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Investigation of New Hampshire hydropower potential

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***Abstract*-The popularity of green and renewable energy has risen sharply in recent years, and hydropower has consistently been the most common form of renewable energy in both the US and the state of New Hampshire. As a result of this strong green movement, government organizations have seen increased pressure to produce figures to the public detailing the amount of hydropower potentially available in the country. Often these figures will depict very attractive numbers for the untapped hydropower potential in the country, yet the data do not seem realistic to anyone familiar with hydropower generation. This paper will attempt to de-rate these general estimates made for hydropower potential by government organizations, specifically in New Hampshire. It will be determined if these parties are ignoring basic hydropower design challenges in their estimations, such as system efficiency, generator capacity factors, and the economic feasibility of the projects themselves. These results should reveal the inaccuracies (if any) of the estimates by the government groups. To analyze the general feasibility of hydropower projects in New Hampshire, three case studies in hydropower system design will be examined.**

INTRODUCTION

Although many institutions have offered estimations for hydropower potential in New Hampshire, there are two of note—the US Department of Energy (DOE), and the New Hampshire Department of Environmental Services (NHDES) Dam Bureau.

The DOE worked in association with the Idaho National Laboratory to create the Hydropower Evaluation Software (HES). Reference [1] described the HES as a computer model which allows the DOE to obtain estimates for undeveloped hydropower in any specific region. The department applied this model to NH, and produced hydropower estimates for all sites that the HES predicted should be able to produce any significant levels of power. A total of 97 sites were evaluated in [1], and the results from each were consolidated into figures and tables in order to analyze the data sets.

The HES model found that 63 of the 97 total NH sites were sites that had some form of water impoundment or diversion already, yet no developed system of power generation. The remaining 34 sites had neither a form of impoundment nor power generation.

The estimated potential for each site was separated into three categories: under 100 kW, between 100 kW and 1 MW, and between 1 MW and 5 MW. The HES plotted the results of this grouping in Fig. 1.

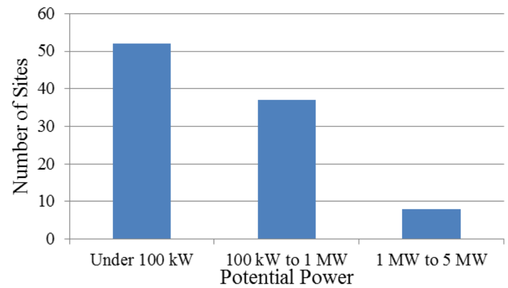

Fig. 1. DOE-modeled amount of sites with undeveloped hydropower potential in New Hampshire.

The combined nameplate capacity of each potential site was stated in [1] to be 116.4 MW, with 51.2 MW of this total being attributed to sites with developed water impoundment and 65.3 MW being attributed to undeveloped sites. Nameplate capacity, however, does not give an accurate estimation of potential power. Nameplate capacity provides the maximum power a system can output, but offers no insight into the average power the system may expect to produce during its period of operation. To account for this, the HES model also gives adjusted average power estimates in [1].

The realistic hydropower estimation of all NH sites with impoundments is reduced roughly 50% from the nameplate capacity figure, and is approximated at 25.5 MW. The realistic estimation for undeveloped sites is down to 6.5 MW of power output—reduced nearly 90% from the nameplate capacity estimation. This sets the total HES-modeled hydropower potentials at 32.0 MW, as outlined in [1]. These values are shown in Fig. 2, contrasting the nameplate capacities to the realistic estimations performed by the HES.

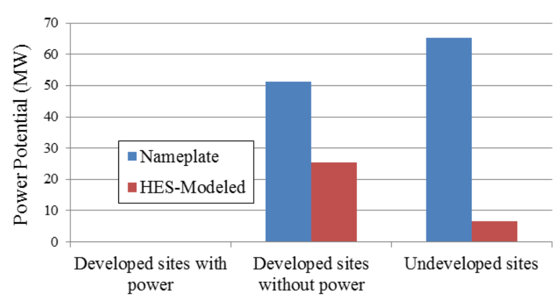

Fig. 2. DOE-modeled projected outputs of potential hydropower sites in NH (Nameplate Capacity vs. HES-modeled)

The NHDES Dam Bureau also performed estimations of power output levels for potential hydropower sites in NH in [2]. The major difference between this analysis and that done by the DOE is that the Dam Bureau only gathered data from state-owned existing dams, thereby ignoring potential hydropower sites without any form of water impoundment already installed.

The Dam Bureau has gathered the specifications of 307 state-owned dams in NH, compiled these data into a spreadsheet, and used some simple calculations to determine the potential output that each dam could produce if hydropower were installed. NHDES concluded that a total of 35.6 MW can be generated at these potential sites in [2].

The majority of this power is generated from the ten largest of the 307 dams, and the Dam Bureau estimates of the power and energy potential of these sites are shown in Table 1.

The total value of 35.6 MW potential, found by the NHDES, is slightly higher than the total value of 32.0 MW found by the DOE. This doesn't make much sense, because the NHDES only looked at state-owned dams in their analysis while the DOE examined all potential sites, including those without any form of water impoundment installed. This raises the question of which estimate is more accurate, or perhaps, whether or not either estimate is accurate at all.

In order to properly assess the accuracy of these estimations performed by the DOE and the NHDES, the process of hydropower system design and installation will be examined. Perhaps it is the case that some of the sites evaluated in [1] and [2] cannot realistically obtain hydropower because of economic feasibility. Perhaps the computer models used in these analyses did not account for certain factors, which in a real system significantly reduce the power output. Whatever the cause of discrepancies, the hydropower system design and installation process will be investigated in the hopes that the actual challenges in creating a hydropower system will be revealed.

Three case studies will be performed and analyzed here; one small scale micro-hydro design, one medium scale system design installed on an existing dam, and one large scale design on an existing dam with much higher flow. After each design project is completed, dissecting the results may bring to light design constraints and challenges that undermine the hydropower estimations made by the DOE and the NHDES.

TABLE 1
NHDES ESTIMATED HYDROPOWER POTENTIALS OF TEN NH DAMS

Sewall Falls Dam	13,614 kW
Murphy Dam	2,945 kW
Allied Leather Forebay	2,188 kW
Gregg Falls Dam	1,863 kW
Pontook Reservoir Dam	1,850 kW
York Dam	1,809 kW
Avery Dam	1,298 kW
Kelley Falls Dam	870 kW
Lochmere Dam	792 kW
Ossipee Lake Dam	725 kW

HYDRO DESIGN BASICS

A. *Power Calculation*

Although actual hydropower systems can be quite complex, determining the maximum power potential at any given site is very simple. The power available is a function of the head H (the difference between the top and bottom water levels) in meters, the flow rate of water Q in cubic meters per second, and the specific weight of water γ. Because the specific weight of water is always very close to 1000 kg/m^3, it can be assumed that it is a constant and it may be safely removed from the equation. Then all that is needed is the gravitational acceleration constant g, and the equation for the power P (in kW) available at any given site becomes

$$P = g * H * Q. \tag{1}$$

Of course, the maximum power available in a system is never the same as the output that is observed. The output power value is reduced by the efficiency of the system. If we assume that η is the overall efficiency of the hydropower system, then the power output P (in kW) that we may expect to see from the generator is given by

$$P = g * H * Q * \eta. \tag{2}$$

If the head and flow rate at any given moment are known (and the efficiency of the system, if it varies over time), then using (2) the power output of the hydropower generator may found. However, because these variables can vary so much, if the power output of the system over an entire year is to be predicted then these variables must too be predicted.

B. *Capacity Factor*

The simplest method used to predict the annual power or energy output of a hydroelectric generator involves something called the capacity factor (*CF*). The *CF* of a system, according to [3], is a percentage that represents the ratio of actual annual power output versus the maximum annual power output. Without the capacity factor, (2) would not be enough to predict the annual output of a hydropower system. If the flow rate at the site is lower than usual, then the generator may not be able to produce electricity. Adding the *CF* to (2) as a coefficient takes into account these deviations from the maximum power over the year, and a more accurate equation for average power P over a year is

$$P = g * H * Q * \eta * CF. \tag{3}$$

This may be a simple technique to estimate average power output over a year, but the difficulty lies in finding the correct capacity factor. Usually data from previous years is used to get a good approximation of the *CF*, but when the potential hydropower is being examined at sites with no current hydropower system installed, it is impossible to find the capacity factor this way and other methods must be observed.

C. Flow Duration Curve

When the capacity factor cannot be used reliably, a slightly more complex method of power output prediction must be used. While the head at the site will probably vary slightly over time, the magnitude of these fluctuations are generally negligible compared to the variability of the flow rate at the site. If the changing of the flow rate over the year can be predicted with some degree of accuracy, the power output over that year can also be predicted.

The typical manner in which the annual flow rate data are presented is in something called the flow duration curve of the site. In [4], the flow duration is defined as the percentage of time for which a particular flow rate is equaled or exceeded. In this case, the time interval would be over an entire year. The curve typically starts at zero percent at the origin, and runs to one hundred percent. So, for example, at the 95 percent mark, the value given at this interval is the flow rate that is equaled or exceeded 95 percent of the time at the site. Fig. 3 depicts an example flow duration curve; this particular one is the estimated flow duration curve at the Oyster River Dam site in Durham.

In order to utilize a flow duration curve to estimate the projected power generation over a year, the average flow rate must be calculated. Once this is found from the curve, using this value of Q in (2) will produce the average power output value (in kW) over the year.

D. Turbine Design

Before power can be generated, the type of turbine for the hydropower system must first be selected. There are two basic types of hydro turbines: a reaction type, and an impulse type.

The reaction type of turbine is one that draws energy from the pressure drop between the top and the bottom of an impoundment of water. Due to the fact that this type of turbine must be fully immersed in the water to be operational, reaction turbines are generally best suited for low head locations.

The impulse turbine type is one that draws kinetic energy from a moving body of water. It does this by funneling moving water down a long pipe (a penstock), forcing it out a nozzle at high pressure, and aiming the stream at the runners of the turbine. The runner shapes are specially designed to draw the most kinetic energy from the stream, while shooting the used water off to the side so as to avoid turbulence from colliding streams of water. This type of turbine is suited well for high head and low flow rate sites, unlike reaction turbines.

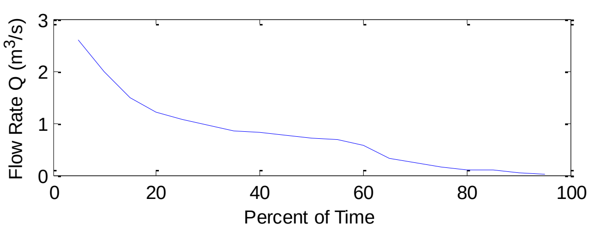

Fig. 3. Flow duration curve for the Oyster River Dam site in Durham

MATLAB MODEL

A. Flow Duration Acquisition

As previously described, in some cases the design process of a hydropower system is sensitive enough that the flow duration curve for the particular site is crucial. Of the three case studies performed here, two require a level of precision in their turbine design that demand the acquisition of the flow duration curves before the turbines can be sized.

When finding the flow duration curve of any site, the U.S. Geological Survey (USGS) stream gage data must be used. If there happens to be a USGS gage at the site for which the flow duration is desired, then there are free programs provided on the USGS website that will show you the particular flow curve. However, when no gage exists on site, certain procedures will make possible the estimation of the flow duration at the site.

One such procedure is called "watershed delineation," and is outlined in [4]. This method involves finding the ratio of the watershed size of the site versus the watershed size at the nearest USGS gage, and adjusting the flow data from the gage with this ratio. Another USGS program, StreamStats, will find the watershed area of the hydropower site. The watershed area of the closest stream gage will be provided on the USGS website, so by comparing these two values, a watershed area ratio can be obtained.

On the same website, the stream flow data of the gage closest to the hydropower site can be found and downloaded for free. The typical form that these data are found in is one average flow rate per recorded daily, over the lifespan of the gage (close to a century for many gages). In order to be useful in the case studies performed here, one year's worth of data must be isolated and converted into a flow duration form. To accomplish this, a computer model will be created using the computational tool MATLAB.

This piece of software will first gather 365 consecutive samples from the USGS gage data set (one year's worth). In order to convert these pseudorandom flow rate values into a flow duration curve, the software must sort them using their magnitude as the classifier. Once they are arranged in this manner, the set will have the form of Fig. 3 if plotted out. Then, the MATLAB model simply has to multiply each value by the watershed area ratio, and an approximated flow duration curve for the desired hydropower site will have been created.

B. Annual Generation Estimation

It is obviously an essential part of the design of a hydropower system to predict the power generation that may be expected for a given turbine type and size. As three hydropower design case studies are being investigated here, another MATLAB model must be formed in order to estimate the power output of a hydro turbine.

The two most significant variables in this set of calculations will be the turbine type, and the turbine size. The turbine type is relevant because every turbine has differing efficiency characteristics, which in turn have a strong influence on the power generation. One class of turbines (i.e. reaction vs. impulse turbines) will be more appropriate for a given site than the other. The size of this turbine also has a heavy influence on power generation, because the turbine dimensions must be matched with the site's flow rate characteristics to produce the most energy efficient design over the span of the entire year. Smaller turbines will not be able to capture larger flow rates for power generation, while larger turbines will have a difficult time rotating during low flow periods. The computer model will be able to optimize this design element for the maximum energy output over the span of one year.

There are several ways to approach this process—one method that slightly reduces the complexity of the model is to select the type of turbine prior to using the software, then adjusting the efficiency characteristics within the MATLAB model to reflect that specific turbine. In this way, the only variable that would need to be adjusted for generation optimization would be the size of the turbine. The type of turbine may be selected beforehand based upon the head and average flow rate of the site, and empirical data from existing hydropower systems that suggest what turbine types operate best under these conditions.

Once a turbine type is selected, the MATLAB model will accept a starting turbine size, and determine the operational flow rate of the generator based on this size. The model will then compare this operational flow rate to the actual flow rate at any time interval, by using the flow duration curve found previously by MATLAB. Using the mechanical efficiency characteristics of the specific type of turbine being used, the model can then determine the mechanical efficiency that can be seen at a specific time interval. By integrating this process over an entire year, the power generation curve vs. time can be obtained.

An example power generation curve is shown in Fig. 4. The time axis of the curve is in the same form as the flow duration curve of Fig. 3, meaning this curve can be interpreted in a similar manner; at any particular time interval, the power being generated will always equal or exceed the power shown at that interval. The curve is zero for a small percentage of the year, meaning that with this turbine size, at rare occasions the flow rate is not large enough to turn the turbine and generate power. On the other side of the graph the curve appears to reach a maximum power, because the flow rate at that particular maximum power happens to be the operational flow rate of the turbine.

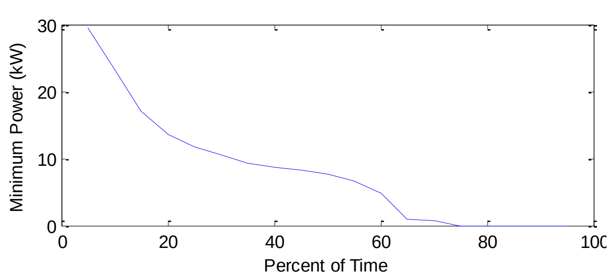

Fig. 4. Example of a power generation curve for a given turbine.

C. Financial Analysis Model

For the purpose of dissecting the hydropower potential estimations performed by the DOE and NHDES, the primary comparison point could be on overall potential power generation, which the previous described MATLAB models would be able to provide. However, in order for this analysis to have any practical merit, the financial feasibility of these projects must also be examined. In uncommon situations the motivation for installing hydropower may be purely nonfinancial, yet the majority of the potential hydropower projects require at least some financial benefits before they can be seriously considered and initiated.

Once again, a MATLAB model will be created and combined with the first two in order to complete a financial analysis of the hydropower project. The main feature of this model will be to perform a Life Cycle Cost (*LCC*) analysis of the system, to determine how much revenue or expenses the system will accrue in its lifetime. A general equation for the *LCC* of a system is given in [3] as

$$LCC = C + M + E + R + S, \qquad (4)$$

Where C is the capital cost of the system, M is the maintenance cost, E is the cost (or revenue) of energy or fuel, R is the replacement cost, and S is the salvage value of the system after its life cycle.

This formula is applicable to one period (e.g. one year) of operation, but in the case of hydropower systems, it is desirable to look at the *LCC* of the system over its entire lifespan of several years. In this case, the costs at later years will need to be adjusted for inflation (both general inflation and electricity inflation). Also, to obtain a meaningful value for the *LCC* over the entire lifespan of the system, the adjusted costs over later years will need to be readjusted back into how much they would cost in 2012 dollars—the "present worth" or "present value" of the cost.

Given a future value of F, a discount rate d, and an interval of n years in the future, [3] offers an equation for the present value P of a revenue gained in the future:

$$P = F * \mathrm{PVF}(d\ , n), \qquad (5)$$

where the present value function PVF is given by

$$\mathrm{PVF}(d\ , n) = [(1 + d)^n – 1] / [d * (1 + d)^n]. \qquad (6)$$

This formula, however, assumes that there is no inflation rate; something that obviously must be accounted for. If the inflation rate (general or electricity inflation) is e, then [3] gives an equation for the adjusted discount rate d' as

$$d' = (d – e) / (1 + e). \qquad (7)$$

To utilize this, the adjusted discount rate d' is used in the present value function as if it is the regular discount rate. This new present value function will now give you the present value of a cost or revenue applied in the future, adjusting for any relevant inflation rates. By combining (5), (6), and (7), a condensed equation for present value is found to be

$$P = F * [(1 + d')^n - 1] / [d' * (1 + d')^n]. \quad (8)$$

This equation is used in the MATLAB model to find the present value of each component of the *LCC* (except for the capital cost *C*, as this is a single expense and does not carry over to subsequent years). When (4) is updated to account for the Life Cycle Cost of a system over several years using the present value equation (8), then the new *LCC* becomes

$$LCC = C + M_{PW} + E_{PW} + R_{PW} + S_{PW}, \quad (9)$$

where the subtext "PW" in each represents the present worth of that value in 2012 dollars.

During each of the three case studies, the values used in this MATLAB model will have to be tuned slightly to reflect the differing costs of the maintenance on each turbine type, the replacement cost of individual components in the generator, etc. After the model is tuned to the specific turbine properties, the model will accept values found by the previous MATLAB models regarding annual energy generation and maximum power output. These calculated values should help this model compute both the overall expenses, and the overall revue gained from selling the electricity (if the system is to be tied into the grid). This will provide the *LCC* of the system, and hopefully reveal how financially plausible it would be to begin the installation process in the first place.

D. *MATLAB Model Application*

Once all of the separate pieces of software outlined above are compiled into one MATLAB computer model, this program will give us two main pieces of information: the generation characteristics of a particular turbine design over a year, and the financial feasibility of the hydropower project.

In order to appropriately utilize this computer model, the main motivations of the stakeholders of the potential hydropower project should be examined. If the entity investing in the project is someone with a large surplus of money and is willing to spend it on a hydropower project regardless of the capital cost, then the power generation data set given by the MATLAB model should be given more attention than the financial data. An example of a situation like this could be a municipally or state-owned dam that has hydropower potential, and that town or state is looking to reduce their carbon footprint and install more environmentally friendly generation systems.

In other cases, the financial facet of the potential hydropower project may be the only relevant aspect to the person or group who is considering investment. In New Hampshire, some of the potential sites are privately owned impoundments or property where an impoundment may be placed. This means that, in order for the hydropower project to be a potential at all, it needs to have a *LCC* that has a higher net present value than other investments. If this is not the case, then the project is unlikely to proceed at all.

FIRST CASE STUDY: MACALLEN DAM

A. *Overview of Macallen Dam Site*

The Macallen Dam is located in Newmarket, New Hampshire, and is on the Lamprey River. The specifications of the dam are described in [5], and include a thirty meter length and 8 meter height. There is a fish ladder installed on the right side of the spillway (when looking downstream) that is owned and operated by the New Hampshire Fish and Game Department. Deteriorated remnants of an old hydropower system still can be found on site, left from when the system was decommissioned in the 1950's. A proposal from the town of Newmarket to remove the inoperative parts of these remains and install a new hydropower system was submitted to the Federal Energy Regulatory Commission (FERC) in 1999. This application, [5], outlined the details, goals, and purposes of the project.

The main objective of this project is claimed in [5] to be to develop a hydropower system to supply clean renewable energy to the community, while preserving the surrounding environment. It was intended by the Town to either sell this energy to an outside distributor, such as the Public Service Company of New Hampshire (PSNH), or create an "enterprise zone" to supply reasonably priced power to the mill area adjacent to the dam.

To connect to the electrical grid, the Town recognized in [5] that a 19.9 kV PSNH transmission line was roughly eighty meters from the area the proposed generator would be placed. A step-up transformer could be installed to raise the generator voltage to a suitable level, and enable it to be connected to the grid. The cost of the transmission line would be included in the cost to the Town of the overall system.

B. *Potential Power Generation*

Because [5] was a preliminary permit application, there was no detailed design performed yet by the Town, and thus a flow duration curve was not needed for this stage in the process. All the Town used in [5] were flow values close to the highest and lowest seen on the Lamprey; this was sufficient to size a generator and turbine to be able to handle the approximate range of flow rates across the Macallen Dam.

The Town compiled the dam attributes relevant to power generation in [5]. Table 2 lists these values, as well as the rated power of the proposed generator, and how much total annual energy a generator of this size would be able to produce.

TABLE 2
POWER AND ENERGY POTENTIAL OF MACALLEN DAM SITE

Gross Head	7.25 m
Tidal Head Loss	0.305 m
Average Net Head	7.01 m
Max Design Flow	11.33 m^3/s
Min Design Flow	2.266 m^3/s
Capacity Factor	43.8%
Rated Power	600 kW
Annual Energy Output	2,300,000 kWh

Instead of power generation over time during a given year as in Fig. 4, Table 2 simply lists the nameplate capacity of the proposed generator. This does not correspond to average power generated, but instead to the rough maximum power generation of the generator—this means that it would not be accurate to simply multiply this value by the hours in a year to find the annual energy output. Instead, the Town estimated a capacity factor *CF* by comparing capacity factors of similar hydropower systems. They then multiplied these values found in Table 2: the rated nameplate capacity of 600 kW and this capacity factor of 43.8%. This produced an average power estimation over the year, which gave them the value found in [5] of 2,300,000 kWh of annual generation.

C. *Financial Analysis*

The third portion of the MATLAB model described above will be used to perform the financial analysis of this proposed hydropower system. There are certain areas of the model that will have to be adapted for this project, due to values specific only to the generator and turbine types outlined in [5].

First, aspects of the model which calculate the capital cost of the system will have to be adjusted. Due to figures being discussed in Newmarket town meetings concerning the Macallen Dam, it can be safely assumed that the overall capital cost of the system will be fairly large; around $5,000,000.

Second, the replacement cost area of the MATLAB model call for some alterations. This generator is proposed as being synchronous, meaning that it will not need any inverters to convert power to three phase, 60 Hz ac power. Because the replacement costs of the other system components are not very frequent, and are negligible compared to the capital cost, for the sake of this estimation the replacement costs over the lifespan of the hydropower system will be ignored.

Third, the part of the computer model that handles energy production revenue will have to be adjusted. This does not need much attunement; essentially, because the Town is planning on selling this power to the mill area and not to PSNH (if possible), the revenue the Town will make will be higher because they can sell electricity to the mill at a higher price than to PSNH. For this analysis, a selling rate of 0.1 $/kWh was used.

There is now enough information to use the MATLAB model to perform a financial analysis. A conservative system lifespan of 25 years was used, and the results from this analysis are shown below in Table 3.

TABLE 3
FINANCIAL ANALYSIS OF MACALLEN DAM SITE
OVER LIFESPAN OF 25 YEARS

Capital cost	$5,000,000
Energy sales revenue	$6,404,000
Net profit	$1,404,000
Avoided PSNH energy cost	$7,089,000
Net present value	$8,493,000

Table 3 depicts several values significant to the financial analysis of the proposed hydropower system on the Macallen Dam. First are the capital cost and the energy sales revenue over the lifespan of 25 years. This energy revenue value was found assuming the electricity was sold to the mill rather than to PSNH. This value was found by the MATLAB model by using (8), assuming a discount rate d of 6% and an electricity inflation rate e of 5%.

The Life Cycle Cost of the system was actually a profit, because overall the system accrued more revenue than expenses (in 2012 dollars). The computer model computed this value with (9), while assuming that the maintenance, replacement, and salvage values were so negligible that they could be ignored.

The final value shown in Table 3, the net present value *NPV*, was computed using a novel but very basic formula. To find the *NPV* of a system, the *LCC* of the system is simply compared to the cost of not installing the system, and the difference is found. In this case, not installing the hydropower system means that the Town must purchase that much more energy from a supplier such as PSNH. This means that the *NPV* is the difference between the *LCC* of the system and the 25 years of electricity bills accumulated by the Town. Since the *LCC* is given in Table 3 as a profit of $1,404,000, and the cost of 25 years of PSNH energy is given as $7,089,000, the *NPV* is the difference between them: $8,493,000.

D. *Conclusion*

The values shown in Table 3 are very attractive financially. Despite a large capital cost, the system pays for itself within roughly 20 years, and then pulls in a revenue of about one million dollars from energy sales between then and the end of its life. Compare this to the roughly seven million dollars of expenses going towards PSNH energy if the generator is not installed, and the system has a very high net present value. The lifespan of 25 years was also somewhat of a conservative estimate, which means that the actual lifespan may easily be longer—meaning even more lifetime revenue from electricity sales.

The project proposal [5] was submitted to FERC almost 13 years ago, which begs the question: why hasn’t such a financially appealing project begun development for more than a decade?

The answer lies in the townspeople. Though there are plenty of town residents who approve of the project, there are an equal amount who are opposed to it. Some have property on the impoundment and riverfront upstream of the dam, and are worried that any work will upset the water level and affect their property value. Others believe that the dam should be removed altogether, so they strongly oppose any plans for hydropower development. As long as there is this much opposition, especially with waterfront property owners, a project such as the Macallen Dam hydropower project will have a difficult time getting off the ground.

Unfortunately, the potential hydropower sites in the state with the most capacity for generation are also the largest, and thus will cause the most sociopolitical turmoil and opposition.

SECOND CASE STUDY: OYSTER RIVER DAM

A. *Overview of Oyster River Dam Site*

The Oyster River Dam is located in Durham, New Hampshire, and is also sometimes called the Mill Pond Dam. It is jointly owned by the town of Durham and by the property owners adjacent to the right abutment (looking downstream) of the dam. This family also happens to own the power rights to the dam, so if any hydropower system is to be installed at this site, it has to be approved, coordinated, and funded by this family.

This dam site has a much lower overall flow than the Macallen Dam site in the first case study, which means that the revenue from any energy sales from this potential project are going to be much less. Compounded with the fact that a family is going to be providing most of the funding and not the Town, this project cannot afford the relatively simple power analysis performed in the first case study. The entire MATLAB computer model will be utilized in this case study to ensure that the hydropower system is as cost efficient as possible.

B. *Turbine Selection*

The first step in the analysis process is the selection of the turbine being used in the hydropower system. The site has a very low head of around 2 meters, which indicates that a reaction turbine would be better suited to the site. In order to judge which type of reaction turbine should be selected, it would be useful to obtain the flow duration curve for the site. There is no USGS gage on the site, so the first part of the MATLAB model involving watershed delineation will be used in parallel with the USGS website to create an estimated flow duration curve.

From the USGS website, it is determined that the watershed at the Oyster River Dam is 1.71 times larger than that at the nearest USGS flow gage. Using the MATLAB model in conjunction with daily flow rate samples from this USGS gage, a flow duration curve for the gage is found. By multiplying each of these new values by the watershed delineation ratio of 1.71, a flow duration curve for the Oyster River Dam site is created. This curve is shown in Fig. 5 below.

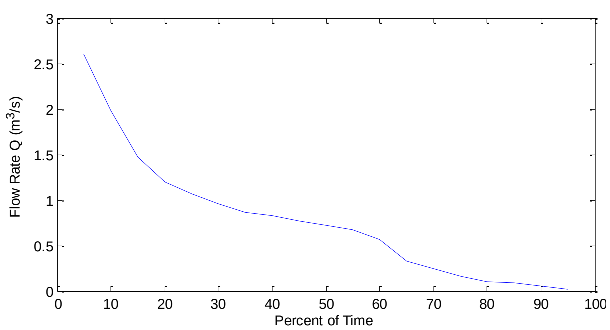

Fig. 5. Flow duration curve for Oyster River Dam site. Created in MATLAB model.

From the flow duration curve in Fig. 5, it can be seen that the flow rates across this impoundment are rather low, and fluctuate often. When selecting the turbine, this means that a turbine with a higher mechanical efficiency at lower flow rates would be ideal. Because of this, the Archimedean Screw hydroelectric generator should be the best suited for the Oyster River Dam site. This type of turbine has been used for millennia as a water pump (hence the namesake of Archimedes), but only recently has this process been reversed and the turbine become an electric generator. In Fig. 6, the mechanical efficiency of the Archimedean Screw is plotted against the ratio of the design flow rate to the actual flow rate through the turbine.

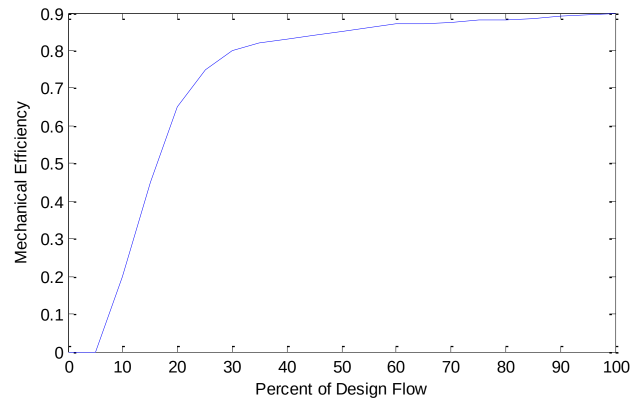

Fig. 6. Mechanical efficiency of the Archimedean Screw vs. flow rate.

C. *Power Generation MATLAB Model*

To begin the process of predicting the power generation of a hydropower system, (2) needs to be examined to determine which of the variables will have the most influence on generation patterns. The head H of the dam can be found by looking at [6], which is a report to the Town evaluating the structural condition of the dam. Because the downstream side of the dam is tidal, this gross head level can vary somewhat between high tide and low tide conditions. To simulate worst-case conditions (a common design practice), the minimum net head will be used in the MATLAB model. This value was found to be roughly 1.8 meters: 3 meters of gross head, minus 1.2 meters of average tidal fluctuation.

It can be seen from Fig. 6 that the MATLAB model will have to be adjusted to account for the varying mechanical efficiency of the turbine. This will be done in the part of the model that computes η, the overall efficiency of the system. The plot shown in Fig. 6 shows that the mechanical efficiency is a function of the flow rate through the turbine. The flow rate Q can be found by using the flow duration curve in Fig. 5. In order to find the annual generation patterns with the MATLAB model, the software will look at each flow rate from the duration curve separately. The model will use each of these flow rate samples to compute what the mechanical efficiency will be for that flow rate, then multiply this by the efficiency of the rest of the system; it will be assumed that the efficiencies of the generator, inverter, and gear box all combine to about 75% efficiency.

When computing the overall efficiency, one more variable has to be considered in the MATLAB model used for this case study. The Archimedean Screw turbine is unique in the sense that most reaction turbines are completely immersed in water to retain pressure, while in the Archimedean Screw, water only fills the bottom half of the rotor and trough. Unfortunately, this means that when the flow rate through the turbine is higher than the designed flow rate the water tends to slosh and splash out of the trough. This causes a reduction in overall efficiency, which can be modeled in the computer software. It will be approximated as a linear decrease in mechanical efficiency, down to a 500% increase in flow rate ratio; at this point, it will be assumed that the turbine will have to cut out and halt energy production. With these adjustments, the new plot of mechanical efficiency against the ratio of designed to actual flow rate is shown in Fig. 7.

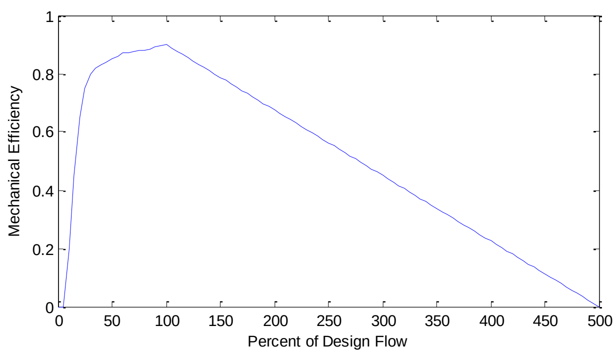

Fig. 7. Adjusted mechanical efficiency of the Archimedean Screw, vs. flow rate.

In order to produce results, the MATLAB model will have to begin with the flow duration curve for the Oyster River Dam site. Each flow rate sample in this curve will be manipulated separately to determine the mechanical efficiency of the turbine at this particular flow rate. Then, the model can use (2) to calculate the power the hydropower system will generate with this particular flow rate and efficiency. By performing this operation on each flow rate sample, the power generation results may be integrated together to obtain the power production over an entire year. From this curve, both the maximum power generated and the overall annual energy production can be obtained. These two parameters will be the most important to the financial analysis because the maximum energy generated will size the generator and affect capital cost, and the total energy output will determine the revenue acquired from energy sales.

D. Cost Efficiency Optimization

In this case study, the power generation characteristics of the hydropower system are not as important as the financial feasibility. The Life Cycle Cost of this project will determine if the family will make the investment in the first place, which is the main focus of this study. With that in mind, a conservative design flow could be used to make the screw smaller and reduce initial capital costs, but there is a significant disadvantage to this approach—a smaller screw generates less power, and thus makes less overall revenue. To begin the optimization process, the first step will be finding the turbine size which produces the most energy over the year.

Using a MATLAB program, it was found that the design flow which produces the most energy over the year is 2.5 m^3/s, and Fig. 8 depicts the power generation curve for this design.

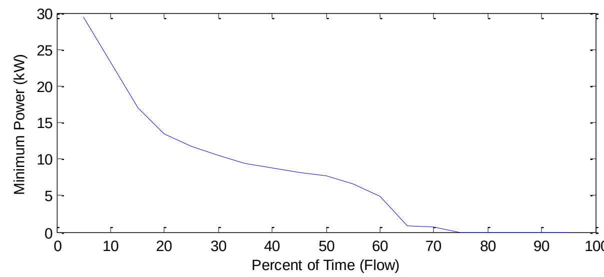

Fig. 8. Power generation curve for design flow of 2.5 m^3/s.

This design has the disadvantage of not producing power about 30% of the time, because when the flow rate is too low, it is not enough to turn this larger turbine (with this design flow rate, the turbine diameter would be about 1.75 meters). This would be an issue if the system was being designed to power a household or building, but because the family is only concerned with selling the overall energy in this scenario, the fact that this generator design has a lower capacity factor than a smaller design is irrelevant if it generates more energy overall.

The MATLAB model computing the financial feasibility for this design needs the two values taken from the first section of the model—the rated power (i.e. maximum power) of the generator, and the total energy generated over the year (in kWh). Then some assumptions must be made, including an installation cost of $100,000, a lifespan of 40 years for the Archimedes Screw, and a rate of $0.06/kWh for selling surplus energy back to PSNH.

With this information, the MATLAB model can compute the *LCC* of the system over 40 years. The results of this analysis are shown in Table 4. The computer model gives us a negative Life Cycle Cost, which means that the system has a positive profit over its entire lifespan. Table 4 lists the profit as only $64,000 over 40 years, however.

TABLE 4
FINANCIAL ANALYSIS OF TURBINE WITH DESIGN FLOW OF 2.5 m^3/s

Life cycle of system	40 years
Household energy use	16,000 kWh/year
PSNH buying rate	$0.06/kWh
Capital cost	$240,000
Maintenance costs	$20,800
Energy sales revenue	$409,000
Replacement costs	$84,000
Salvage revenue	$0
Life Cycle Cost	–$64,000

This in an unappealing result, and it seems as if the financial feasibility may be improved if the initial size of the turbine is altered. In order to verify this, a sort of trial-and-error routine will have to be employed with the MATLAB model. This is done by considering varying sizes of turbine design, obtaining the power and energy outputs that the first part of the computer model produces, and entering these results into the financial analysis portion of the program. The goal of this process is to find the design that produces the best *LCC* by comparing the results of each MATLAB model trial. After some experimentation, it was found that a turbine design flow of 1.6 m^3/s gives us the system most cost efficient. The power generation curve for this design is shown in Fig. 9, and the results of the financial analysis are shown in Table 5.

From Fig. 9, it can be seen that the maximum power generation is lower for this turbine design. This reduces the capital costs of the system, as can be seen by comparing Table 4 and Table 5. This is the most significant difference between the feasibility of the two systems; the smaller turbine may produce less energy, but the more substantial reduction in capital costs makes the smaller turbine more cost efficient in the end.

E. Conclusion

Although the values seen in Table 5 indicate that this project makes a profit during its lifetime, that lifetime is also 40 years—a net profit of $104,100 is not a lot to accrue over this time span when $201,000 was invested. This project is then considered marginally feasible, because it may make a net profit, but over 40 years there are better investments one could make.

This is a problem when considering the original goal of this case study: to analyze the probability that a potential hydropower project of this size would be feasible. The fact that one would barely make a profit when investing in a hydropower project on the Oyster River Dam suggests that it is unlikely the project will find funding from the family owning the power rights. This will disrupt the hydropower potential estimations performed by the DOE and the NHDES, because this means that some of the sites analyzed by them with midrange flow rates may be impossible hydropower sites due to lack of financial feasibility. This will be assessed further in the final section of this paper.

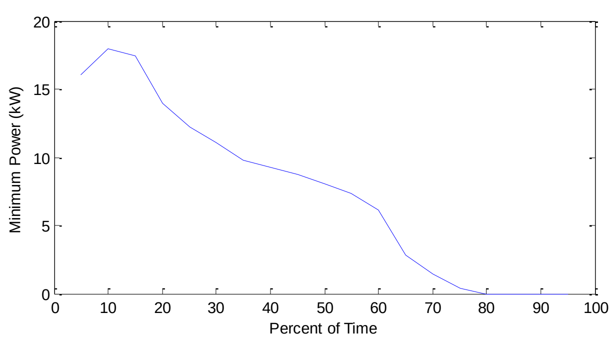

Fig. 9. Power generation curve for design flow of 1.6 m^3/s.

TABLE 5

FINANCIAL ANALYSIS OF TURBINE WITH DESIGN FLOW OF 1.6 m^3/s

Life cycle of system	40 years
Household energy use	16,000 kWh/year
PSNH buying rate	$0.06/kWh
Capital cost	$201,000
Maintenance costs	$19,500
Energy sales revenue	$375,000
Replacement costs	$51,000
Salvage revenue	$0
Life Cycle Cost	–$104,000

THIRD CASE STUDY: GRAFTON POND TRIBUTARY

A. Overview of Site

The third case study is examining the feasibility of a micro-hydro system in Grafton, New Hampshire. It is called a micro-hydro system because it is a very small project with very low stream flow, and is only expected to produce less than a kilowatt of power.

The system is being considered by a couple living in Grafton, who are looking to build a house on a piece of property that they had recently purchased. This property is in a heavily wooded area, and is adjacent to several small tributaries of the nearby Grafton Pond. They are considering installing a run-of-the-river hydropower system on the property to draw power from one or more of these streams. It is called a run-of-the-river system because there is no traditional impoundment installed, as in a dam; instead, the system will divert a portion of the flow into a pipe (or “penstock”), run this through a turbine, and send the generated power to their house via a transmission line.

B. Turbine Selection

From measuring performed on the site, it was determined that the maximum head that could be gained from the site is about 24 meters. Because of this high head, an impulse turbine should be the type that is best suited for this project. It is stated in [3] that a Pelton Wheel turbine is among the most efficient of impulse turbines, and is for that reason is perhaps the most common and readily obtainable. For these reasons, the analyses performed here will be done assuming a Pelton Wheel turbine type.

C. Flow Duration Curve

In order to find the flow duration curve for this site, a very similar process to that done in the second case study will be performed. From the USGS website, it is determined that the watershed at the high point of the 24 meter head is about 0.07 square miles. It is also determined from this website that the closest USGS gage is on the Smith River in Bristol, and this gage site has a watershed area of about 86 square miles. To convert these into a practical figure, a ratio of these two values is created—a watershed area ratio of 0.000814.

Using the first part of the MATLAB model in conjunction with daily flow rate samples from this USGS gage and this watershed ratio, a flow duration curve is found in Fig. 10.

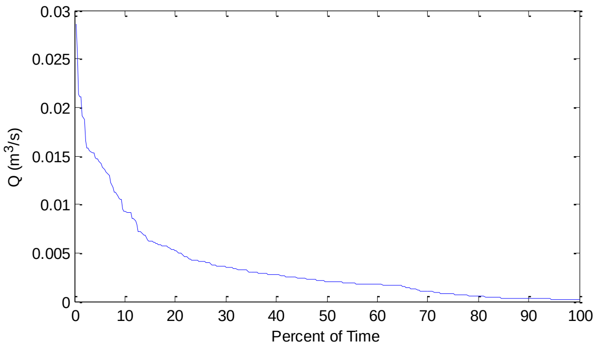

Fig. 10. Flow duration curve for the Grafton site.
One stream used.

D. Power Requirements

From the Grafton site flow duration curve in Fig. 10, it is seen that the flow rates can reach very low—close to nonexistent. This means that the family building the house on this site will have to install a transmission line to the nearest utility line if they wish to use hydropower. In doing this the family will be able to sell any surplus energy back to PSNH for a profit when the flow rate is high, and purchase energy from them when the flow rate is too low to support the needs of the house solely on the hydropower system.

Because the power and energy usage of the house plays an important role in this system design case study, a simple analysis of the household energy requirements was performed. The results are shown in Table 6. From these values, it is seen that the house requires about 15 kWh per day, and the maximum power that the house would need at one time is roughly 15 kW.

E. Cost Efficiency Optimization

The MATLAB model used to optimize the power output and the cost efficiency in this case study will have the same structure as in the previous case study, but some modifications must be made. When designing a micro-hydro system, a significant amount of analysis must go into the design of the penstock and nozzle of the turbine. This is because head loss in penstock piping is a major obstacle to efficient power generation, and especially when the budget is an issue, great care must be taken to find the balance between the cost of the piping and the head loss in the system.

TABLE 6
POWER AND ENERGY REQUIREMENTS OF GRAFTON HOUSE

Appliance	Energy usage per year (kWh)
Hot water dispenser	931
Well pump	3,420
Stereo	95
TV	741
Lights	760
Ceiling fan	1,615
Box fan	589
Computer	343
Total	8,494

From measurements taken on the site, the length of the penstock will be about 230 meters. The type of penstock piping, as well as the diameter of the piping used, affects the head loss in the penstock. The friction coefficients for some common piping diameters and materials are given in [3]. With some quick internet research, basic prices were found for the pipe varieties. Both of these variables were added to the MATLAB model, so that they could be optimized once all other variables were accounted for. The equation for the point at which the power is at a maximum, given a head loss H_L and a gross head H_G, is offered in [3] as

$$H_L = 0.333 * H_G. \qquad (10)$$

When sizing the nozzle of the turbine, the desired flow rate Q through the turbine runners has to be determined first. This is because a more narrow nozzle will increase pressure and slightly reduce flow rate, and vice versa. Ref. [3] also gives an equation for the nozzle diameter *dia*, given a net head H_N and a nozzle amount n:

$$d = [0.949 * (Q / n)^{0.5}] / [g * H_N]^{0.25}. \qquad (11)$$

These formulas were both added into the MATLAB model, so that the software could have all variables present when optimizing the system.

The flow duration curve that is plotted in Fig. 10, as noted, is only with the penstock in the system drawing from one stream on site. There is at least one other stream on the property, the nearest of which is roughly 129 meters away. Since the flow is very low with only one stream being drawn from, this system will be analyzed with a concrete channel being built at the top of the two streams. This should compound the flow of the two streams, increasing stream flow, and thus increasing power generation.

In order to create a new flow duration curve, the new stream flow rate data has to be added to the current data shown in Fig. 10. Because these two streams are located in the same water basin, they should have the same flow rate with different magnitudes. The second stream has a watershed area of 0.03 square miles, as found by the StreamStats program on the USGS website. It is a simple thing to create a new flow duration curve—the magnitude of each sample point in Fig. 10 is multiplied by the ratio between the watershed areas of the old and new flow duration data sets: 1.43. The new flow duration curve when using two streams is shown in Fig. 11.

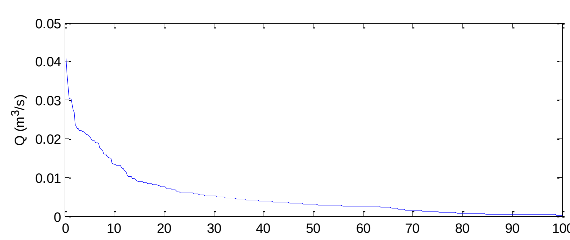

Fig. 11. Flow duration curve for the Grafton site.

Two streams used.

Using the new flow duration curve in the MATLAB model, the software is run until the optimum penstock material, penstock diameter, and nozzle diameter are found. The results of this analysis are cataloged in Table 7, the power generation curve is shown in Fig. 12, and the financial analysis of the system can be found in Table 8.

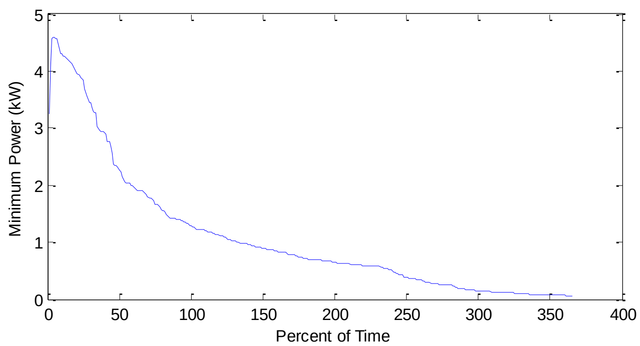

Fig. 12. Power generation curve for the Grafton site. Two streams used.

From Table 8, it can be seen that the cost of installing transmission lines from the house to the nearest PSNH power line is the largest expense of the project. The next largest expenses are the cost of the penstock and channel, and the installation costs of the entire system. The inverter costs around $1,400, and will need to be replaced several times over the lifetime of the entire system, but these costs are virtually negligible compared to the overall capital cost of $32,440.

By looking at the power generation curve in Fig. 12 and comparing this to the power requirements of the household estimated in the last section, it is clear that a tie to the grid is necessary for sustainment of the power needs of the house. A significant area of the power curve is below the power requirements of the house. These times of low flow correspond to the summer months, so it is impossible to remedy the problem with a battery bank—at least, with a battery bank of realistic size. Instead, the house may need most of its power to be purchased from PSNH during the summer, while the hydropower system mitigates some of these fees by continuing to generate a portion of that power. In the other three seasons, however, the system will produce enough surplus power to offset the power required in the summer (as can be deduced from the Table 7 figure depicting 1,130 kWh being sold per year).

TABLE 7

POWER AND ENERGY ANALYSIS OF HYDROPOWER SYSTEM OVER 25 YEARS

Penstock length	230 m
Channel length	129 m
Average flow rate	0.00514 m^3/s
Gross head	24 m
Penstock piping	3” PVC
Net head	22.6 m
Max power	500 W
Annual energy output	9,624 kWh
Annual energy sold	1,130 kWh

TABLE 8

FINANCIAL ANALYSIS OF HYDROPOWER SYSTEM OER 25 YEARS

Penstock & channel cost	$4,380
Inverter/turbine cost	$2,700
PSNH transmission line	$20,000
Additional installation	$5,000
Capital cost	$32,440
Maintenance costs	$860
Replacement costs	$1,420
Total expenses	$34,720
Energy revenue	$3,780
Total cost	$30,940
Net Present Value	–$1,990

F. Conclusion

The values seen in Table 8 indicate that this project is not financially feasible at all. Only just over 1000 kWh are being produced in surplus every year, and assuming a standard lifetime of 25 years for the entire hydropower system, this surplus acquires less than $4,000 over that lifetime. This is nowhere close to the $32,440 in capital expenses that the system costs in its lifetime.

The only way that the system could be financially beneficial at this point is if it would cost more to purchase all of the energy of the household from PSNH, as if the hydropower system was never installed in the first place. However, a quick analysis of this scenario using the MATLAB model reveals that this is not the case. From Table 8, it can be seen that the route of only installing the transmission line and buying PSNH energy would cost $28,950 over 25 years. This is $1,990 less than the *LCC* of the hydropower system. The results of these analyses show that this micro-hydro project in Grafton is not financial feasible.

IMPLICATIONS

It is now possible to inspect the results of each case study, evaluate the data and conclusions supplied by each one, and relate them to the suggestion offered in the previous section—that the figures of hydropower potential in New Hampshire made by the DOE and the NHDES are drastically overestimated.

In the first case study, the Macallen Dam hydropower project in Newmarket, New Hampshire was examined. This is the largest project of the three case studies, and for that reason, the potential changes to the dam affect the most town residents. Many have opposed the project since it was proposed in 1999, because they are concerned that the renovations to the Macallen Dam during the hydropower installment will alter the water impoundment area and have negative effects on any waterfront property. Many others resist the project simply because they wish to see the entire Macallen Dam removed, hydropower or not. This controversy and opposition is the single largest reason why this hydropower project has not become any closer to launching since 1999.

TABLE 9
DISCREPANCIES BETWEEN MATLAB MODEL AND NHDES ANALYSES FOR OYSTER RIVER DAM HYDROPOWER POTENTIAL

	NHDES	MATLAB
Head	4.6 m	1.8 m
Average flow rate	0.93 m^3/s	0.77 m^3/s
Nameplate capacity (maximum power)	42 kW	29.5 kW
Annual energy	369,000 kWh	70,300 kWh

In the second case study, the Oyster River Dam hydropower project in Durham, New Hampshire was evaluated. After the MATLAB model computed realistic power and energy generation figures for this potential project, many discrepancies were found between the figures presented in [2] and those obtain with the MATLAB software. A listing of every inconsistency is detailed within Table 9. This project was deemed to be marginally feasible by this software model; it has a positive net profit at the end of its lifespan, but the profit has a small magnitude when considering it is essentially a 40 year investment.

In the third case study, a micro-hydro project in Grafton, New Hampshire was inspected. After adjusting the MATLAB model for this specific project, the software determined that the project would be a poor investment. The expenses of the system outweigh the revenue gained during its lifetime, and it would cost less overall to simply install a transmission line and purchase all the energy of the household from PSNH.

These case studies reveal much about the process of hydropower planning and installment. To begin with, the differences between the NHDES hydropower estimations and the MATLAB model estimations in Table 9 indicate that there may be something inherently wrong with the model that the Dam Bureau of NHDES was using for these calculations. This is confirmed by using (3): when the values for head H and flow rate Q from Table 9 are applied to (3), with both an efficiency value η and capacity factor CF of unity, the power output P from Table 9 is produced.

This examination of the NHDES method of calculation reveals that they are making irrational assumptions that the efficiencies and capacity factors of the hydropower systems are 100%. Fig. 13 compares the MATLAB modeled estimations for potential hydropower of NH (and specifically Oyster River Dam site) to those made by the NHDES.

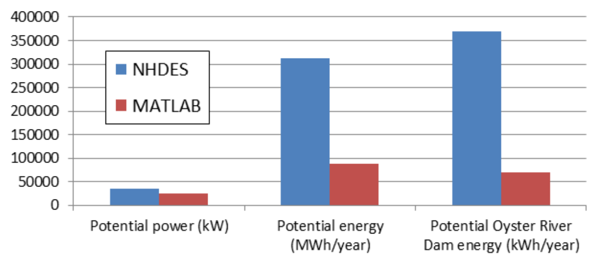

Fig. 13. NHDES estimation inaccuracies for hydropower.

A trend may be observed in Fig. 13: a small discrepancy in power generation levels due to water-to-wire efficiency differences, then a large discrepancy in energy production estimation due to an incorrect 100% capacity factor assumption, and finally an enormous difference in the specific potential estimations for the Oyster River Dam. This is because, as can be seen in Table 9, the NHDES overestimated the head and average flow rate of this site by a significant amount.

The DOE New Hampshire estimations from Fig. 1 can now be related to each of the three case studies performed. The first case study falls into the second column, and the last two case study falls into the first column of projects under 100 kW. The graph in Fig. 1 indicates that the most power in the state can be generated from large sites such as the Macallen Dam. From this case study it is noted that these large projects are going to be the most difficult to initiate, and thus should not indiscriminately be assumed to be possible.

The second two case studies fall into the DOE category of being under 100 kW, which is the category containing the most potential sites in NH. From these case studies, it can be ascertained that many of these projects will be impossible due to financial infeasibility. This means that, although the potential for generation may exist, it is impractical and deceptive to depict the maximum value of potential as the realistic one. There is no point in listing unrealizable values in a DOE report that investigates how much hydropower may exist in New Hampshire at a point in the future.

The results of these analyses show how much the hydropower potential figures, given by organizations such as the DOE and the NHDES, are distorted. Often the media will recite figures similar to these, giving the public a misleading notion of hydropower. In order for these estimations to have any practical merit at all, the DOE and NHDES must adapt their models to the realistic challenges and obstacles that define the reality of hydropower system design.

ACKNOWLEDGMENT

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