Retrofitting Non-Powered Navigational Locks for Hydroelectric Use

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HSA10-5 The Economics of Oil and Energy
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I. Overview

Hydropower is the largest source of renewable energy in the United States today, accounting for 52% of renewables and 7% of overall electricity.[1] While hydropower generates low-emission, low-cost renewable energy, significant environmental drawbacks and a lack of viable sites for new dams have led the installed capacity to stagnate over the past few decades. However, new technology for retrofitting existing non-powered dams has the potential to add up to 12 GW of renewable energy to the grid.[2] In this paper, we will examine the benefits and economic viability of retrofitting navigational locks, a specific type of non-powered dam, for hydroelectric use.

II. Background Information

Hydropower is one of the oldest forms of power, having been used since ancient times to operate various mechanical devices by way of a water wheel. Although hydropower had been widely used in the United States since colonial times for milling, pumping, and other tasks, it was not until 1880 that hydroelectricity was first produced in the United States when a dam at Niagara Falls was used to light streetlamps. Even then, most dams, particularly in the arid West, were constructed largely for irrigation purposes, although some hydroelectricity was generated as a byproduct.[3] Dam construction started to boom during the Great Depression, when dams became attractive large-scale public works projects because of the enormous number of people they employed. Many of the largest dams were built during this period, including Hoover Dam and Grand Coulee Dam. As the United States entered World War

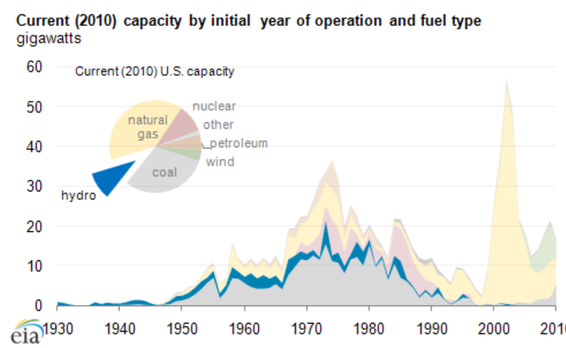

Figure 1
Hydropower capacity in 2010 by initial year of operation and fuel type

http://www.eia.gov/todayinenergy/detail.cfm?id=2130

[1] Hydropower is Available: http://www.hydro.org/why-hydro/available/
[2] Hydropower Resource Assessment and Characterization: http://energy.gov/eere/water/hydropower-resource-assessment-and-characterization
[3] The History of Hydropower in the United States: http://www.usbr.gov/power/edu/history.html

II, electrical needs for the war effort outstripped supply, and dams provided a cheap and relatively straightforward way to rapidly increase power production. After the war, hydropower continued to surge, with dam building peaking in the 1960s. However, few dams were built in the 1970s or later, due in part to the growing awareness of the harmful environmental impacts of dams. Additionally, remaining sites that large dams could be built on proved mostly suboptimal; an unsound geologic location was determined to be a significant cause for the $2 billion failure of the Teton Dam in 1976.[4]

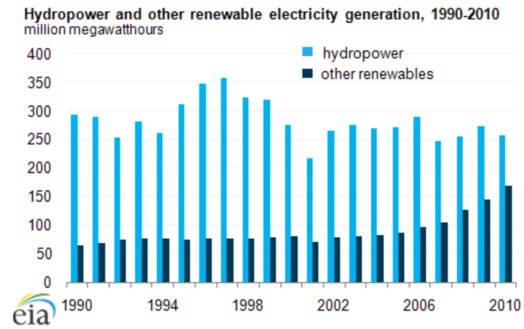

Figure 2
Hydropower generation by year

http://www.eia.gov/todayinenergy/detail.cfm?id=2650

Located in eastern Idaho, the Teton Dam spanned the Teton Canyon; the site was composed largely of basalt and rhyolite, two highly porous volcanic rocks.[5] The site had been scouted as early as 1935, but an early geologic study of the site noted the high permeability of the canyon walls and concluded that building a dam there was not economically viable.[6] However, in 1961, the Bureau of Reclamation began drilling tests at the site. These drilling tests showed that the rock in the canyon was fissured and unstable, but a Bureau of Reclamation memorandum concluded that these fissures could be sealed by injecting high-pressure grout.[7] After construction on the dam began in 1971, the fissures were discovered to be significantly larger than first thought, but the Bureau of Reclamation pushed ahead with project. Construction was completed in November 1975. On the morning of June 5, 1976, just as the dam was nearing full capacity for the first time, workers noticed a small leak in the face of the dam.[8] Efforts to plug this leak proved unsuccessful; four hours later, the dam collapsed, sending 80 billion gallons of water downstream. Eleven people were killed and the nearby towns of Wilford, Sugar City, Hibbard, and Rexburg were almost completely destroyed.[9] A subsequent Congressional investigation concluded that poor site selection and inadequate design and construction for the

[4] Teton Dam Failure: http://www.slcdocs.com/utilities/NewsEvents/news2009/news6292009.htm
[5] The Teton Dam: Rhyolite Foundation + Loess Core: http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2451.1992.tb00347.x/abstract
[6] Teton Dam Failure Narrative: http://www.geol.ucsb.edu/faculty/sylvester/Teton_Dam/narrative.html
[7] Teton Dam: https://en.wikipedia.org/wiki/Teton_Dam
[8] Teton Dam Failure: http://www.slcdocs.com/utilities/NewsEvents/news2009/news6292009.htm
[9] Teton Basin Project: http://www.usbr.gov/projects/ImageServer?imgName=Doc_1305643698603.pdf

site were to blame. One geologist stated in his testimony that such a dam would not have been built “40 to 50 years ago… we would have [had] much better sites to select from.”[10]

Today, hydroelectricity continues to be of key importance in the U.S. energy market and is the largest source of renewable energy in U.S, generating 79.64 GW of electricity in 2014.[11] Hydropower capacity has remained relatively level over the past decade (Figure 2); from 2005 to 2013, only 1.48 GW of capacity was added (an increase of only 2% in total capacity), the majority of which can be attributed to upgrades (largely replacement of turbines) at existing facilities.[12]

III. Hydropower Generation

Fundamentally, hydropower relies on changes in the gravitational potential energy of water. A dam impounds water in a reservoir and raises the water level on one side of the dam to create head, or vertical distance that the water falls as it passes through the dam. Water in the reservoir is driven through the penstock through a turbine or series of turbines, which generate electricity through electromagnetic induction. The water is then returned to the river or stream below the dam. The energy that is created is proportional to the head (the distance the water falls) and the streamflow. While navigational locks tend to have small head heights, they tend to be located on major rivers with high streamflows.[13]

Dams are generally categorized into two groups: storage facilities (Figure 3) and run-of-the-river facilities (Figure 4). Storage facilities, like Hoover Dam and other large dams, impound a large amount of water behind them and release it at a carefully measured pace to generate electricity. Run-of-the-river dams have little or no storage behind their impoundment wall; as water flows to the dam, it is run almost straight through the turbines. Navigational lock and dam projects are run-of-the-river plants, as they typically have only a small amount of storage, called “pondage.” Because commercial vessels must be able to continue to travel along the river, run-of-the-river dams on navigable rivers tend to divert water from the main lock through a series of spillways to a generation station and then back to the main course of the river.

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[10] Teton Dam Disaster Hearings: http://njlaw.rutgers.edu/collections/gdoc/hearings/7/77600503/77600503_1.pdf

[11] Hydropower is Available: http://www.hydro.org/why-hydro/available/

[12] Hydropower Market Report: http://energy.gov/sites/prod/files/2015/05/f22/2014%20Hydropower%20Market%20 Report_20150512 _rev6.pdf

[13] Why Do We Have Locks and Dams: http://www.mvr.usace.army.mil/Media/NewsStories/tabid/6636/Article/476805/why-do-we-have-locks-and-dams.aspx

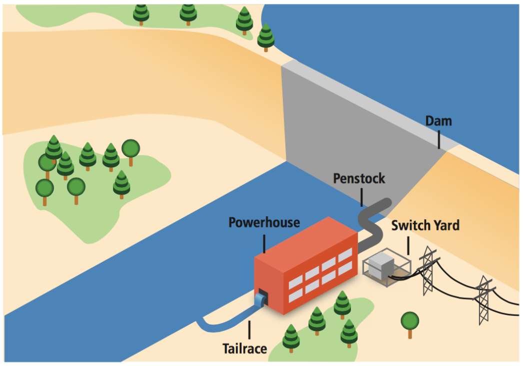

Figure 3
Diagram of a Storage Facility

http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch05.pdf

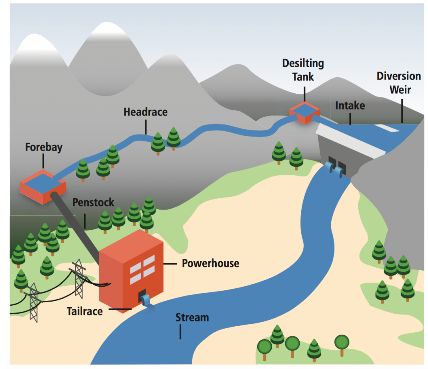

Figure 4
Diagram of a Run-of-the-River Facility

http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch05.pdf

IV. Non-Powered Dams

The focus of the future of hydropower has largely shifted away from new stream reach, or the building of new dams on previously undammed rivers, to adding hydroelectric capacities to non-powered dams; according to the Department of Energy, this could add up to 12 GW of capacity.[14] Of the more than 80,000 dams listed in the Army Corps of Engineers' National Inventory of Dams, only 2,198, or about 3%, are used to generate hydroelectricity.[15] The remaining 97% of dams, collectively called non-powered dams, have a variety of purposes, from recreation to irrigation to flood control, and many of these have the potential to generate significant amounts of hydroelectricity (Figure 5). Because the fuel (water) is free, the largest cost in a hydroelectric plant, as much as 75% of the kWh cost of hydroelectricity[16], is the initial investment in the dam infrastructure. While non-powered dams would have to undergo construction to retrofit turbines into the structure, this cost is fairly minor in comparison to the overall cost of the original structure. In addition, retrofitting non-powered dams avoids many of the environmental problems associated with new dam construction. Environmental concerns for

[14] Hydropower Resource Assessment and Characterization: http://energy.gov/eere/water/hydropower-resource-assessment-and-characterization
[15] Hydropower Market Report: http://energy.gov/sites/prod/files/2015/05/f22/2014%20Hydropower%20Market%20 Report_20150512 _rev6.pdf
[16] The Economics of Hydroelectricity: http://www.hydro21.org/div_media/pdf/pdf_economie_en.pdf

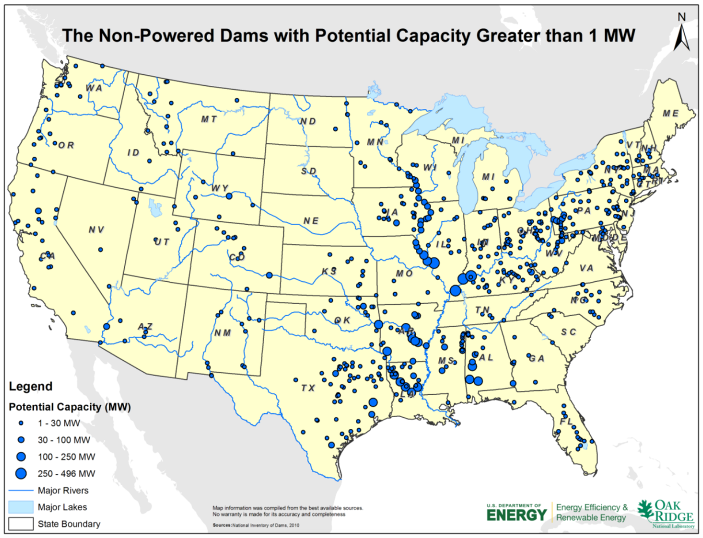

Figure 5
Map of the non-powered dams with potential capacity greater than 1 MW

http://www1.eere.energy.gov/water/pdfs/npd_report.pdf

dams include flooding of land for reservoirs, destruction of plant and animal habitat (particularly for fish species), and silting of rivers.[17] Because retrofitting uses previously existing dams, most of these concerns are mitigated. The vast majority of environmental impacts result from the building of the structure and initial filling of the reservoir.[18] Non-powered dams also tend to be located closer to population centers than traditional hydroelectric dams, which reduces transmission losses, although unsightly and often environmentally harmful transmission lines must be built.[19]

V. Design and Use of Navigational Locks

Virtually all free-flowing rivers are unnavigable for commercial vessels due to varying depths, hydrologic features such as waterfalls, and elevation changes. To allow for commercial boat travel, many large rivers are dredged to a minimum depth and width. (The Mississippi, for example, is dredged to a minimum depth of 9 feet and a minimum width of 400 feet along the 670 miles of navigable river.[20]) To solve the problem of elevation gain as well as maintain this dredged depth, a series of locks and dams is often constructed along the river. These locks and dams create a staircase-like series of pools at differing elevations. To travel upstream or downstream between these pools, locks raise and lower the boats using the gravitational potential

[17] Environmental Impacts of Hydropower: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-hydroelectric-power.html#.VtgAXrQ-DR0
[18] The Trouble With Dams: http://www.theatlantic.com/past/politics/environ/dams.htm
[19] Hydropower's Untapped Potential: http://www.power-eng.com/articles/print/volume-119/issue-6/features/hydropower-s-untapped-potential.html
[20] Why Do We Have Locks and Dams: http://www.mvr.usace.army.mil/Media/NewsStories/tabid/6636/Article/476805/why-do-we-have-locks-and-dams.aspx

energy of water; if a boat is traveling downstream, the lock gates are closed and water is allowed to flow out of the lock until the water level in the lock is the same as the downstream water level (Figure 6). If the boat is traveling upstream, water from upstream is allowed to flow into the lock until the water level in the lock is the same as the upstream water level.[21] Because locks are commonly located along high-flow rivers and are permanent because they are required for navigation, locks are ideal sites for retrofitting hydroelectric turbines. Of the 100 sites identified in a 2012 study of potential sites for hydroelectric retrofitting by Oak Ridge National Laboratory[22], 81 of the 100 sites, and all of the top ten, are lock and dam projects.

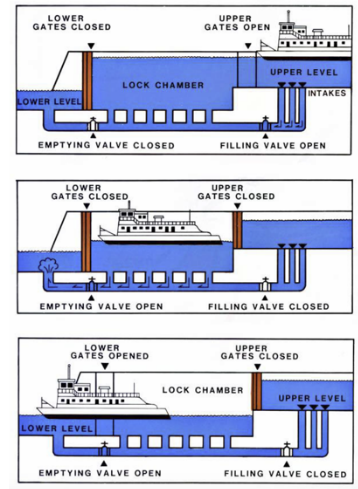

Figure 6
Diagram of a lock

http://mvs-wc.mvs.usace.army.mil/arec/Images Photos/locking-1.jpg

VI. Economics of Retrofitting Locks for Hydropower Generation

In order to estimate the electricity generated and the costs of retrofitting a navigational lock, I will use Lock and Dam 25, which spans the Mississippi River near Winfield, Missouri (Figure 7). Lock and Dam 25 was constructed in 1939 by the Army Corps of Engineers as part of a larger project to ensure a nine-foot deep navigational channel of the Mississippi River. Lock and Dam 25 is intended to be a representative choice of navigational locks able to be retrofitted for hydroelectric generation; like the vast majority of locks, it is managed by the Army Corps of Engineers and is part of a larger river management project. Additionally, Lock and Dam 25 has a head of 15 feet, which is typical of lock head sizes as cited by the Oak Ridge National Laboratory study.[23]

Figure 7
Lock and Dam 25 near Winfield, Missouri

http://www.mvs.usace.army.mil/portals/54/siteimages/navigation/LocksandDams/LockDam25_0118.jpg

To determine the average generating power of a dam we can use the following equation:[24]

[21] How TVA Locks and Dams Make Navigation Possible: http://www.tvakids.com/river/navigation.htm
[22] An Assessment of Energy Potential at Non-Powered Dams in the United States: http://www1.eere.energy.gov/water/pdfs/npd_report.pdf
[23] An Assessment of Energy Potential at Non-Powered Dams in the United States: http://www1.eere.energy.gov/water/pdfs/npd_report.pdf
[24] Hydropower Generation: http://www.engineeringtoolbox.com/hydropower-d_1359.html

$$Power\ (in\ W) =\ \mu\rho q g h$$

where ρ is the density of water (1000 kg/m^3), q is the average flow (in m^3/s), g is the acceleration due to gravity (9.8 m/s^2), h (in m) is the gross head for hydropower, and μ is the generating efficiency of the dam (in the Oak Ridge National Laboratory study, the generating efficiency was assumed to be 0.85[25]). According to the same study, the gross head height of Lock and Dam 25 is 15 feet, and the flow rate is 76,764 cfs. Therefore,

$$Power\ (in\ W)$$
$$= (0.85) * \left(1000\ \frac{kg}{m^3}\right) * \left(76{,}763\ cfs * \frac{0.02832\ \frac{m^3}{s}}{1\ cfs}\right) * \left(9.8\ \frac{m}{s^2}\right)$$
$$* \left(15\ feet * \frac{0.3048\ m}{1\ foot}\right)$$

$$P = 8.28\ x\ 10^7\ W = 82.8\ MW$$

While this is the total potential hydropower generation for the dam, the turbines will have to be installed in a diversionary route so that commercial vessels can continue to pass through the locks. Therefore, recalculating for a fifth of the river span:

$$Power\ (in\ W)$$
$$= (0.85) * \left(1000\ \frac{kg}{m^3}\right) * \left(\frac{1}{5} * 76{,}763\ cfs * \frac{0.02832\ \frac{m^3}{s}}{1\ cfs}\right) * \left(9.8\ \frac{m}{s^2}\right)$$
$$* \left(15\ feet * \frac{0.3048\ m}{1\ foot}\right)$$

$$P = 1.66\ x\ 10^7\ W = 16.6\ MW$$

[25] An Assessment of Energy Potential at Non-Powered Dams in the United States: http://www1.eere.energy.gov/water/pdfs/npd_report.pdf

Total costs for installing turbines are difficult to determine because turbines are built largely on a case-by-case basis, and installation costs vary widely from location to location. However, a 2010 Lancaster University study cites an empirical formula for average costs of electromechanical equipment and installation for dams with capacities between 5 and 1,000 MW and heads between 10 and 300 m:[26]

$$C_{EM}\ (cost\ in\ USD) = 32700 * \frac{kW^{0.7}}{H^{0.35}}$$

where kW is the installed capacity in kW and H is the hydraulic head in m.

For Lock and Dam 25, with a head height of 15 feet and an estimated installed capacity of 16.6 MW (16600 kW):

$$C_{EM}\ (cost\ in\ USD) = 32700 * \frac{(16600\ kW)^{0.7}}{(15\ feet * \frac{0.3048\ m}{1\ foot})^{0.35}}$$

$$C_{EM}\ (cost\ in\ USD) = \$17.3\ million$$

However, because water must be diverted from the lock, a spillway or other diversionary channel must be constructed, which can add significant cost. Spillways are unique to their location and the location's hydrologic features, so costs for a particular location are difficult to estimate. A 2013 study of cost scaling for spillways cited a cost of $1.45 million for an 80 foot spillway.[27] The study also concludes that the cost of the spillway is largely linear with length; therefore, a reasonable estimate of the cost of two 250 foot spillways, as would be standard for a run-of-the-river dam with a similar hydroelectric capacity[28], would be $9.1 million.

This would bring the total cost of the retrofitting to $26.4 million, or about $1600 per kW. This is significantly less than the construction of power plants for other fuels. A nuclear power plant,

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[26] Cost of Small-Scale Hydro: http://www.brad.ac.uk/research/media/centreforsustainableenvironments/documents/Cost_of_small_scalehydro.pdf
[27] Cost of a Spillway Improvement Project: https://c.ymcdn.com/sites/www.aspenational.org/resource/resmgr/Techical_Papers/October_2014_TP.pdf
[28] Federal Energy Regulatory Commission Notices: https://www.gpo.gov/fdsys/pkg/FR-2011-12-01/pdf/2011-30873.pdf

for example, costs between $4,000 and $6,000 per kW to construct (without fuel).[29] A coal fired power plant generally costs in the range of $3,000 per kW to build (without fuel).[30] Therefore, even disregarding the costs of fuel (which is free for hydroelectricity), increasing capacity by retrofitting non-powered dams is significantly cheaper than building new power plants.

While these estimates provide a rough idea of the overnight cost of installing new generation facilities, they do not show the true cost of energy generated from retrofitted navigational locks. Unlike traditional energy sources like coal and natural gas, where fuel is a significant portion of the cost per kWh, hydropower plants typically have high capital costs, low operating costs, and essentially free fuel.[31] Therefore, to more accurately compare the costs of hydropower generated from retrofitted navigational locks with energy generated from other sources, I will use amortization to calculate the kWh cost of energy produced at Lock and Dam 25.

The basic formula for cost amortization is

$$VAC = \left[\frac{FC * (1+r)^n * r}{(1+r)^n - 1}\right]$$

where VAC is the variable annual cost, FC is the amount to be amortized, r is the discount rate, and n is the life of the project in years.

I will use the estimate of the cost of retrofitting Lock and Dam 25 ($26.4 million) as the amount to be amortized and assume a discount rate of 6%. The life of the project is somewhat harder to determine; estimates of the life of dams range from 50 to 100 years.[32] While there are a number of dams in the US older than 100 years still producing hydropower, I will use a conservative estimate of 50 years as the life of the project, given that it is cited as the age at which a dam generally needs renovation.[33] Thus,

[29] Nuclear Power Plant Construction Costs: http://www.psr.org/nuclear-bailout/resources/nuclear-power-plant.pdf
[30] Coal-Fired Power Plant Construction Costs: http://schlissel-technical.com/docs/reports_35.pdf
[31] The Economics of Hydropower: http://www.hydro21.org/div_media/pdf/pdf_economie_en.pdf
[32] Advantages of Hydropower Production and Use: http://water.usgs.gov/edu/hydroadvantages.html
[33] Enduring Hydropower: https://www.hatch.ca/News_Publications/Energy_Innovations/June2015/pdf/Guest-CClark-Enduring-Hydropower-2.pdf

$$VAC = \left[\frac{(\$26.4\ million)\ (1+.06)^{50}\ (.06)}{(1+.06)^{50}-1}\right] = \$1.68\ million$$

In addition to this annual capital payment, the annual cost must include operating and maintenance (O&M) costs as well. Like turbines and spillways, O&M costs are highly specific to the dam site and its surrounding hydrologic features. However, a study conducted by Idaho National Laboratory found a correlation between installed capacity and annual O&M costs of

$$C_{O\&M}(cost\ in\ USD) = fixed\ O\&M + variable\ O\&M$$
$$= 27000 * MW^{0.75} + 27000 * MW^{0.80}$$

where MW is the installed capacity in MW.[34] For Lock and Dam 25, with an installed capacity of 16.6 MW,

$$C_{O\&M}(cost\ in\ USD) = 27000 * (16.6\ MW)^{0.75} + 27000 * (16.6\ MW)^{0.80}$$

$$C_{O\&M}(cost\ in\ USD) = \$480{,}000$$

Thus, the total annual cost of the dam, including both the variable annual cost and the O&M costs, would come to about $2.16 million.

To find the kWh cost of electricity, we must also find the annual energy generated at Lock and Dam 25. To find the amount of energy generated at a dam with a given capacity, we can use the following equation:[35]

$$G\ (in\ MWh) = PF * C * time$$

where G is energy generated in MWh, PF is the average plant factor (a measure of efficiency), C is the installed capacity in MW, and time is the period in hours over which the energy is generated.

[34] Estimation of Economic Parameters of US Hydropower Resources: http://www1.eere.energy.gov/wind/pdfs/doewater-00662.pdf
[35] Estimation of Economic Parameters of US Hydropower Resources: http://www1.eere.energy.gov/wind/pdfs/doewater-00662.pdf

The plant factor is determined in part by the location of the dam, the season, and the type of dam; for a plant with a capacity greater than 1 MW in Missouri (the location of Lock and Dam 25), the study by Idaho National Laboratories cites an average annual plant factor of 0.4453.[36]

Therefore, assuming an operating season of 330 days (to allow for maintenance and possible periods of low flow),

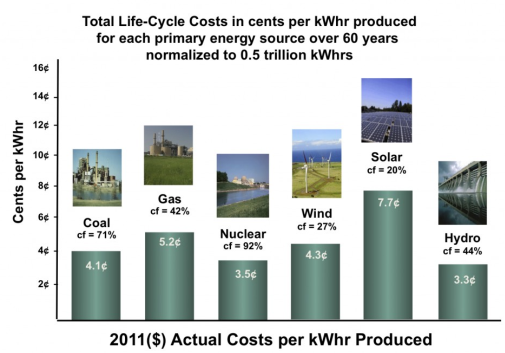
$$G\ (in\ MWh) = (0.4453) * (16.6\ MW) * \left(24\ \frac{hours}{day} * 330\ days\right)$$

$$G\ = 5.85\ x\ 10^4\ MWh = 5.85\ x\ 10^7\ kWh$$

Therefore, the cost per kWh generated at Lock and Dam 25 would be

$$\frac{annual\ cost}{annual\ electricity\ produced} = \frac{\$2.16\ million}{5.85\ x\ 10^7\ kWh} = 3.7¢\ per\ kWh$$

This is comparable to the cost per kWh of hydroelectric power generated at existing large hydro facilities (2-4¢ per kWh[37]), and significantly less than many conventional forms of electricity generation – coal fired power plants generally range from 4-9¢ per kWh, and nuclear power plants can range from 2-15¢ per kWh.[38] Retrofitting existing non-powered navigational locks appears to be a clean, cheap, and viable source of energy for the future.



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[36] Estimation of Economic Parameters of US Hydropower Resources: http://www1.eere.energy.gov/wind/pdfs/doewater-00662.pdf

[37] Hydropower Costs: http://www.c2es.org/technology/factsheet/hydropower

[38] Energy Source Cost Comparisons: http://des.nh.gov/organization/divisions/water/wmb/coastal/ocean_policy/documents/te_workshop_cost_compare.pdf