United States trends in non-powered dam electrification

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Over the past two decades, retrofitting existing non-powered dams for electricity generation has been the primary hydropower development activity in the United States. From 2006 to 2017, a total of 58 power projects on non-powered dams were licensed to produce an estimated 3.7 TWh of energy annually from 888 MW of cumulative installed capacity. In this article we provide a review of development trends, focusing on the variety of dam types developed, strategies by type, cost data, environmental mitigation trends, and market drivers.

Introduction

Hydropower plants produce approximately 7% of the United States annual electric power output. Most of the installed generating capacity of the existing fleet was constructed in the 20th century – the average age of a currently operational hydropower plant is over 60 years (Samu et al., 2018). In recent decades, the hydropower industry has largely shifted from development of greenfield hydropower to retrofits of existing non-powered dams (NPDs). The opportunity for energy development at NPDs is significant – of the nearly 83,000 dams situated on US rivers, more than 80,000 were built exclusively for non-energy purposes and currently do not produce hydropower. These NPDs range in size from small farm pond impoundments to locks and dams on large waterways, and can have several authorized purposes, including flood control, recreation, navigation, irrigation, and water supply. Retrofitting NPDs for hydropower has become an attractive development strategy based on the assumption that many of the fixed capital costs and environmental impacts of construction have already been incurred, thus reducing the technological and business risks and time frames compared to new dam construction.

To initiate development of a NPD hydropower retrofit, a developer must complete a licensing process managed by the Federal Energy Regulatory Committee (FERC)[1]. The goal of this process is to obtain an original license for generation, with terms and conditions for operation negotiated amongst various stakeholder groups and established following an environmental assessment (EA). From 2006 to 2017, 58 NPD retrofit projects with generating capacities from 100 kW to over 100 MW have completed an EA and obtained an original hydropower license (there projects are referred to herein as licensed NPDs)[2]. In this study, we aggregate technical, cost, and environmental mitigation data from these 58 EAs to assess trends in US NPD retrofits[3]. We couple this information to data from the US Army Corps of Engineers (USACE) National Inventory of Dams (NID), the National Hydropower Asset Assessment Program (NHAAP), and a US resource assessment of NPDs (Hadjerioua et al., 2012) to provide a holistic overview of trends in non-powered dam electrification[4].

Characteristics of NPD hydropower retrofits

Location and size

A general overview of location, capacity, turbine rated head, and plant hydraulic capacity of licensed NPDs is shown in Figure 1 and compared to the broader population of undeveloped NPDs with potential capacity greater than 100 kW (data obtained from Hadjerioua et al., 2012). Development activity is concentrated in several regions of the country that contain high NPD potential: along the Ohio River basin in the central US, on the southern Gulf Coast, and scattered through the Pacific Northwest. In general, these regions either have high-discharge waterways with existing navigational lock structures (central and southern US), or they have storage reservoirs used for water supply and flood control (Northwest). The Mississippi River that runs along the central region of the country retains a high amount of NPD potential that has yet to be developed.

The mean installed capacity of licensed NPDs is 15 MW, with a median of 6 MW and a minimum and maximum of 80 kW and 105 MW, respectively. The larger plants tend to be lower head, less than 10 m, with powerhouse capacities greater than 100 cms. Smaller plants less than 1 MW also tend to be low head. All licensed projects tend to have higher flow capacities compared to the broader resource of undeveloped NPDs, which contains many potential sites with flow less than 20 cms and head less than 10

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[1] In addition, if the dam is owned by the U.S. Army Corps of Engineers (USACE), the developer needs to obtain a Section 408 permit from USACE.

[2] We do not include power projects built on US Bureau of Reclamation dams as part of a lease of power privilege agreement

[3] EAs for all licensed NPDs can be found at https://www.ferc.gov/docs-filing/elibrary.asp

[4] Only 11 of the 58 licensed NPD retrofits have been commissioned and are currently generating electricity

m. Historically, these small low-head sites have been the most difficult to develop economically (O'Connor et al., 2015).

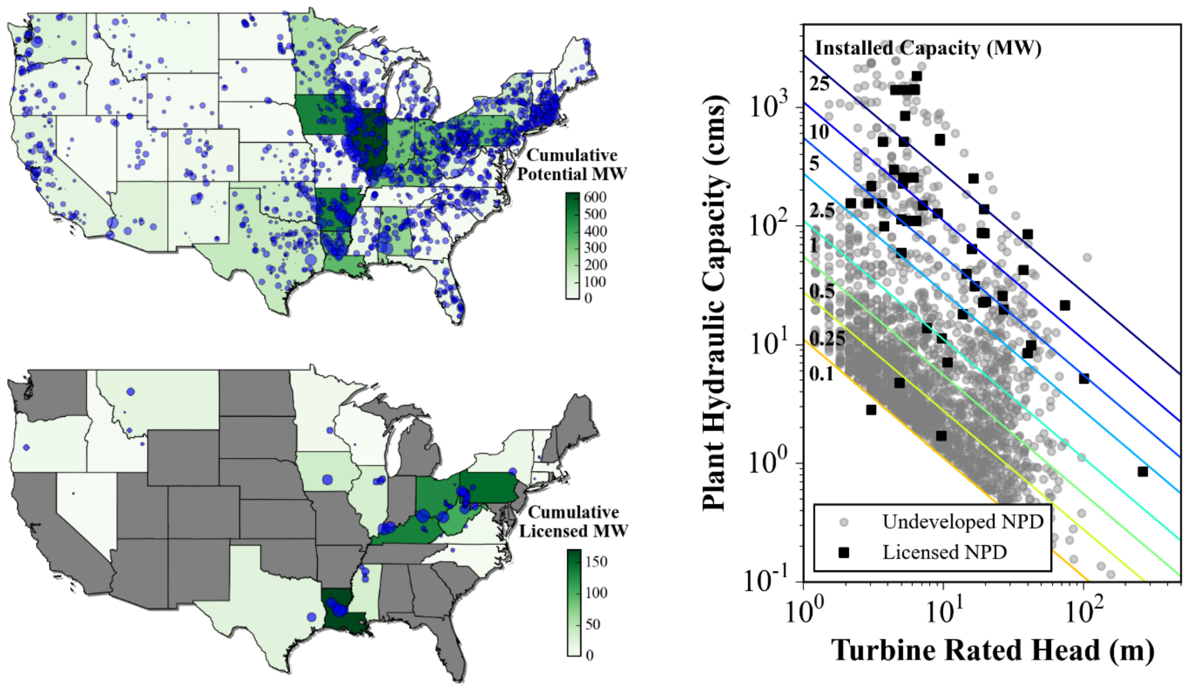

Figure 1. Top left: Geospatial distribution of NPDs with > 100 kW of potential capacity. Bottom left: geospatial distribution of licensed NPDs (not shown is one project in Alaska). Each blue marker represents a NPD. Gray states indicate 0 MW. Right: Turbine rated head and plant hydraulic capacity of undeveloped and licensed NPDs, with estimated installed capacity shown as diagonal lines.

Dam type and purpose

Most NPDs are authorized and developed for multiple purposes, including flood control, navigation, water supply, and recreation, and come in a variety of types, from earthen embankment dams to concrete gravity dams. Dams can also have multiple types, e.g., an earth dam with a gated concrete spillway. The primary and secondary purposes and types of licensed NPDs show the most common projects are gravity dams with navigation as a primary purpose (Figure 2). The trend towards development at dams with navigation locks is present in many states for a few reasons. Navigation locks maintain a consistent pool for navigation, making generation more predictable and reliable, and simplifying the development of intake works. In many states navigation locks are no longer functional, and a powerhouse can be developed in the lock channel. Powerhouse additions to NPDs are pursued at dams with recreation, flood control, and water supply purposes in equal numbers, while irrigation structures are less , largely due to their seasonally limited operation.

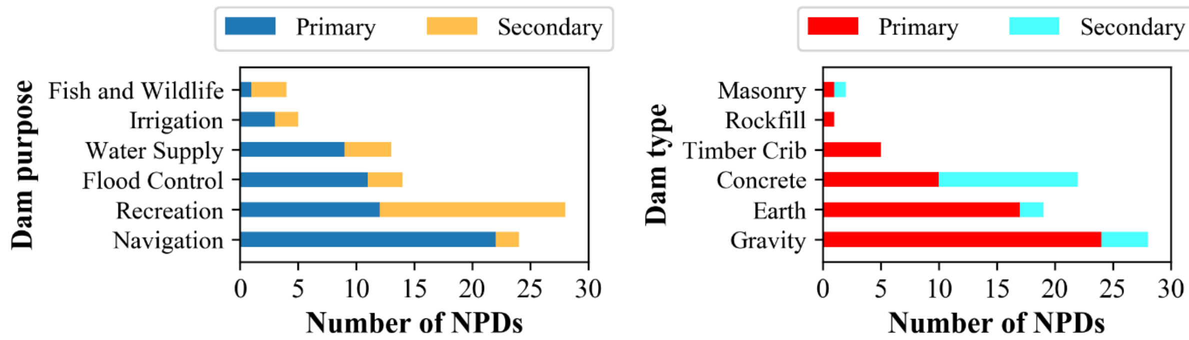

Figure 2. Left: Purpose of licensed NPDs. Right: Type of licensed NPDs.

A comparison of licensed NPDs to all NPDs shows that navigation dams are preferentially targeted for hydropower retrofits (Figure 3, top). Nearly 40% of licensed NPDs have navigation as a primary purpose, while less than 5% of all NPDs are navigation dams. A partial explanation for this preference is that navigation locks with similar head and flow characteristics are often found in series on a single river system. Developers have recently been successful in retrofitting such sequential NPDs as a cluster of projects using a common, replicable powerhouse design. Gravity and concrete dams are also preferentially targeted, while Earth dams are proving more challenging to develop, as they represent roughly 30% of licensed NPDs but greater than 50% of all NPDs (Figure 3, bottom). A series of aging timber crib dams on the Muskingum River have recently been approved for NPD retrofits, increasing their representation in licensed NPD dam type compared to all NPDs.

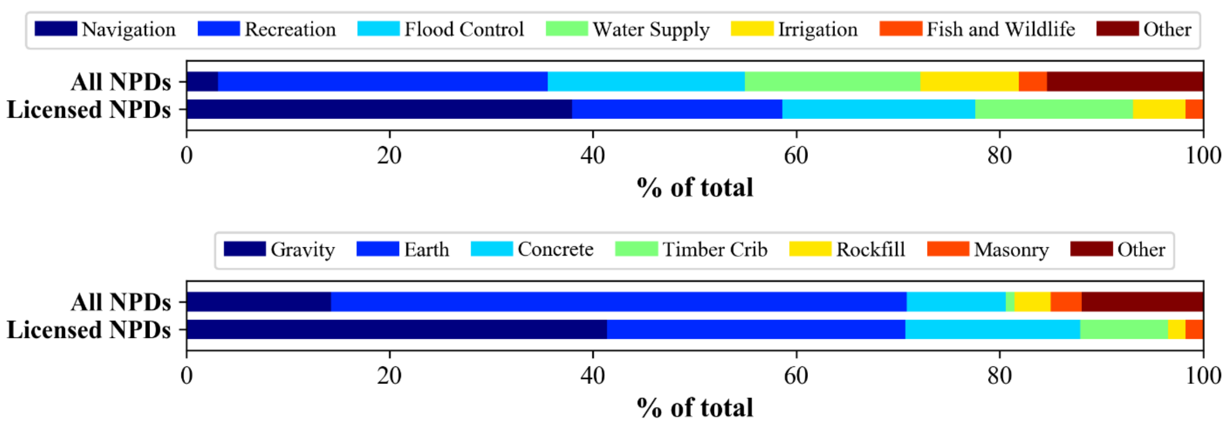

Figure 3. Top: Percentage distribution of primary purpose among licensed and all NPDs. Bottom: Percentage distribution of primary dam type among licensed and all NPDs.

Powerhouse location

Powerhouse layouts for licensed NPD retrofits generally fall into six categories:

- Through dam – a portion of the existing dam, spillway, or abutment is removed or modified to accommodate an intake structure, penstock, or powerhouse;
- Adjacent to dam – the powerhouse is constructed on an embankment or land parcel adjacent to the dam;
- Through lock – a powerhouse structure is built inside a decommissioned lock;

- Downstream of dam – a combined intake and powerhouse structure is built directly downstream of a dam or spillway gate in the river channel;
- In gate – generating units are placed within intake or spill gates;
- Downstream penstock – a powerhouse is constructed downstream from the dam and connected to the reservoir via a penstock using a new or existing outlet.

Additional technical details regarding these powerhouse arrangements are shown in Table 1, and aerial images are shown in Figure 4. Nearly all high-head dams (> 20 m) are developed using a penstock or by placing turbines in an intake gate. These approaches commonly take advantage of existing pressurized outlets or plugged conduits that can be retrofitted, lined, pressurized, and connected to a powerhouse. Most low-head structures are lock and dams developed with powerhouses adjacent to the dam or downstream of a spillway gate. These projects tend to have larger nameplate capacities, as the dams are on the mainstem of rivers and pass larger flows than higher head tributary or storage dams.

Table 1. Powerhouse location and relevant statistics. Note that 'In lock' developments are at structures that have been decommissioned for navigation and now serve primarily for water supply purposes. N = Navigation, R = Recreation, FC = Flood Control, WS = Water Supply, I = Irrigation, FW = Fish and Wildlife.

Powerhouse location	# of NPDs	Mean rated power (MW)	Mean turbine head (m)	Mean plant flow (cms)	Mean estimated capacity factor (%)	Primary Purpose					
						N	R	FC	WS	I	FW
Downstream penstock	19	8.1	38.1	36.1	42.8	1	3	6	6	2	1
Adjacent to dam	14	34.8	5.9	709.5	50.8	9	4	0	0	1	0
Downstream of dam	11	12.8	5.5	285.3	52.5	10	1	0	0	0	0
Through dam	6	11.7	5.3	230.8	60.0	1	4	1	0	0	0
In gate	5	3.8	22.2	39.7	43.1	1	0	4	0	0	0
In lock	3	3.4	5.0	77.4	44.6	0	0	0	3	0	0

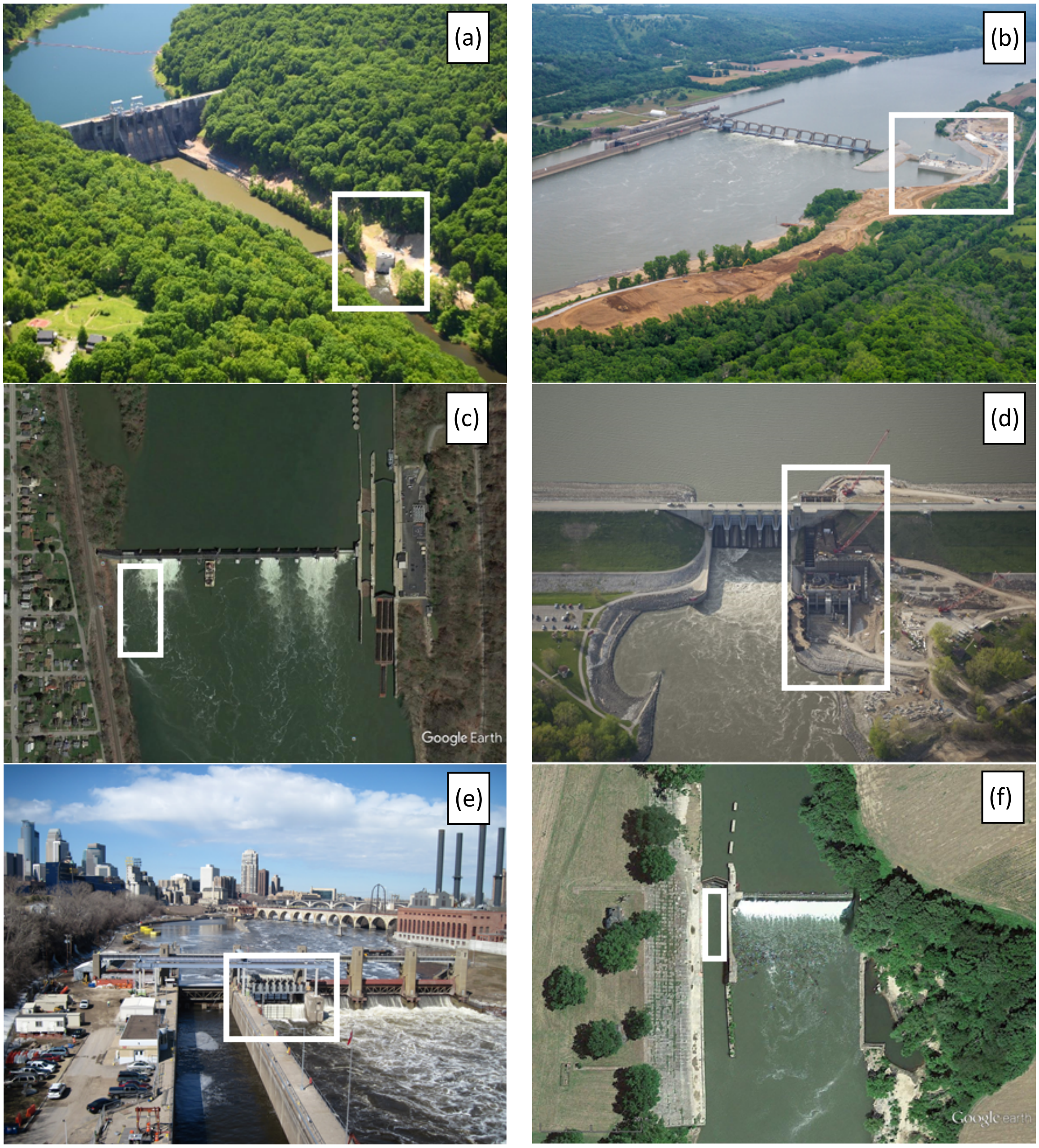

Figure 4. Six common powerhouse arrangements at non-powered dams: (a) downstream penstock (Mahoning Creek Hydroelectric Project, photo courtesy of design engineer, Mead & Hunt), (b) adjacent to dam (Meldahl Hydroelectric Facility, photo courtesy of Aerial Innovations of TN&KY, Inc.), (c) downstream of dam (proposed Montgomery Locks and Dam Hydroelectric Project), (d) through dam (Red Rock Hydroelectric Project, photo courtesy of Missouri River Energy Services), (e) in gate (Lower St. Anthony Falls Hydroelectric Project, photo courtesy of Andritz Hydro GmbH), (f) in lock (proposed Heidelberg Hydroelectric Project). The white box in each image depicts the location of the constructed or proposed powerhouse. Aerial images: Google (© GoogleEarth).

Proposed operational modes

Most licensed NPDs are owned and operated by the USACE. A proposed power project owned by private or non-federal public entities can only pass flows through a new powerhouse when use of flow does not interfere with the original purposes of the dam or lock. This mode is termed 'run-of-release' and is the proposed mode of operation for 36 of the 58 licensed NPDs. A run-of-river mode of operation, in which outflow from the project always equals inflow and the impoundment water surface elevation is not drawn down for generation, is proposed for 17 projects, 2 of which operate with modified rules during irrigation season. The remaining 5 NPDs operate based on a rule curve established as part of EA negotiations. Strict minimum flow regimes are prescribed for 30 projects. In aggregate, operating in run-of-release mode tends to limit developers estimates of annual generation – the mean estimated capacity factor of these projects is 47% compared to 56% for projects operating in run-of-river mode. Operating based on a rule curve is generally more restrictive, with a mean estimated capacity factor for these projects of 45%. Powerhouse arrangement also influences estimated capacity factor – powerhouse through the dam has the highest capacity factor of 60%, while a downstream powerhouse with a penstock has the lowest at 43%.

Estimated capital and licensing costs

Licensed NPDs are required to report an estimated capital cost for their project and an estimate of how much it costs to develop a license application, including the studies required to establish environmental protection, mitigation, and enhancement measures. Project cost trends show a strongly correlated log-log relationship between installed capacity and total capital cost (Figure 5, left). In general, capital costs decrease slightly on a $/kW basis as project capacity increases, while licensing costs increase exponentially on a $/kW basis for smaller projects (Figure 5, right).

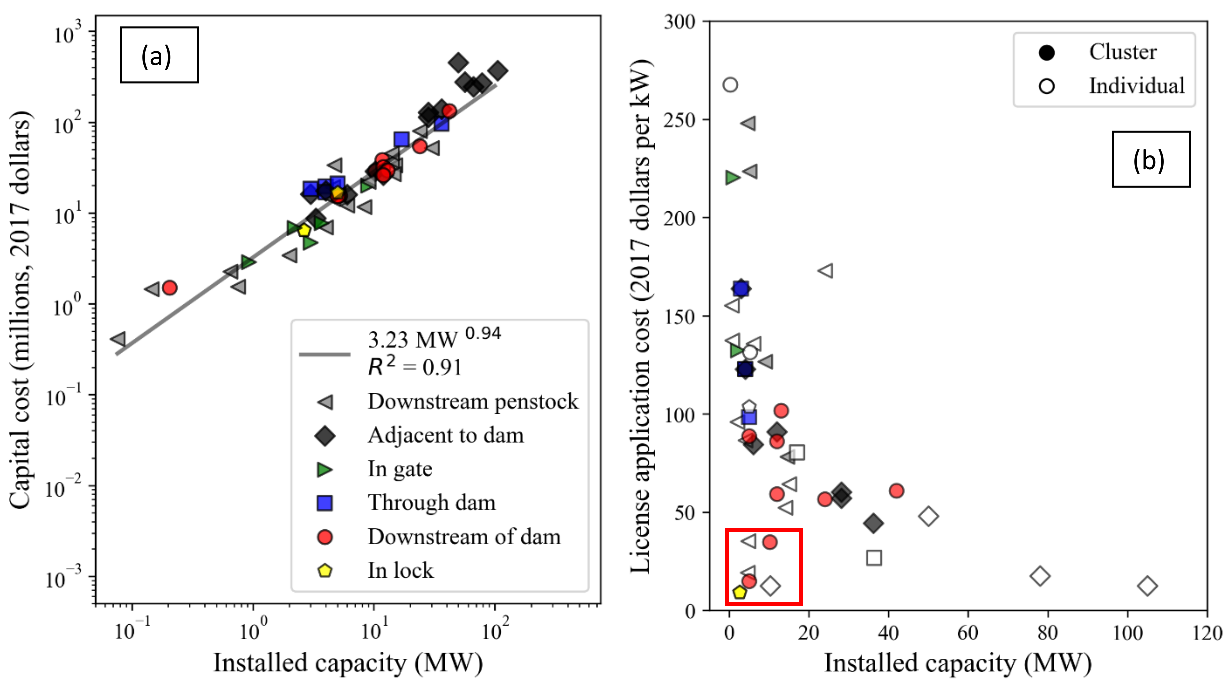

Figure 5. Cost estimates as reported in each licensed NPD EA, escalated to 2017 dollars: (a) capital cost estimates, (b) cost to develop a license application. Filled markers on right indicate the license application contained multiple NPDs submitted as a cluster of projects. Marker shapes are same across plots.

Nearly half of all projects are being developed as part of a cluster strategy, where a project developer retrofits multiple NPDs simultaneously. In these cases, two to six NPDs on a single river system are targeted to enable cost savings through economies of scale and time savings in multiple steps of licensing, development, and construction. Despite the clustering trend, there do not appear to be significant cost savings associated with clustering projects from a license application standpoint (Figure 5, right), though there may be time savings that are not captured in this analysis. Approximately eight projects are outliers that have recorded lower licensing costs compared to most other projects (red box, Figure 5, right). In general, these projects leverage existing civil works such as existing but unused intake works and decommissioned lock structures, resulting in minimal excavation and construction activities, lower civil costs, and fewer environmental impacts from construction.

Costs to operate and maintain (O&M) power projects on NPDs are also strongly influenced by the installed capacity. Annual estimated O&M costs range from $13.6/kW to $524/kW ($2.5/MWh to $85.6/MWh), with a mean of $61.8/kW ($15.1/MWh). Like other hydropower projects, NPD retrofits benefit from economies of scale in O&M, and as such the average O&M cost for small projects < 10 MW ($69.7/kW, $17/MWh) is higher than for larger installed capacities ($51.3/kW, $12.5/MWh).

Environmental protection, mitigation, and enhancement

During the FERC licensing process, a NPD developer must examine the effects of construction and operation of the project on the environment. Following studies and consultation with project stakeholders, a list of protection, mitigation, and enhancement (PM&E) measures are established and codified within the EA. A description of PM&E measures by category is provided in Table 2. Licensed NPDs generally implement anywhere between four to fifty PM&E measures per project as part of the original design and/or following recommendations from FERC, a state government agency, or a citizens' rights group. Following a cost-benefit analysis, a licensed NPD must report the capital cost, annual O&M cost, and annualized total cost of each mandatory PM&E measure. Annualized costs generally range from $0 to $500,000 ($0/kW to $92/kW), though only one in six exceeds $5,000 ($0.75/kW).

Table 2. Common protection, mitigation, and enhancement (PM&E) measures for licensed NPDs.

Category	Description	Example measures
Aquatic resources	Measures to protect aquatic animals, water quality, and riverine health	Trash-racks, fish screens, water quality studies, aquatic species relocation
Cultural resources	Measures to protect historic structures, areas, or artifacts	Avoidance of burial grounds, notification of native peoples if artifacts are discovered
Geological resources	Measures to protect against soil erosion, sediment accumulation, and hazardous waste	Sediment control plans, erosion control plans, contaminated soils removal
Land use and aesthetic resources	Measures that call for land acquisition, promote compliance with existing land use patterns, and or minimize visual disturbances	Acquiring land rights, matching project aesthetics to style of surrounding areas, reducing project-related noise pollution
Recreation resources	Measures to implement new recreation opportunities or accommodate those affected by construction and operation	Provision of: boat ramps, campgrounds, fishing platforms, parking lots, restrooms, prescribed flow or water levels for boating
Terrestrial resources	Measures that protect land animals, avian populations, and vegetation	Replanting of vegetation on disturbed areas, establish transmission corridors, protection plans for birds and animals
Threatened and endangered species	Measures designed for protection of specific endangered species	Relocating animals, conducting studies on population dynamics, ongoing protection plans

A comparison of recommended PM&E measures shows that over 40% are related to aquatic resources, independent of project capacity (Figure 6). The major measures in this category are generally structures for screening fish and debris, including the studies to determine optimum designs, and implementation of best practices related to siting water quality monitoring devices and compliance reporting of water quality parameters. Terrestrial and recreation resource PM&E measures generally make up 20% and 10% of all measures, respectively. PM&E measures with the largest capital costs tend to vary by project capacity: smaller project (< 10 MW) costs are evenly split among measures; mid-size project (10MW – 30 MW) costs are significantly weighted towards geological resource measures; larger project (> 30 MW) costs are even more substantially weighted towards recreational resource measures. Larger NPDs tend to be on structures owned and operated by the USACE, the largest provider of water-based recreation in the country. To remain consistent with this mission, these NPDs generally include fishing piers, parking lots, picnic and play areas, lighting, and restrooms as part of their development package. From an ongoing PM&E operations and maintenance (O&M) cost perspective, measures also vary by project capacity: smaller projects spend more on land use and aesthetic resource maintenance, including landscaping and maintaining a spill flow during summer months for aesthetic purposes; mid-size project costs are generally driven by aquatic resource protection, including maintenance of fish passage facilities and air admission systems to enhance dissolved oxygen; larger projects spend more on terrestrial resources, including wetland construction and monitoring, invasive species management, and annual surveys of terrestrial species along transmission corridors. In general, O&M costs for PM&E measures are a small fraction of overall project O&M – from 7% for small projects to 1% for mid-size and large projects. Across all NPDs, the number of unique PM&E measures and their associated capital and annual O&M costs (in $/kW) decrease as project capacity increases.

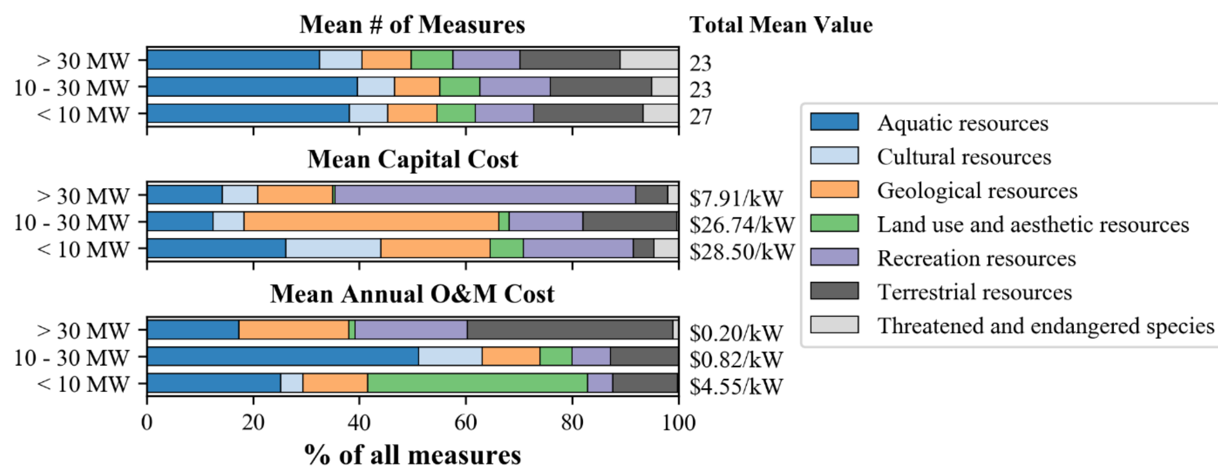

Figure 6. Categorical breakdown of mitigation measures by installed capacity range, including mean number of mitigation measures required per project (top), mean capital cost of each measure (middle), and mean annual O&M cost of each measure (bottom). The column on the right gives mean total value for each category.

NPD market drivers

It is worth assessing whether there is significant correlation between NPD project location and revenue-side factors like electricity market structure and prices or state-level renewable energy incentives. In general, having access to organized wholesale markets for energy and ancillary services is attractive for private developers pursuing NPD projects, and most of the licensed NPDs are located within the footprint of a deregulated energy market coordinated, controlled, and monitored by Independent System Operators (ISO) or Regional Transmission Organizations (RTO). This does not necessarily mean the facility owners will participate in these markets as merchant generators, but it gives them the option to do so if the terms offered by utilities in power purchase agreements are unattractive. Approximately 75% of the licensed NPD projects and 90% of licensed NPD capacity are in the service territories of Midcontinent ISO (MISO) or PJM RTO. For both ISO/RTOs, hydropower represents a very small fraction of the electricity generation mix.

The median estimated capacity factor of 49% for licensed NPDs is significantly higher than the median for the existing U.S. hydropower fleet, approximately 35% from 2014-2016 (Samu et al., 2018; Uría-Martínez et al., 2018). Since most NPD projects are licensed to operate as run-of-release or run-of-river facilities, however, their operational flexibility will be limited. With high capacity factors and limited ability to schedule generation to coincide with peak price periods, average energy prices are a key metric for overall project revenue. Based on average wholesale electricity prices reported by the Energy Information Administration, the average in recent years (2014-2017) for trading hubs representative of the MISO and PJM markets where most licensed NPD projects are located have been $39.63/MWh (Indianapolis Hub) and $44.11/MWh (PJM West Hub) respectively.[5] These average prices are roughly in the middle range compared to those in the Northeast region (e.g., $49.96/MWh in Massachusetts NEPOOL Hub), and in the Western half of the country ($28.47/MWh for Mid-Columbia hub, $32.01/MWh for Palo Verde hub in Arizona).

State-level renewable energy portfolio (RPS) policies do not appear to be a significant driver for NPD site selection. RPSs often impose constraints on the eligibility of hydropower projects (e.g., size, low-impact certification requirements, year of construction/operation) limiting their value for encouraging development of the available NPD resource (Stori, 2013). Half of the licensed NPD capacity since 2000 is in states that have no renewable portfolio standards, and only 3% of licensed NPD capacity is in California, Oregon, New York, or Vermont, states with the most ambitious RPS goals (mandatory targets of 50% or more renewable generation in their state electricity generation mix).

A patchwork of federal regulatory changes and subsidy policies may be a more likely driver of NPD development. The Hydropower Regulatory Efficiency Act of 2013 was designed to streamline the licensing process for nonfederal NPDs with less than 10 MW of capacity, and a 2016 FERC-Department of Energy Memorandum of Understanding introduced a two-phased synchronized process to obtain the needed FERC license and USACE Section 408 permit, aimed at reducing total permitting time for USACE-owned NPDs. Recent expansions of federal subsidies like the Renewable Electricity Production Tax Credit and guaranteed loan financing through programs like the Rural Utilities Service Electric Program have also been crucial to improving NPD retrofit economic feasibility.

Summary

From 2014 to 2017, 39 NPDs with 636 MW of cumulative capacity received an original license to add a hydropower project, a significant increase from the 19 NPDs with 252 MW of cumulative capacity licensed in the prior eight years. The most common targets for NPD hydropower retrofits have been large capacity, low-head, high flow navigation dams along major waterways. While a few dozen similar NPDs remain targets for development, thousands of undeveloped NPDs have small installed capacities and a primary purpose that is not navigation. Current trends suggest the economic development of these NPDs could be achieved using a cluster approach, where dams with similar head, flow, purpose, type, and location are retrofitted for hydroelectric generation using a standard plant design.

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Biographies

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