the Connecticut River and controls access to 85% of the spawning habitat in the river basin [19]. The operation of hydropower plants also alters the flow regime of the river, which has further ecological consequences. The alteration of each flow component in the river (*i.e.,* magnitude,

frequency, duration, timing, and rate of change) is tied to a particular ecological response. For example, when the magnitude of flow changes it disrupts the life cycle of fish species. Alterations to rate of change of flow can cause nutrients to be washed away and failed seedlings [26]. Increased short-term flow fluctuations can lead to the loss of stable spawning, rearing, and riparian habitats for fishes and invertebrates [26]. Adequate temperature, depth, and substrate conditions must be maintained in order to ensure species survival. Overall, there is strong consensus within the science community that maintaining, as closely as possible, the natural flow regime of rivers is important for the sustainability of these ecosystems, particularly for fish [27]. In this paper we focus on the rate of change in magnitude of the river, and timing of these changes, particularly the months during which fish migration is the greatest.

The seasonal movement of the species observed in the Connecticut River watershed can be seen in Table 2. The activity includes spawning behavior as well as migration upstream. The most common months for fish migration are May, June, and July. April is of particular concern because of its importance to Shortnose sturgeon, the only federally endangered migratory fish species in the Connecticut River. The shortnose sturgeon lives in watersheds south of Turners Falls and migrates upriver to spawn. This species matures slowly and does not spawn until the age of 8–12 years old.

Fig. 2 illustrates the location of fish species in the Connecticut River watershed in New England. The left panel shows the total number of fish species found in each subregion, including those on tributaries [34]. The regions with the greatest number of fish, more than 32 species, are concentrated along the river mainstem. The center panel shows the number of species of concern in each subregion watershed in New England. 'Concern' means that the species is listed or proposed as "Endangered", Threatened", or "Candidate" under the Endangered Species Act (1973), or ranking "Critically endangered", "Endangered", "Vulnerable", or "Near threatened" under International Union for the Conservation of Nature (IUCN) [35]. The right panel shows the number of fish species with high spawning seasonality, meaning that their spawning season is temporally restricted. More specifically, this represents fish in the lowest 10th percentile of spawning season duration (number of months) among all species. These species are found all along the Connecticut River and are of particular interest because their life cycle behavior (*e.g.,* reproduction) depends on their ability to travel up or down the river. Hydropower operations could potentially be altered to protect these species during key fish life cycle times.

3. Methodology

In this section, we first describe the electricity model used in our analysis. The electricity model in our case study evaluates wind and hydropower operation in the northeastern U.S. (*i.e.,* the New England region). The model estimates the expected energy production for a given portfolio of electricity generation technologies, projected to the years 2030 through 2035. Following the electricity model description, we detail the methods for calculating the variability of hydropower, and for estimating the impact of hydropower generation and river flow. We then discuss the offshore wind energy scenarios we consider.

3.1. Electricity model

We use the electricity grid simulation model from Nock and Baker [36]. Given a portfolio of technology capacities and electricity demand, it estimates the energy contribution of each technology [36]. The electricity model operates with a merit-order dispatch based on historical trends in the New England region. At each time period, the electricity model determines if there is unmet demand, and if so, it dispatches technologies in the following order: nuclear, solar, onshore wind, offshore wind, natural gas and hydro together based on historical trends, followed by oil, until the total demand at each specific time period is satisfied. The model output includes hourly electricity production and yearly capacity factor by technology for a 5-year time period.

3.2. Measuring hydropower variability

Short-term, artificial flow events arise when a hydropower plant is dispatched to match peaks in electricity demand or valleys in renewable energy supply. The disturbances to the natural flow regime disrupt sediment, vegetation, and other aspects of riverine habitat. We define the *ramp,* in Eq (1), as the change in generation (or load in the case of demand) from 1 h to the next. Specifically, the ramp for technology $i = [\text{wind}, \ \text{hydro}, \ \text{load}]$, $V_{i,t}$ is defined as the difference in generation (or load) from hour t to hour $t+1$; units are in MW. $x_{i,t}$ represents the average power generated by technology i (or the load) in the hour beginning at time t. The magnitude of ramp is also important and is computed by taking the absolute value of ramp, $|V_{i,t}|$, which we refer to as *absolute ramp.*

$$V_{i,t} = x_{i,t+1} - x_{i,t} \tag{1}$$

3.3. Flow approximation

A marginal change in hydropower production translates to a change in the river flow observed downstream of the turbines. We use the specifications of Wilder Dam (see Appendix D, Fig. D1 and Fig. D2) to make this approximation because of the accessibility of the pre-application documents detailing the operation of the dam and important studies for the relicensing process. Wilder Dam is operated as a peaking plant in the Connecticut River with an installed capacity of 35.6 MW. Eq. (2) shows the relation between P, average hourly hydropower

Table 2
Life-cycle movement of common anadromous fish species.

	Month												Source
	1	2	3	4	5	6	7	8	9	10	11	12	
American shad				✓	✓	✓							[20]
Sea lamprey					✓	✓	✓			✓	✓		[28]
American eel		✓	✓	✓	✓	✓	✓						[29]
Alewife					✓	✓	✓	✓	✓	✓	✓		[30]
Blueback herring					✓	✓	✓	✓	✓	✓	✓		[30]
Gizzard shad					✓	✓	✓						[31]
Striped bass				✓	✓	✓							[32]
Shortnose sturgeon				✓	✓								[33]
Atlantic salmon										✓	✓		[33]
Total	0	1	1	4	8	7	5	2	2	4	4	0	

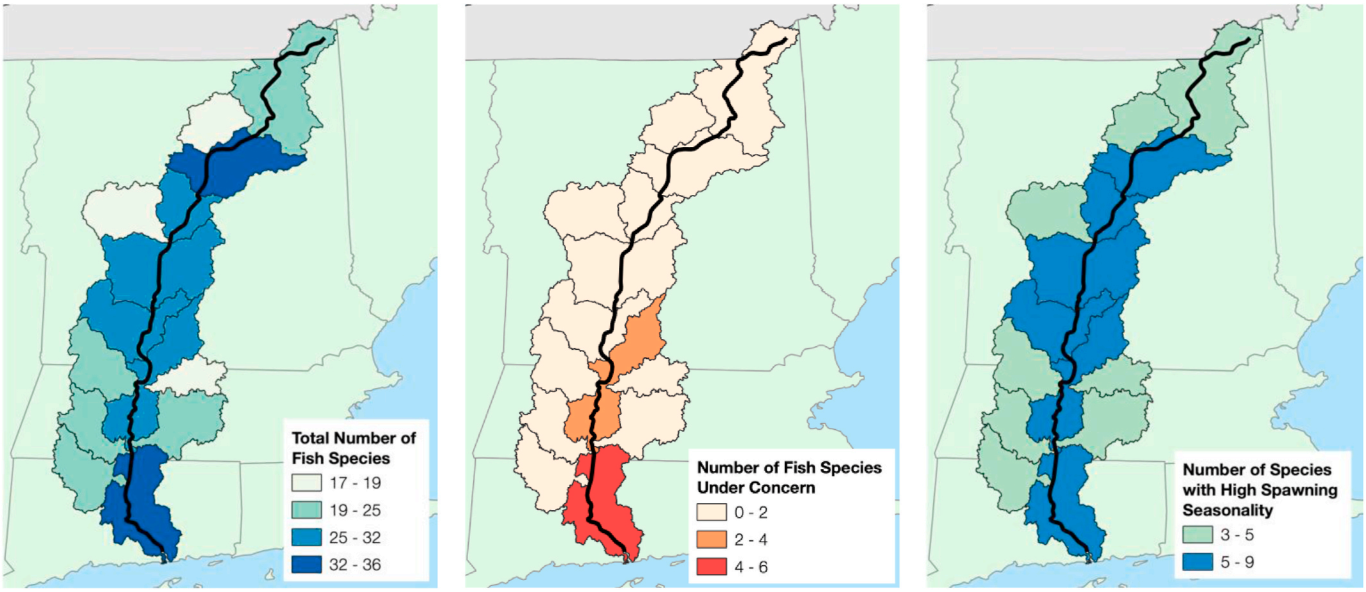

Fig. 2. Map depicting number of (left) total fish species, (center) fish species of concern, and (right) species with high spawning seasonality.

output (MW), and Q, the mass flow rate of water through the generators in kg/s (though we ultimately convert to the more commonly used volumetric flow rate, cubic feet per second or cfs). We assume a constant hydraulic head, $\Delta h = 17.983$ m, which is the maximum height of the Wilder Dam above the river; this value in practice depends on the river level. The density of water, ρ is 1000 kg/m^3 and gravity g is 9.8 m/s^2. Given this, we estimate that an additional 1 MW of power produced by Wilder Dam corresponds to an increased river flow of 200 cfs downstream from the plant.

$$P = \rho \cdot g \cdot \Delta h \cdot Q \tag{2}$$

The traditional hydropower plants along the Connecticut River are typically operated as daily peaking plants, meaning they operate when there is high demand for electricity. These types of plants are those most likely to compensate for the variability in offshore wind energy output [11,37].

3.4. Wind energy scenarios

We evaluate the impact of installed offshore wind capacity on hydropower variability in the context of the energy system. We do this by using a set of 9 energy portfolios, which vary only by the installed capacity of offshore wind. The capacity for onshore wind (200 MW), solar (300 MW), natural gas (18,750 MW), hydropower (3300 MW), oil (6000 MW), and nuclear (3500 MW) is assumed to be constant for all nine portfolios. As of 2020, wind power proposals dominate ISO-NE's Interconnection Request Queue, with over two-thirds, a total of 14,000 MW, being for wind projects, mostly offshore. We evaluate nine different levels of installed capacity for offshore wind over nine scenarios. Scenario 1 has 1600 MW of offshore wind, Scenario 2 has 3000 MW, then each portfolio has an addition of 1000 up to Scenario 9 with 10,000. Our sensitivity analysis explored different levels of hydropower, between 3300 and 10,000 MW, but found negligible differences for different levels of hydropower. See Appendix, Section A (Table A1) and B for more details regarding the data used in the electricity model.

3.5. Sustainability evaluation

Here we evaluate the system sustainability of electricity portfolios through using loosely coupled electricity and sustainability models. The methodology for calculating the system sustainability of a generation portfolio is originally presented and discussed in more detail in Nock and Baker [36]. We expand the work of Nock and Baker [36] by integrating more wind generation sites and focusing on the impact that increasing wind capacity in the region will have on the various sustainability metrics. We evaluate the change in sustainability that is associated with increasing offshore wind penetration using six sustainability metrics, which represent measurements of economic, environmental, and social sustainability. Our metrics include a system cost, greenhouse gas and air pollution emissions, jobs, fatalities, and water consumption. These metrics (Table 3) are calculated using a portfolio score.

Note, we use the levelized cost of energy (LCOE) of the system, as opposed to individual technologies. The total value of sustainability metric j depends on the energy generation and installed capacity of the technology being evaluated, as defined in Eq. (3). Let $x_{ij\tau}$ be the value of metric j for technology τ in portfolio i; and let $F_{j,\tau}$ and $V_{j,\tau}$ represent the fixed value per unit of capacity and variable value per unit of electricity for metric j, respectively. We note that the capacity factor $CF_{i\tau}$ depends on the specific portfolio i, technology τ. The capacity factor is determined endogenously to our electricity model; h is the number of hours in one year.

$$x_{ij\tau} = \frac{F_{j,\tau}}{hCF_{i\tau}} + V_{j,\tau} \tag{3}$$

4. Results and discussion

We present the output of the electricity model, which estimates the

Table 3
Sustainability metrics [Nock and Baker 2019].

Sustainability	Metric	Units
Economic	Levelized Cost of Energy (LCOE)	$/kWh
Environmental	Life cycle greenhouse gas (GHG) emissions	Grams of CO_2 equivalent (gCO_2eq)/kWh
	Life cycle air pollution (SO_2, NO_X, PM)	Milligram (mg)/kWh
	Life cycle Water consumption (on-site, direct, operational)	Liters(L)/MWh
Social	Fatalities	Fatalities/GWh
	Jobs	Full-time equivalent (FTE)/GWh

energy contribution by hydropower under increasing levels of offshore wind capacity. We then evaluate the effect of wind capacity on daily hydropower operation, considering the resulting change in flow of the river from ramping of an individual representative hydroelectric plant based on Wilder Dam. Lastly, we consider the concurrence of periods of high hourly hydropower ramps with important fish life-cycle movements.

4.1. Hydropower generation

The hypothesis guiding this work was that increasing offshore wind capacity will ultimately have ecological impacts on riverine fish populations due to changes in hydropower operation. To visualize the changes in energy output, Fig. 3 depicts the hourly hydropower generation profile in New England for two levels of offshore wind capacity: a) Low (1600 MW) and b) High (10,000 MW). We use the demand, wind, and insolation from the year 2015. We found similar generation profiles for other years tested in our analysis (2010–2014). By comparing the hydropower generation profiles for low and high wind scenarios, we observe that peaks in hydropower generation are maintained as offshore wind capacity is added but the valleys (or lows) are reduced, thus the overall result is more extreme changes in generation. Specifically, in the presence of low offshore wind capacity, hydropower generates a minimum of 739 MWh in each hour; when a high level of offshore wind capacity is present, hydropower production is shifted out of the market following the merit-order dispatch in our electricity model and hydropower generation drops to 0 MWh for 614 h per year, on average. For both levels of wind, hydropower still reaches its full generation potential. The 10th, 50th, and 90th percentile values for hydropower generation are 1,070, 1,530, and 1960 MWh respectively for low levels of wind, and 170, 830, and 1660 MWh respectively for high levels of wind.

The operation of hydropower facilities can impact the water flow of facilities further downstream, however this relationship is difficult to model. Thus, in order to estimate the pointed effect of wind capacity on individual facility operation, we calibrate the electricity model generation profile to Wilder Dam. Fig. 4 clearly shows the pattern of increasing daily operating ranges as installed offshore wind capacity increases. The average daily peak in hydropower remains stable across levels of wind, while the average daily low in hydropower drops linearly as offshore wind capacity increases from 1600 MW to 8000 MW. Average monthly flow and generation at Wilder Dam are found in the Appendix, Section D.

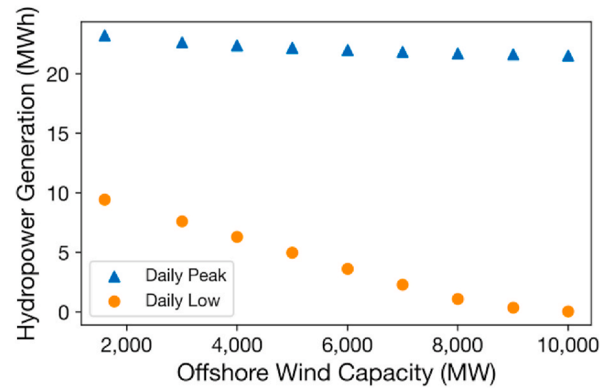

Fig. 4. Average daily peak and daily low in hourly hydropower generation.

4.2. Hydropower ramp

Fig. 5 shows hourly ramp in Wilder Dam hydropower against hourly ramp in demand. We observe that the extremes of the hourly hydropower ramps (greater than 5 MW in magnitude) increase with additional wind capacity. At 1600 MW of installed offshore wind, the vast majority of ramps at the individual power plant are small, with only 7% of hours ramping up or down more than 2 MW during a one-hour time period. At 10,000 MW of installed wind, we observe that 19% of hours experience absolute ramps that are greater than 2 MW. The average ramp increases with offshore wind capacity in a near-linear fashion, increasing 74% as we move from 1600 to 10,000 MW, with an average ramp of 1.36 MW at the top end, as shown in the left panel of Fig. 6. Fitting a trendline to this relation, we estimate that the hydropower ramp increases approximately 70 kW for every 1000 MW of offshore wind capacity that is added to the energy system. The right panel of Fig. 6 shows that the 90th percentile ramp increases significantly with increased offshore wind, from 1.8 to 3.3 MW.

4.3. Hydropower ramp and fish activity

Hydropower operation changes suggest that we can expect changes in the flow regime, and consequently, ecological impact to the species within the ecosystem [38,39]. In Fig. 7, the percent increase in the average absolute hydropower ramp as we move from low (1600 MW) to high (10,000 MW) offshore wind capacity is shown for each month of

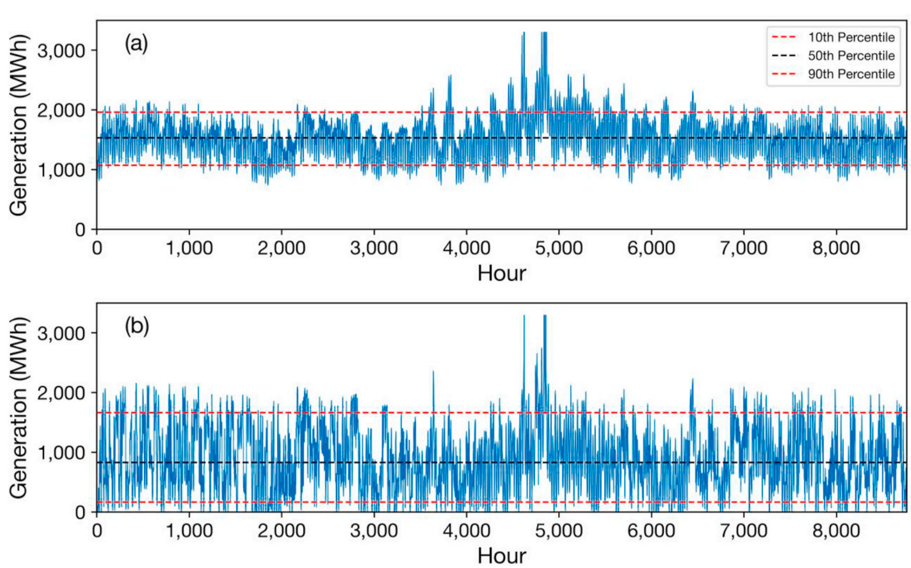

Fig. 3. Hourly hydropower generation for (a) low (b) high installed offshore wind capacity.

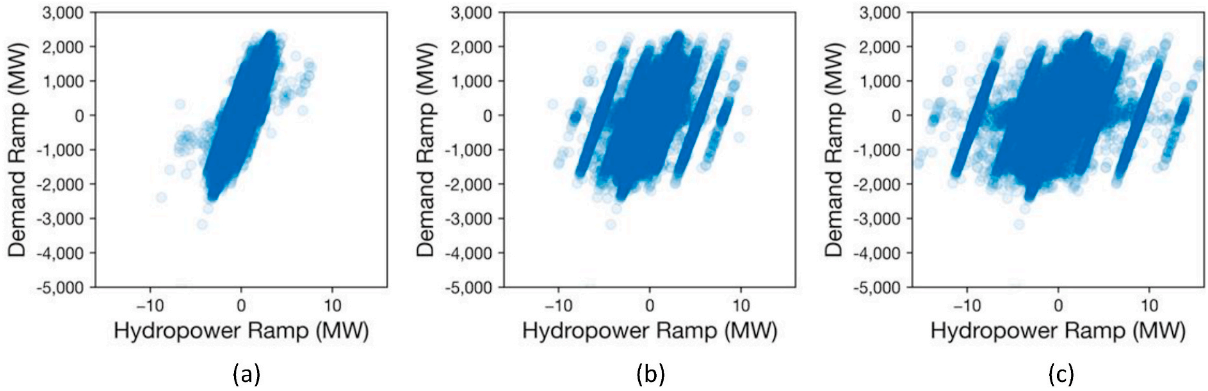

Fig. 5. Hydropower ramp for three levels of offshore wind capacity: (a) 1600 MW, (b) 6000 MW, and (c), 10,000 MW.

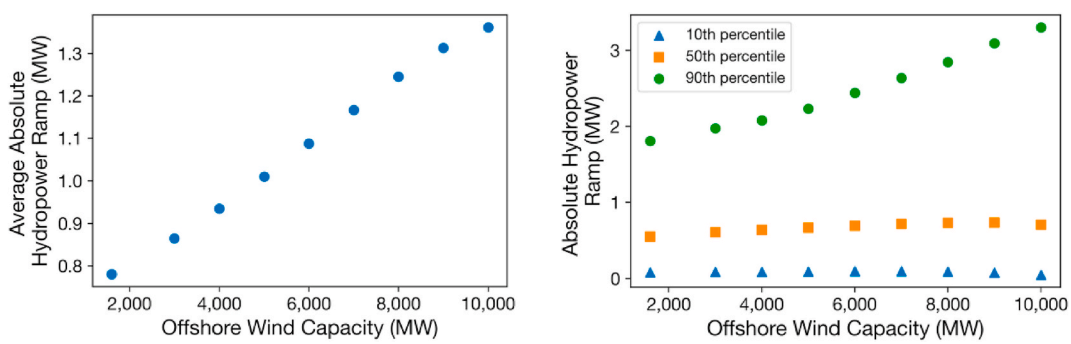

Fig. 6. (left) Average absolute hourly hydropower ramp, (right) 10th, 50th, and 90th percentiles in hydropower ramp.

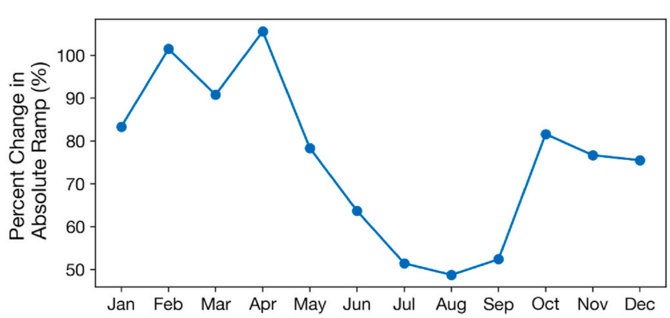

Fig. 7. Percent change in average absolute hourly hydropower ramp from 1600 MW to 10,000 MW of offshore wind capacity.

the year. The highest increase is during the month of April, where on average the hourly hydropower ramp more than doubles with increasing offshore wind capacity. The month of May, during which 8 out of 9 fish species migrate, sees an increase in average hydropower ramp of 78%. The 10th, 50th, and 90th percentile of hydropower ramp for each month is shown in Fig. 8, along with the total number of fish active in each month. For both the 50th and 90th percentile of hydropower ramp in the high wind scenario, fish may be highly impacted during the months of May, June, July, October, and November, however April is the month with the highest percent change in ramp. The winter months of January, February and March have the highest percent change in ramp, most likely resulting from natural gas pipeline constraints, but fortunately these months do not coincide with migration activity. Hydropower ramp in late spring to early summer could have the greatest ecological impact since this is the period with the largest fish life-cycle related movement.

The maximum drawdown (drop in water level of the impoundment) allowed at Wilder Dam under the operating restrictions is 5 ft, though under normal non-spill conditions it is limited to 2.5 ft. A flow of approximately 3000 cfs results in an elevation change of approximately 0.1 ft, and drawdown rates cannot exceed 0.3 ft per hour [40]. The Wilder Dam minimum flow restriction ranges from 1131 cfs in September to 4360 cfs in April [40]. Thus, a hydropower ramp of 4 MW (90th percentile, high wind) corresponds to an additional 800 cfs, or a change in elevation of 0.026 feet in one hour. While this elevation change is safely within the bounds of the operating limits, a general upward trend in ramp with the addition of wind should be noted. These limits on operation are established during the relicensing procedure of a hydropower facility; it is important to consider restrictions that will accommodate and protect migratory fish species during their spawning seasons. We note that our analysis does not consider how concrete structure removal or fish passages would aid in fish migration periods [41].

4.4. Sustainability results

In Fig. 9, we show the percent change in the six system level sustainability metrics (LCOE, GHG emissions, Air Pollution, Water Consumption, Fatalities, and Jobs) from the low installed wind capacity to the high installed wind capacity. The values associated with these percent changes in each metric are shown in Table 4. We observe that the addition of installed wind capacity improves all metrics, with the exception of LCOE. One key finding is that water consumption decreases in the presence of high offshore wind capacity. This decrease is likely due to offshore wind energy replacing natural gas, whose power plants rely on large quantities of water in the form of steam and in cooling systems. The reduction of natural gas plant usage also translates to air pollution emissions savings and associated fatality reductions. Thus, while the presence of additional offshore wind impacts the ramping of hydropower facilities, reduced water usage may offset overall harm to fish, along with other sustainability benefits. The system LCOE most likely increases due to our work taking a short-term look at

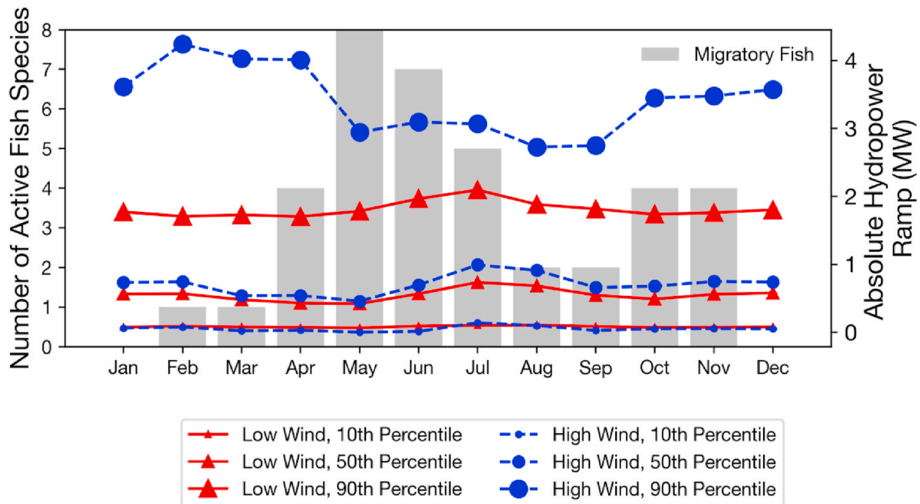

Fig. 8. Right axes (lines): Absolute hydropower ramp for low (1600 MW) and high (10,000 MW) offshore wind capacity; Left axes (bar chart): fish activity (gray bars).

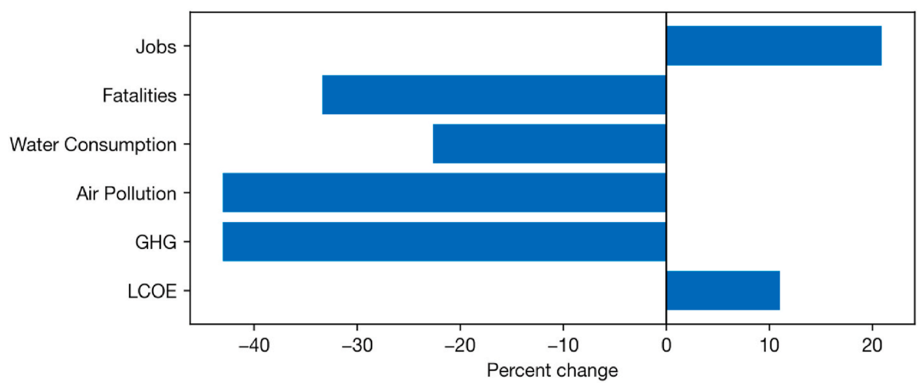

Fig. 9. Percent change in six sustainability metrics from low installed offshore wind capacity (1600 MW) to high (10000 MW).

Table 4
Values of six sustainability metrics (per unit) for resulting from energy systems with low and high installed offshore wind capacity.

	Installed Offshore Wind Capacity	
	Low (1600 MW)	High (10,000 MW)
LCOE ($/kWh)	0.128	0.142
GHG (gCO_2eq/kWh)	288.72	164.59
Air Pollution (mg/kWh)	635.67	362.32
Water Consumption (L/MWh)	994.49	769.55
Fatalities/GWh	6.86E-06	4.57E-06
Jobs (FTE/MWh)	0.679	0.821

sustainability. With a long-term view we would expect to see power plant retirements, which would improve the economic sustainability of our system.

5. Conclusions

This work highlights the importance of considering the electricity system as a whole, rather than technology-by-technology. We present a method for evaluating the potential impact of increased offshore wind capacity on hydropower operation, and consequently, on migratory fish populations. We focus on hydropower ramp, the change in generation from one hour to the next. Changing the ramp rate impacts the flow of the river due to changes in intake and outtake of water in the generation facility.

Reproduction and early life cycle stages of fish are highly sensitive to variability in river flow. Some studies have found that fish avoid migrating during changing flow magnitudes [1]. To minimize ecological impact it is recommended that discharge is stabilized during the spawning period [42]. Our results indicate that an increase in offshore wind capacity will lead to larger ramps on the river, which may adversely impact fish. We find that the average ramp of hydropower operation increases linearly in the capacity of offshore wind, and that, while the peak in hydropower generation is unchanged, the minimum level is reduced frequently.

Hadian and Madani's [43] system of systems framework estimates a relative aggregate footprint index of different energy sources, taking a more holistic view of energy production impacts and considering the tradeoffs between the interacting subsystems (*e.g.,* water, land, climate, and economy) and associated uncertainties. Although they find that hydropower ranks moderately in the relative aggregate footprint index (*e.g.,* lower footprint than solar photovoltaic and natural gas but higher than geothermal, wind energy, and nuclear), the authors determine that hydropower is one of the least robust due to a high standard deviation in the relative aggregate footprint index, highlighting yet another form of hydropower's variability. Similar to our study, the authors find that the water footprint of natural gas is greater than offshore wind, and thus replacing natural gas with wind energy leads to sustainability savings from a water perspective.

Other studies have looked at broader sustainability consequences of energy systems that are increasingly reliable on intermittent

renewables. Brick and Thernstrom [44] find that intermittent renewable-heavy systems must be built approximately two times larger than balanced portfolios (*i.e.,* systems with low-carbon baseload and 25% wind and solar) in order to achieve the same CO_2 reductions. Thus, high renewable systems are associated with reduced land-use efficiency. We did not specifically consider land use in our evaluation, and therefore cannot compare on this matter. Additionally, these intermittent renewable heavy systems are more expensive on a dollars-per megawatt-hour basis, similar to our own finding of high wind penetration being associated with higher system LCOE. Notton et al. [45] evaluate the economic implications of high renewable energy systems and the costs associated with intermittency, arguing that improved forecasting is key in achieving reduced integration costs and achieving maximum economic benefits. Ultimately, policies which provide broader incentives for low-carbon emissions targets (including consideration of electricity storage, demand response, and flexible generation) rather than technology-specific renewable energy targets may provide the most sustainable solutions [46].

While the studies mentioned above consider the water consumption, cost, and greenhouse gas emission impacts of hydropower and wind energy they fail to provide a framework for accounting for fish populations, and how energy production and capacity changes impact migratory species. Our work expands the field by developing a framework for integrating key lifecycle ecological events into energy systems analyses. Fortunately, we find that most of the months that see the greatest increase in ramp have little activity by the fish most affected by changes in river flows. However, there is a significant increase in average ramp in the month of April, which is when shortnose sturgeon, an endangered species, migrates upriver to spawn. This suggests that these concerns about ramping should not be used to limit the capacity of offshore wind; rather that systemic impacts should be considered when crafting solutions to grid integration. For example, the design of demand response programs could include concerns about ecosystem impacts of using hydro to balance intermittency.

Future work could incorporate hydropower dam management options [47]. The collection of species passage counts, as well as non-migration related metrics connected to overall health such as weight, length, and other parameters should be prioritized in the coming years to provide data for studies to more quantitatively assess how populations are affected by changes to the flow regime.

Credit author statement

Olivia Pfeiffer: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft preparation, Visualization, Investigation. Destenie Nock: Supervision, Methodology, Software, Investigation, Data curation, Writing – review & editing. Erin Baker: Supervision, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A. Data Preparation: Electricity Model

We use three onshore and three offshore wind locations to represent the existing wind resource in New England. The three onshore sites are wind farms: Kibby Wind, Groton Wind, and Kingdom Community Wind. For offshore, we select Block Island Wind, the only currently existing offshore wind farm in New England. The other two wind farms, "Revolution" and "Vineyard," were selected by cross-referencing two sets of information: 1) offshore wind project proposals, and 2) location-based capacity factors estimated by the Wind Integration National Dataset (WIND) Toolkit created by the National Renewable Energy Laboratory. The Revolution project (proposed by Deepwater Wind) is a 400 MW offshore wind farm south of Rhode Island with plans to come online in 2024. Vineyard Wind is an 800 MW wind farm proposed south of Martha's Vineyard, MA. Hourly wind speed data was obtained MERRA-2 for all wind sites and are shown to be accurate [48].

Average seasonal wind speeds for the three offshore locations are listed in Table A1. Wind speeds are higher for offshore than onshore sites. On average, wind speeds are higher in the winter than in the summer. The wind speed data obtained was recorded at an elevation of 50 m, and the method for estimating the wind speed at the height of a wind turbine hub is detailed in the following section.

Table A1
Wind Farm details of selected sites. Sites denoted with * do not currently exist.

Wind Site	Location	Number of Turbines	Installed Capacity (MW)	Summer Wind speeds (m/s) Mean (SD)	Winter Wind speeds (m/s) Mean (SD)
Groton Wind, NH	Onshore	24	48	8.16 (3.02)	10.64 (4.51)
Kibby Mountain Wind, ME	Onshore	22	66	8.83 (3.28)	12.05 (4.88)
Kingdom Community Wind, VT	Onshore	21	63	7.99 (3.05)	10.73 (4.44)
Block Island Wind, RI	Offshore	6	30	15.15 (6.23)	20.21 (8.72)
Revolution*	Offshore	N/A	N/A	15.19 (6.26)	20.21 (8.73)
Vineyard*	Offshore	N/A	N/A	16.85 (7.49)	21.65 9.72)

B. Wind speed Extrapolation

For this study, the Power Law [49] was used to extrapolate the measured wind speeds to the wind speeds found at wind turbine hub heights. Equation (B1) shows how the wind speed in m/s at height z, U, is related to U_r, the wind speed at reference height z_r, and α, the shear coefficient, which

increases with the roughness of the terrain. The hub height of a wind turbine depends on the turbine design. In our model, the hub height for all onshore wind turbines is assumed to be 90 m, and the hub height for all offshore wind turbines is assumed to be 150 m. The MERRA-2 wind speed data was measured at an elevation of 50 m [50]. Higher hub heights allow the rotor blades to harness stronger, more consistent wind that exists at higher altitudes, and over the past decade this has driven the average wind turbine hub height to increase. The value for α that is used in this study is 0.1 for offshore wind and 0.15 for onshore wind. Onshore wind turbines were assumed to be 5 MW turbines, with rotor disk area of 12,469 m^2 and hub height of 90 m. The cut-in and cut-out wind speeds are 3 and 25 m/s, respectively. The offshore wind energy power calculation is based off of the General Electric 6 MW offshore wind turbine, with a rotor diameter of 150 m, blade length of 73.5 m, rotor swept area of 17,860 m^2, and hub height of 100 m.

$$U = U_r \cdot \left(\frac{z}{z_r}\right)^{\alpha} \tag{B1}$$

C. Hydropower Resources

Here we present the tabular data for the Connecticut River hydroelectric facilities in Table C1. This table details the plant name, capacity, annual electricity generation, ownership and licensing information for each facility.

Table C1
Connecticut River hydroelectric facilities [51].

Plant Name	Facility Ownership Type	FERC License Issuance Date	FERC License Expiration Date	Number of Units	Total Capacity (MW)	Average Annual Net Generation (MWh)
Hadley Falls	Publicly Owned Utility	08/15/1999	08/27/2039	2	33.4	186845.24
Boatlock	Publicly Owned Utility	08/15/1999	08/27/2039	3	3.1	13361.82
Beebe Holbrook	Investor-Owned Utility	08/15/1999	08/27/2039	2	0.516	
Skinner	Investor-Owned Utility	08/15/1999	08/27/2039	1	0.3	
Northfield Mountain	Wholesale Power Marketer	05/09/1968	04/26/2018	4	*1168	*940062.06
Bellows Falls	Wholesale Power Marketer	07/29/1979	04/26/2019	3	40.8	231198.24
Wilder	Wholesale Power Marketer	12/05/1979	04/26/2019	3	35.6	151915.41
Vernon	Wholesale Power Marketer	06/20/1979	04/26/2019	10	35.9	140574.47
Mcindoes	Wholesale Power Marketer	04/03/2002	03/27/2042	4	10.4	43653.12
Comerford	Wholesale Power Marketer	04/03/2002	03/27/2042	4	167.8	354921.59
S C Moore	Wholesale Power Marketer	04/03/2002	03/27/2042	4	190.8	292706.18
Canaan	Investor-Owned Utility	01/11/2009	07/27/2039	1	1.1	6590.59
Dodge Falls Associates	Private Non-utility	06/06/1984		1	5	27461.63
Gilman Mill	Private Non-utility	04/08/1994	03/27/2024	4	4.8	19667.24

D. Wilder Dam

Average monthly flow and generation at Wilder Dam can be seen in Figures D1 and D2. Figure D1 details how the mean river flow changes monthly across the five years included in our analysis. Figure D2 illustrates the monthly net generation changes across the five years included our study.

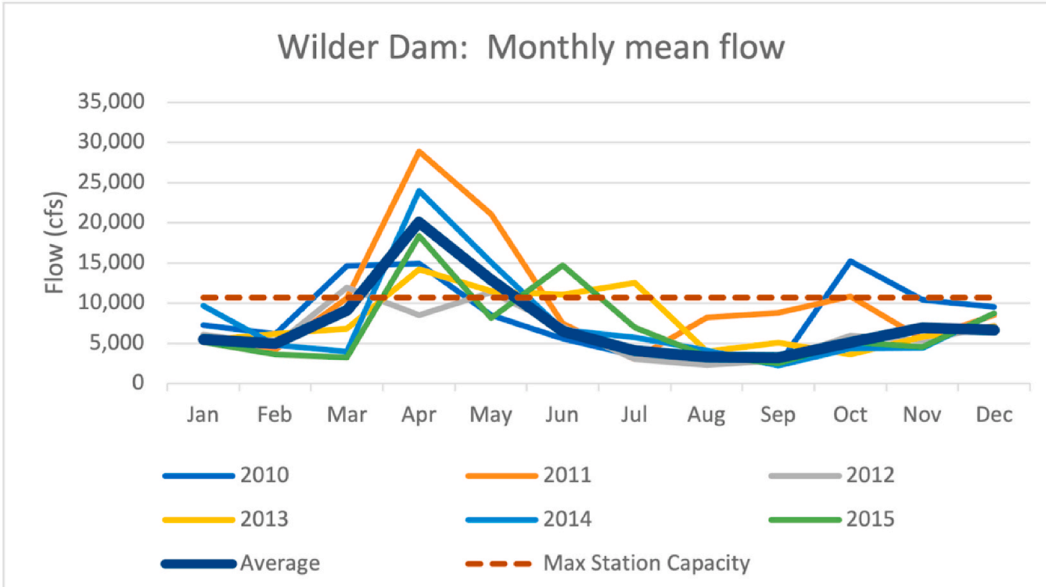

Fig. D1. Mean monthly flow in Connecticut River from Wilder Dam [52].

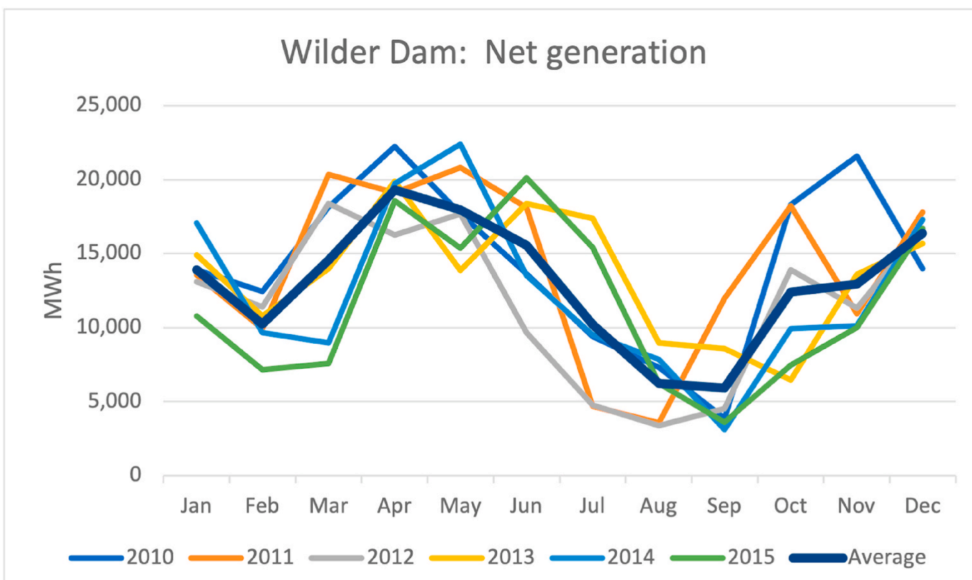

Fig. D2. Net Generation at Wilder Dam [53].

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