Micro-Hydro Power Potential for Caroline, NY
A Feasibility Study

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Abstract

Micro-hydro energy is a form of renewable energy that has been gaining popularity in recent years. The advantage of micro-hydro energy is that it enables energy to be harvested from a stream that would otherwise be too small for implementation of a hydro-electric dam. The general principle of operation is that a portion of water from a stream is diverted, brought downstream, and then used to drive a turbine before being returned to the stream. Here we consider the feasibility of installing micro-hydro systems in Caroline, NY. We were able to identify two possible micro-hydro sites along Six Mile Creek in Caroline. Based on field measurements and United States Geological Survey (USGS) data, we estimated the yearly energy production of each of these sites to be about **91.5 MWh**. Based on the information that we have been able to acquire thus far, it is unclear whether or not micro-hydro is economically feasible for Caroline since the cost of licensing and permits for the implementation of such a scheme is difficult to ascertain. Specifically, for each of the sites we identified, we found that the cost of a Department of Environmental Conservation (DEC) permit has to be less than $25,000 for a micro-hydro system installed there to have a positive Net Present Value (NPV).

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1 Introduction

Hydro-power is a major renewable resource leveraged throughout the world. The energy contained in flowing streams, rivers, and oceans can be harnessed via a turbine and generator; the flowing water drives the turbine and generator which, in turn, produces electricity. Hydro-power has been a crucial energy resource throughout human history and will persist as one as the world transitions to a predominantly renewable energy portfolio. The installed capacity of a hydro-power generation plant comes in an array of sizes: consider the Hoover Dam in the USA, which has a nameplate capacity of 2,080 MW, and the Three Gorges Dam, the largest power generation station in the world, has a nameplate capacity of 22.5 GW [1] [2]. Table 1 delineates between different hydro-power system sizes.

Table 1: Hydro-Power System Size Classification [3]

Classification	Nominal Capacity
Large-Hydro	>100 MW, connected to grid
Medium-Hydro	15 - 100 MW, connected to grid
Small-Hydro	1 - 15 MW, connected to grid
Mini-Hydro	100 kW - 1 MW, either connected to grid or independent systems
Micro-Hydro	5 kW - 100 kW, typically servicing individual communities
Pico-Hydro	<5 kW

Society stands to benefit from utilizing smaller streams, creeks, and rivers which could provide energy independence for small local communities, as systems using these water sources are often of sizes better suited to service individual communities. Isolated rural communities bereft of extensive electricity transmission systems would benefit from such systems in particular. Typically, hydro-power systems placed along streams and creeks have an installed capacity on the order of 5 to 100 kW. Hydro-power systems of this size are deemed *micro-hydro systems*.

Micro-hydro power systems are generally run-of-the-river systems where a portion of a river or a stream's water is diverted and delivered to a turbine via a water conveyance system. Unlike large hydro-power systems, micro-hydro systems do not require large dams or reservoirs that often generate unintended ecological consequences. Furthermore, if the stream on which the system resides has constant and sufficient water flow throughout the year (a key requirement for identifying a suitable micro-hydro site), micro-hydro systems generate continuous electric output, unlike more variable renewable energy source like solar and wind.

This report presents a feasibility and viability study for micro-hydro power in Caroline, Tompkins County, New York. It is a rural community located southeast of Ithaca, NY, with a population of approximately 3,300. The town is committed to becoming energy independent; Energy Independent Caroline (EIC) is a board of Caroline residents that strives to implement measures to make Caroline not only energy independent but to also minimize carbon emissions via the use of renewable energy technology. Six Mile Creek, a stream running through the town of Caroline, is the subject of this feasibility study.

1.1 Motivation

The potential for micro-hydro power in Tompkins County, NY, was studied by R. E. Rodriguez, K. J. Kircher, and K. Max Zhang at Cornell University. They approximate the total potential capacity for the county to be 88.5±18.6 MW. Assuming an 8,200 kWh/year energy production from 1 kW of installed micro-hydro power, Tompkins County has the potential to generate approximately 725 GWh annually, which meets 90% of the 2008 power demand of Tompkins County [4].

Volumetric flow rate (or discharge) of a stream and head (change in elevation, the steepness of the stream) are the two key stream parameters necessary for quantifying the potential of a particular site. Both the volumetric flow rate and head are directly proportional to power output of a turbine; with these quantities one can determine the flow rate of kinetic energy through the turbine. In the work done by Rodriguez et. al. the head of a potential site was determined using a Data Elevation Model (DEM) raster, which discretizes Tompkins County and the surrounding areas into 10 meter by 10 meter cells. Each cell is assigned an elevation, and cell-to-cell head can be computed. The study determined stream discharge in two ways. First, when possible, United States Geological Survey (USGS) stream gauges were used. These gauges log the stream discharge. However, only five gauges were used in the study. In all other situations, stream discharge was estimated used a multiple linear regression model. Independent variables were precipitation, drainage area, and stream slope; the dependent variable was volumetric flow rate. The power output of a single turbine was then estimated with the following equation:

$$P = \eta \times (\rho g h) \times \dot{q} \tag{1}$$

P is the turbine power output in watts, η is the turbine efficiency (the amount of kinetic energy converted successfully converted into electricity), ρ is the water density (nominally 1,000 kg/m^3), g is gravitational acceleration (9.81 m/s^2), h is head in meters, and $\dot{q}$ is volumetric flow rate. Note that the quantity in parentheses is the potential energy density of the water. The study identified Six Mile Creek to have many potential sites for micro-hydro potential.

1.2 Objective

The work done by Rodriguez et. al. indicates significant potential for micro-hydro potential along Six Mile Creek and for Tompkins County. However, significant approximations were made in the process of estimating total potential micro-hydro power. Furthermore, the study did not consider terrain conditions. The site-specific terrain determines the particular micro-hydro system suitable for the site and affects the cost of the system. This study evaluates the viability of micro-hydro power along Six Mile Creek in Caroline specifically through the following:

1. Site Reconnaissance & Terrain Evaluation

2. Determination of Head via a DEM Model
3. Determination of Discharge via USGS Gauge Data and Field Measurements
4. Selection of Micro-Hydro System Configuration
5. Research of NY Department of Environmental Conservation (DEC) Regulations

With stream data and site data the appropriate micro-hydro system configuration is selected. With this power potential is estimated. Salient DEC regulations are presented, as these regulations will greatly impact any potential project in the future and will affect project cost. Finally, a preliminary economic analysis is presented.

2 Micro-Hydro System Literature Review

2.1 Micro-Hydro System Components

The major components of a typical micro-hydro development scheme are shown in Figure 1 below:

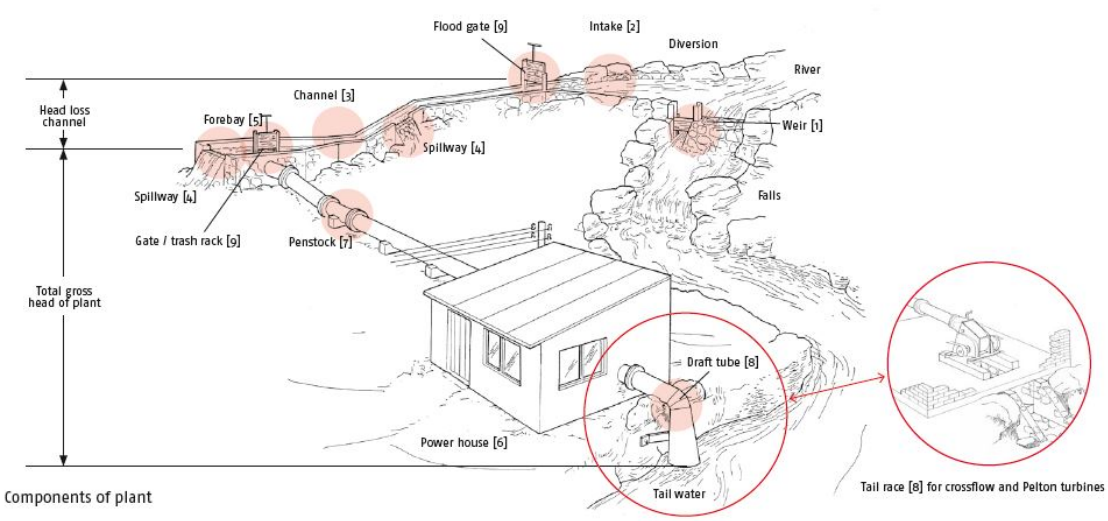

Figure 1: Micro-Hydro System Schematic [5]

The *intake* is the point at which the water from the stream is diverted and is typically the highest point of the hydro system. For water diversion, the river water level may or may not be raised by a barrier called the weir. A filter is also provided at the intake for preventing the entry of dirt and debris in the system.

Headrace refers to the channel that leads water to a forebay or turbine. The headrace follows the contour of the hillside so as to preserve the elevation of the diverted water.

The *spillways* protect the system against damage from excessive water flow.

The water in the headrace is slowed down and collected in a tank, or *forebay* which is situated at the top of a penstock or pipeline. This serves as the final settling basin and also provides a spillway arrangement. The penstock inlet is submerged in the forebay.

Penstock refers to the pipe that focuses all the water from the forebay to the turbine which is situated at the bottom of the pipe. The penstock is a crucial part of the system as it is responsible for creating head pressure with an increase in the vertical drop.

A water *turbine* is used to convert the kinetic energy of flowing water into useful rotational energy. Hydro-power turbines are detailed further in §2.2. The turbine rotor is connected to a generator, which converts the rotational kinetic energy of the turbine shaft into electricity. Note that both the turbine and the generator have associated energy conversion efficiencies, as they are unable to fully convert energy from one form to another. To optimize performance of the generator and turbine, an electronic load controller is traditionally used. The controller can provide a torque on the turbine and thereby control its speed, ensuring the turbine operates at its rated speed.

The *power house* is the heart of the system as it houses the electricity generation equipment (the turbine and generator). The power house is often equipped with an electricity transmission system, connecting the micro-hydro system with local buildings. If there is sufficient energy production, the system may be connected to the grid. For more rural, sparsely populated communities, electrical transmission systems may be prohibitively expensive. In these settings, the system may be fitted with a direct current (DC) generator used to charge batteries which may then be transported to other locations as needed.

2.2 Hydro-Power Turbines

Hydro-power turbines are fall in one of two categories: impulse turbines and reaction turbines.

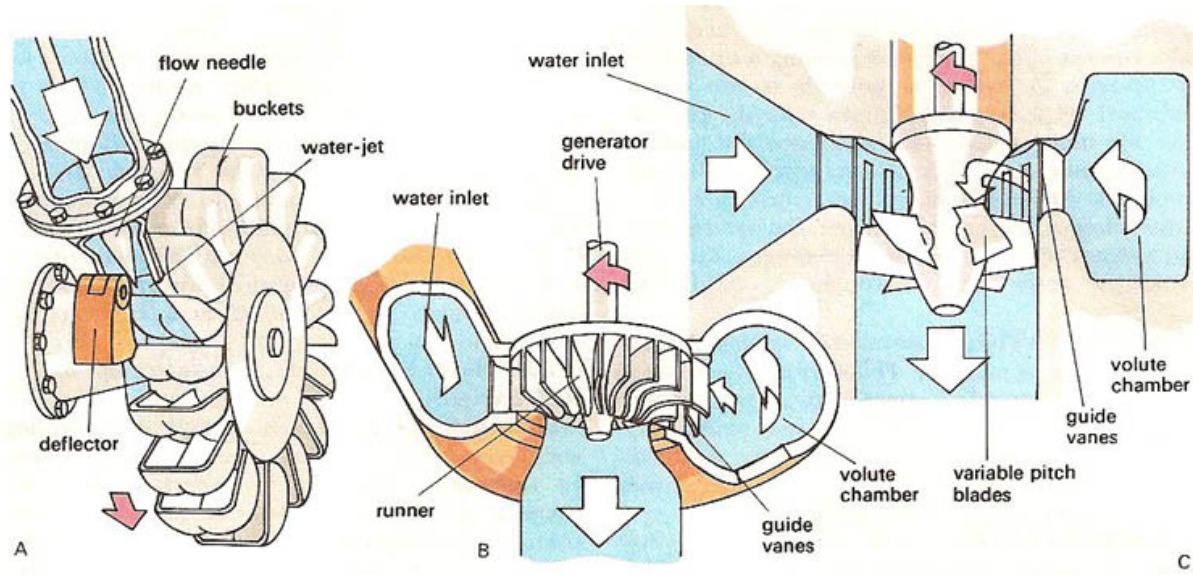

Figure 2: Traditional Hydro-Power Turbines [6]

- **Impulse Turbines**: In these types of turbines, the velocity of the water jet is responsible for rotating the runner of the turbine. The large dynamic pressure of the flowing water is converted to the kinetic energy by directing high speed water through a nozzle at the turbine "buckets;" the blade, or vane, of an impulse turbine. Traditional impulse turbines include the Pelton and crossflow models, the former of which is depicted in Figure 2A above. Impulse turbines are designed for low volumetric flow rate and high fluid velocity conditions.
- **Reaction Turbine**: Momentum of the water is transferred to the turbine rotor by utilizing the total pressure of the water flow. Their working is quite similar to that of a wind turbine where the pressure difference between the upstream and downstream sides of the turbine blades is responsible for creation of a torque that rotates the turbine. The Francis and Kaplan turbines are examples of reaction turbines, which are depicted in Figure 2B and 2C, respectively. Reaction turbines require a large volumetric flow rate of water, as the turbine vanes are fully engulfed in the water. Insufficient volumetric flow rate creates suboptimal performance.

The selection of the type of turbine to be used in a micro-hydro system depends heavily upon the local head and volumetric flow rate of a site (the site head is illustrated for the sample site in Figure 1). The turbine type must be matched appropriately with site conditions to ensure the turbine achieves its rated operated conditions. Figure 3 illustrates a typical turbine application chart, plotting head versus volumetric flow rate and indicating the operating regions for different turbine types, and the nominal capacity of the turbines for the different operating conditions. Note that Kaplan and Francis turbines are reaction turbines, whereas the Pelton, Turgo, and crossflow turbines are impulse turbines. Furthermore, the capacity of the turbine increases proportionally with both head and volumetric flow rate, as the available kinetic energy is proportional to both of these quantities (see Equation 1).

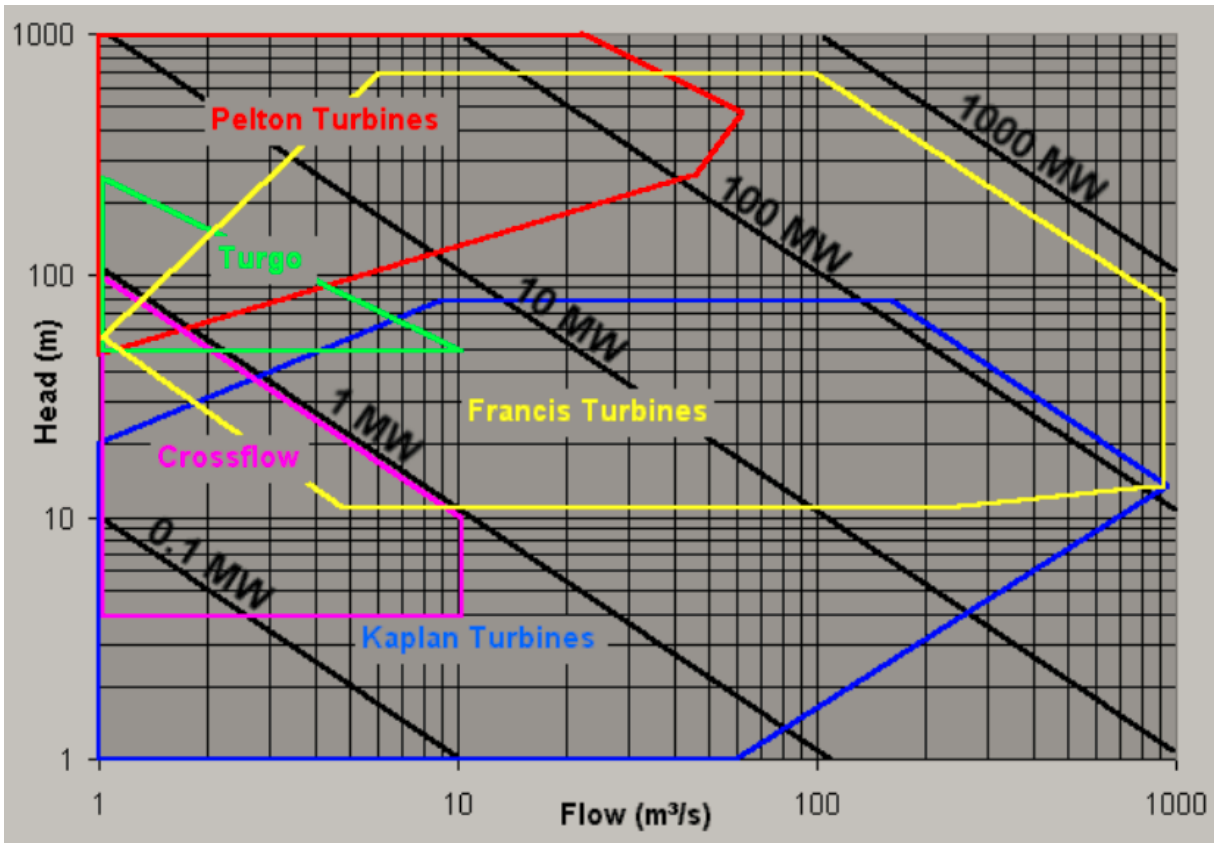

Figure 3: Turbine Application Chart [7]

2.3 Micro-Hydro System Configurations

The placement of the different components of the micro-hydro system are dependent upon site specific terrain. Figure 1 pictures an ideal configuration, one in which the elevation contours and the direction of the stream are set such that a channel can be built to leverage natural head. The banks depicted in the classic configuration are easily manipulated, which may not always be the case. Below are crude depictions of other micro-hydro systems, depending on the site specific geography.

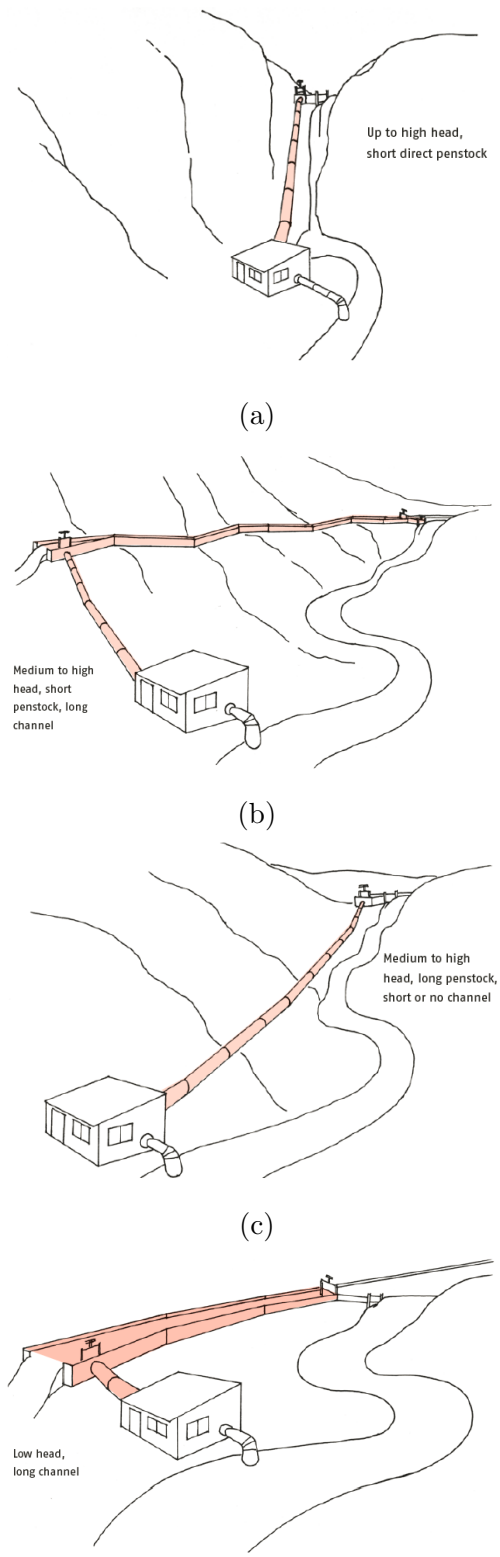

Figure 4: Micro-Hydro System Configurations [5]

3 Six Mile Creek Characterization

3.1 Site Selection

Ideal candidate sites for micro-hydro are endowed with both large water volumetric flow rates and a large head. Natural waterfalls and man-made dams are often ideal micro-hydro site locations. For sites with little head and low stream discharge, weirs or dams may be built to increase the site head. Certain sites with large stream discharge may not require the construction of a dam but instead may allow for run-of-the-river systems in which turbines can be placed within the stream or in a channel running parallel to the stream.

Two sites were visited on Six Mile Creek in Brooktondale, a small hamlet contained within Caroline, NY. These particular sites were recommended by EIC committee members with knowledge of the local stream geography and familiarity with the owners of the sites.

Figure 5: Site 1, Man-Made Dam

Figure 6: Site 2, Natural Waterfall

The vertical drop for both sites depicted in Figures 5 and 6 was estimated to be approximately 4 meters by observation; this serves as the amount of head for the site. The width and depth of the stream immediately upstream of the dam/waterfall was estimated to be 6.75 meters and 0.6 meters, respectively (the former was estimated using a laser measuring tool, while the latter estimated and later measured in the gathering of stream discharge data).

The sites resembled shallow gorges with steep banks made of rock. These banks would pose a challenge for retrofitting a micro-hydro system and would also make energy extraction difficult, as the turbine cannot be placed above the point of water diversion in the stream (a pump would be necessary to extract water in this case). Furthermore, the alterations of the creek banks would require a permit from the NY DEC, which has associated costs (DEC regulations are discussed further in §4). The power house would likely be placed within the gorge and would thus require a barrier necessary to protect against flooding events.

3.2 Head Determination

A DEM model with 1 meter resolution was used for determining the variation in head along the stream. In Figure 7 we were able to plot elevation against distance along Six Mile Creek. The orange region of the figure corresponds to Caroline, which is our region of interest. The rate of elevation change is relatively small within Caroline for the most part. The portion of the stream with the best head is the part near the outlet in Ithaca. Six Mile Creek has the highest rate of elevation change at about $17,000$ m along the creek. This location corresponds

to the Brooktondale region of Caroline. So as a result of this analysis, we decided to restrict our search for micro-hydro sites to Brooktondale.

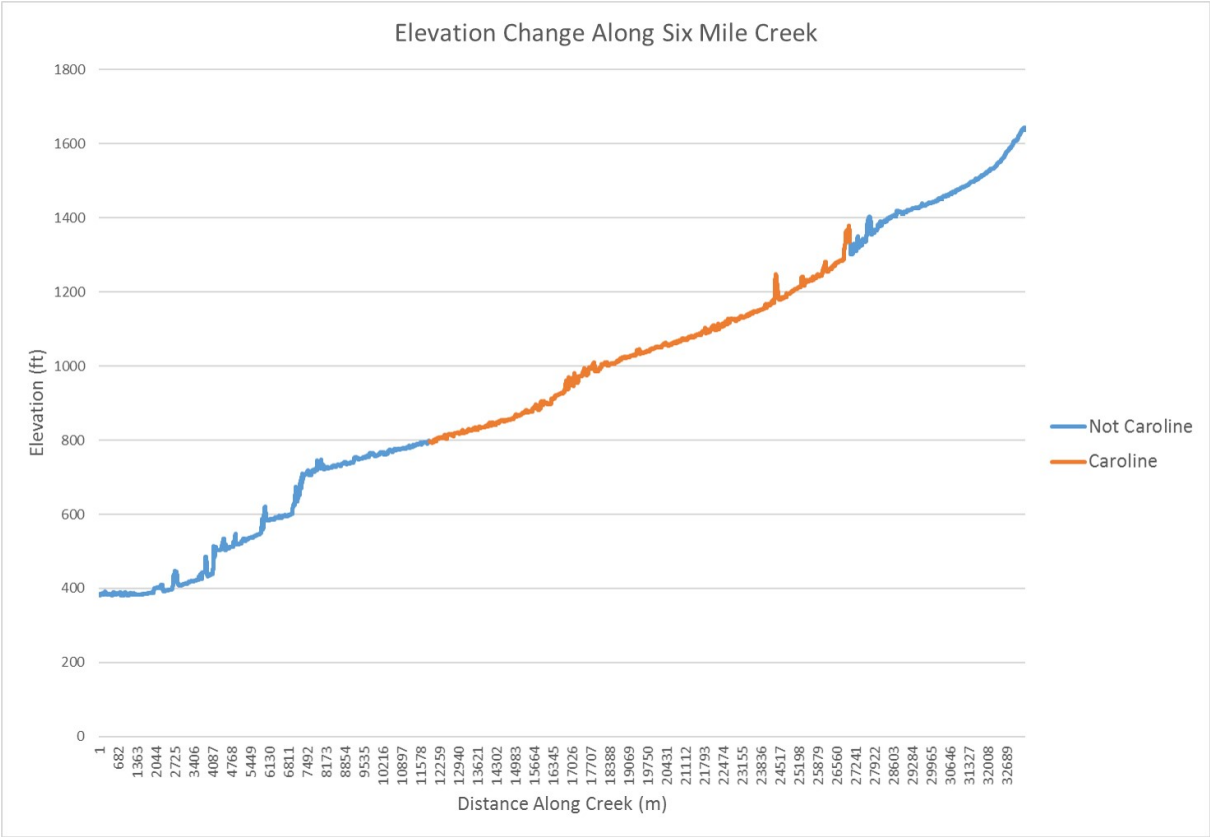

Figure 7: Elevation Along Six Mile Creek (One Meter Resolution Data)

3.2.1 GIS Methodology

We were able to perform this analysis of finding elevation change along the stream using GIS software. First, we found a shape file for Six Mile Creek. In our first attempt at this process, we ended up finding that the shape file for the creek treated the body of water not as one continuous stream but as many small bits of stream. This made our analysis very difficult, so in order to facilitate the process, we ended up using ArcGIS's dissolve function to condense all these discontinuous bits of stream into only four discontinuous sections. The reason that this function could not further condense the stream geometry is that there are reservoirs in the stream that break it into four parts.

Once we had dissolved Six Mile Creek into four pieces, we were able to use two more functions in ArcGIS – densify and feature vertices to points – to break the creek into many evenly spaced points with coordinate values. In our first analysis of the creek elevation, we only had access to topographic data from the state of New York. This data gave the elevation of the whole state at 10 m resolution. For our second analysis, we used 1 m resolution data

that exists only for Tompkins County. The number of points that we broke the creek into to perform our elevation analysis depended on the topographic map that we were referencing. As such, in our first analysis, we broke the creek into points that were 10 m apart, and in our second analysis, we broke the creek into points that were 1 m apart.

Once we had Six Mile Creek broken up into evenly spaced points, we matched those points to topographic data using ArcGIS's extract values to points function. This gave us an array with elevation values for each point along the stream. We exported this array to Microsoft Excel^{TM} in order to better display the data. Since the stream was still broken into four disjoint parts, it was necessary to identify the four regions of the data array and arrange them in the correct order. Once this was completed and the boundaries of Caroline were identified, we were able to plot the data as shown in Figure 7. Note that for the region of Caroline, the average change in elevation along the direction of stream is 0.021 m/m.

To make sure our analysis was sound, we referenced it against Figure 8, which is a topographic map of Caroline. In order to find regions in the topographic map that have the most head, it is only necessary to look for points along the stream where lines of equal elevation are closer together. Reading from Figure 8, we found that the regions with the most elevation change appear to be Brooktondale and the northern end of the stream. This agrees well with our analysis because there are slight increases in slope of the GIS-produced elevation curve in both of these places.

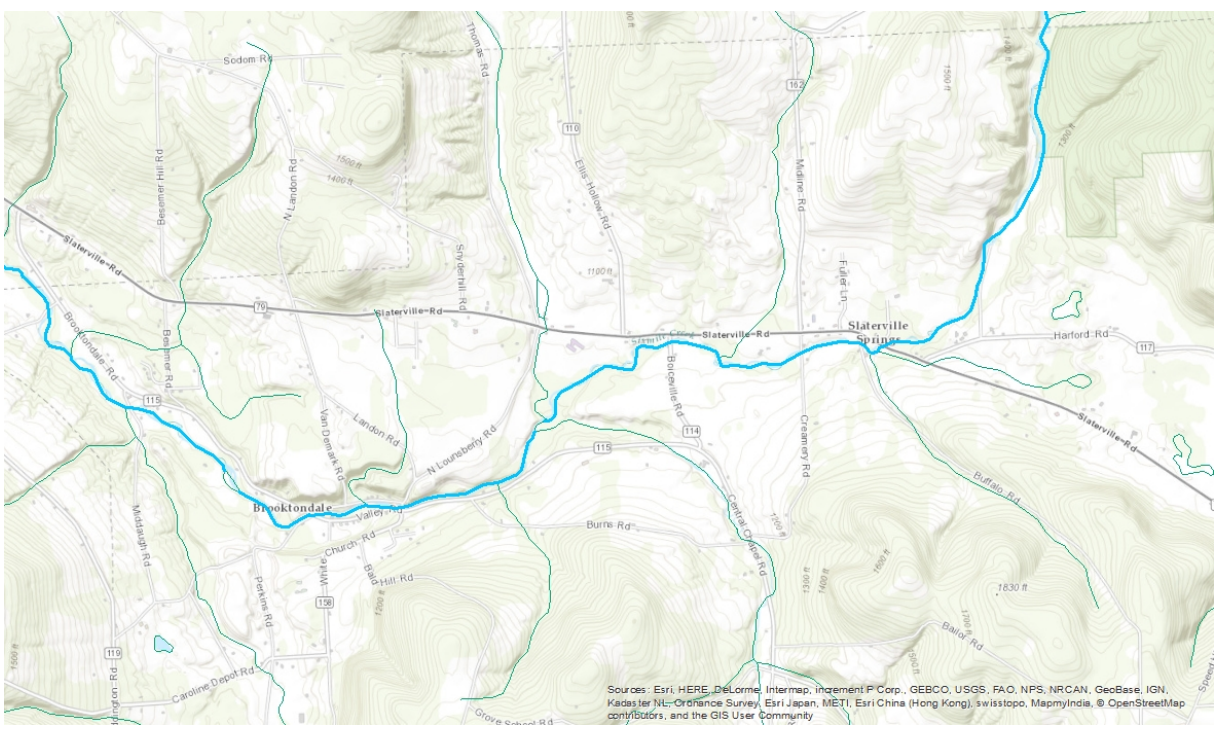

Figure 8: Topographic Map of Six Mile Creek in Caroline

3.3 Volumetric Discharge Determination

For a robust and reliable evaluation of the stream discharge of a particular site, monthly data should be collected at the site using a flow meter, as this will best capture seasonal variability in the stream discharge. However, USGS Gauge 04233286 in Brooktondale provides a time history of the stream discharge at the location of the gauge. Both methods of stream discharge - through the use of the gauge and the use of a flow meter - are explored below.

3.3.1 Field Data

The USGS outlines a methodology for the collection of stream discharge data. The method is, in essence, a Riemann sum of the flow through the stream.

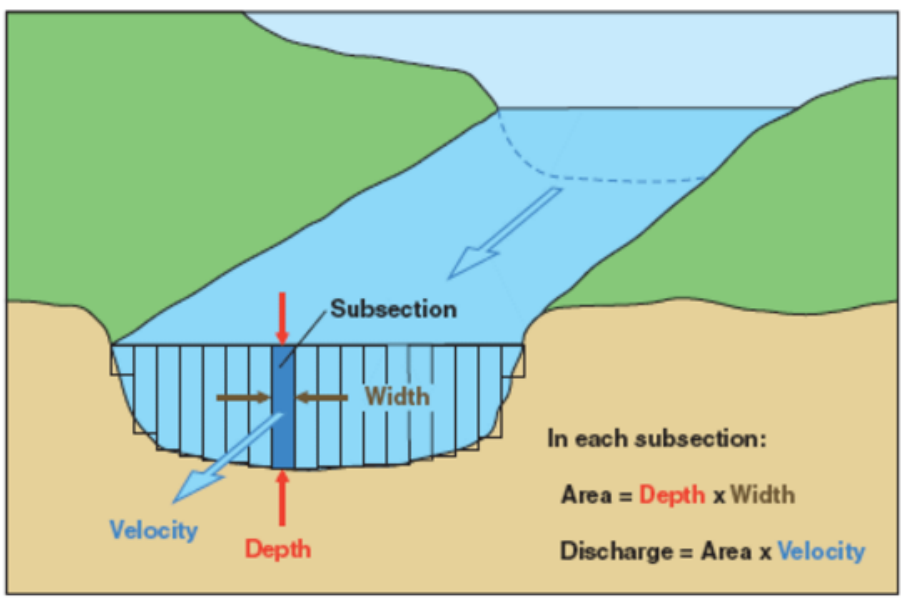

Figure 9: Measuring Stream Discharge [8]

To determine the volumetric flow rate of the stream in a particular location, several subsections along the stream width must be sampled, noting the depth, d, and width, w of each subsection. The linear velocity of the stream, U, is then measured for each section using a stream flow meter. If there are N sections, then the stream discharge $\dot{q}$ is given by:

$$\dot{q} = \sum_{i}^{N} (w_i \cdot d_i) \cdot U_i \tag{2}$$

A Marsh McBirney Flo-Mate Meter, Model 2000, was used to measure the linear velocity of the water. The operating principal of the meter is based upon Faraday's Law of electromagnetic induction, which states that as a conductor moves through a magnetic field, a voltage

is produced. A probe attached to the meter produces this field, and the water acts as the conductor. The induced voltage then gives the speed at which the conductor (the fluid) is moving through the magnetic field [9].

The meter is used in conjunction with a measuring rod. The meter probe is fastened to an adjustable slide on the rod, allowing the user to position the probe at the appropriate depth of the stream: 60% depth of the stream is stated in the USGS gauging protocol [10]. The width of each stream section is measured simultaneously using a tape measure, held by the individual using the measuring rod. Thus, collection of stream discharge data requires a team of three to four individuals.

The meter and measuring rod were provided by Dr. Brian Rahm in the Department of Biological and Environmental Engineering at Cornell University. The equipment was used at a location upstream of the dam pictured in Figure 5. Unfortunately, conditions prohibited the collection of an extensive data set. Safety is a considerable concern when measuring stream discharge, as the temperature and speed of the stream pose threats. A small set of data was collected; however, it is not used in the power estimate presented in §5. Instead, the more robust data set available from the USGS gauge in Brooktondale is used, and is detailed in §3.3.2.

3.3.2 USGS Gauge Data

The Brooktondale gauge is located upstream of Sites 1 and 2. The gauge collects real time stream discharge data every 15 minutes, reported in units of cubic feet per second, ft^3/s. The total volumetric water flow through the section of Six-Mile Creek in Brooktondale is assumed to vary minimally along its length. This is because fluctuations in flow rate would lead to accumulations of water in some parts of the stream and loss of water in others; no sources or sinks of the stream were observed in the visits to Sites 1 and 2. Therefore, for the analysis presented in this report, the data collected by the USGS gauge is assumed to be valid for all locations along Six Mile Creek in Brooktondale. There will, however, be some variation in flow rate along the width of the stream, so the flow rate of water available to each turbine will depend on where the diversion channel for the micro-hydro system is placed. However, the analysis presented herein treats the water speed throughout the width of the stream to be constant.

Stream discharge data from the year of 2016 is considered. The Caroline region experienced a significant drought in the summer and fall months of 2016. This set of data is considered such that a worst case scenario for the performance of the hydro-turbine is predicted, as seasonal and annual variations in system performance are a major consideration when evaluating the viability of a micro-hydro project.

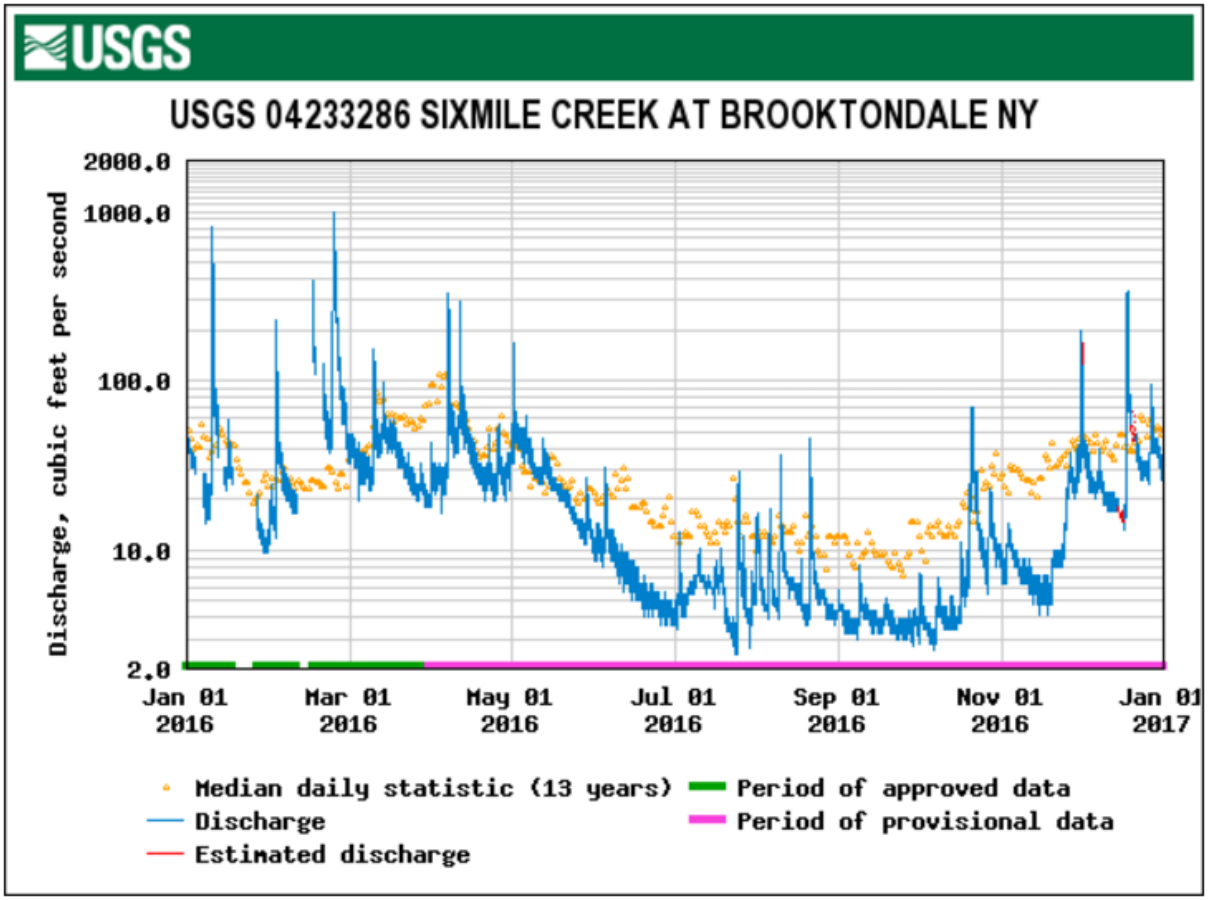

Figure 10: USGS Gauge Stream Discharge Data, 2016 [11]

The data in Figure 10 also presents the median daily stream discharge, based on 13 years of data. This clearly illustrates the drought in the summer and fall season, as the 2016 data (plotted in blue) are considerable below the median daily statistic illustrated by the orange data points. The median discharge for the year of 2016, based on this data, was 19.3 ft^3/s.

4 Environmental Regulations

In attempting to install micro-hydro systems in Six Mile Creek, the issue arises of complying with any environmental regulations that may apply to the stream. DEC regulations are found within Title 6 of the New York Codes, Rules, and Regulations (NYCRR). Six Mile Creek is classified by the DEC as a class A trout stream. According to New York State's Environmental Conservation Law, this makes Six Mile Creek a "protected stream" [12]. Since Six Mile Creek is a protected stream, a Protection of Waters Permit is required to disturb its banks. It is likely necessary to disturb the banks of the creek in order to install a micro-hydro system, so the town of Caroline would have to obtain one or several permits.

The permit application process would require that the town of Caroline first submit its project plans to the DEC division of environmental permits and the DEC Bureau of Habitat (BOH). The division of environmental permits has jurisdiction under Title 6 NYCRR Part 608, which outlines the necessary detail required in the submitted project plan. The BOH determines how the project will impact the wildlife in the stream. For our purposes, the BOH will be largely concerned with making sure that we do not harm the aquatic species population by diverting too much water from the stream. If the division of environmental permits decides that a Protection of Waters Permit is needed, as they most likely will, then a joint application form and the plans for the project must be submitted to the DEC and to the Army Corps of Engineers [13]. Large hydro-power projects are subject to costly licensing from from the Federal Energy Regulatory Commission (FERC); however, exemptions are made for systems below 10 MW in capacity and that use pre-existing dams or natural waterfalls [14].

Because Six Mile Creek is a trout stream, there are regulations governing how much water can be diverted from the stream. Although this water would eventually be returned to the stream, trout could be negatively impacted by reduced flow through the region where flow is diverted. Specifically, micro-hydro systems are not permitted to drive the stream discharge below 80% of the its annual median rate during the winter, and they are not permitted to drive the stream below 70% of its annual median rate during the summer [15]. Here, winter is defined as November-April, and summer is defined as May-October. This means that there will be times when no flow can be diverted for use in driving a micro-hydro turbine because the flow is below 70% or 80% of its annual median value, depending on the time of year. The rest of the time, there is some maximum flow rate of water that may be legally diverted from the stream. This maximum flow rate of water that may be diverted from Six Mile Creek is shown in Fig. 11 for 2016. As can be seen in this figure, the flow rate that is available for use is much higher in the winter than in the summer. This is because there is in general much less flow during the summer. This data gives us an estimate of $658,400,000$ ft^3 for the amount of water legally available to us in Six Mile Creek each year. This equates to an average discharge of 20.9 ft^3/s.

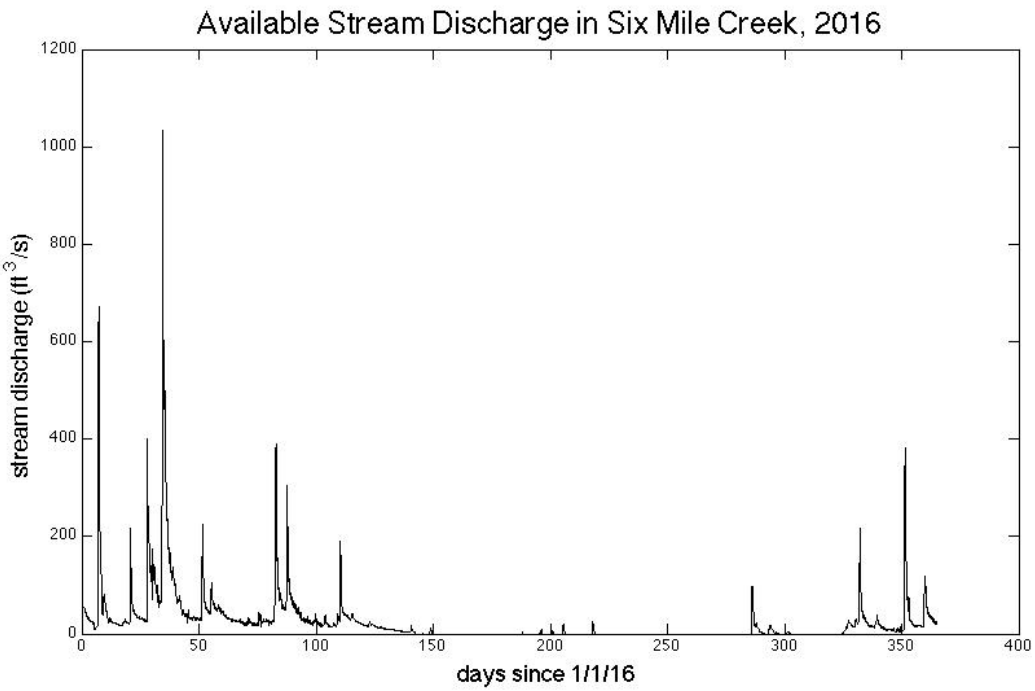

Figure 11: Discharge in Six Mile Creek that may legally be extracted in 2016 [11]

It is important to note that micro-hydro systems return diverted water to the stream at a certain distance downstream of the penstock inlet. Therefore, while this DEC regulation limits the total intake of a given turbine or system at one location along the stream, multiple turbines/systems can be placed along the stream, provided they are sufficiently spaced and that they do not reduce stream discharge beyond the threshold set by the DEC.

5 Estimated Power Output

Based upon Figure 3 and the head data and stream discharge data, the Kaplan reaction turbine is the most suitable choice for potential micro-hydro systems along Six Mile Creek in Caroline. This turbine is depicted in Figure 2C. Kaplan turbines have a rated efficiency (η) of 90% [4].

For the power estimate we first consider a total system output. This is a low order estimate, based upon average stream discharge statistics. We then consider the output of an individual turbine, for which we consider frictional losses that will be observed in the system.

5.1 System Estimate

The data shown in Figure 11 illustrates the volume of water the year of 2016 that can be taken in by the micro-hydro system - $658,400,000$ ft^3. Using the average discharge corresponding to this volume, 20.9 ft^3/s (approximately 0.59 m^3/s), and assuming a net head of 4 meters, as measured at the visited sites, a power estimate of the system is estimated using Equation 1:

$$P_{Sys1} = 0.90 \times 1000 \ \frac{\text{kg}}{\text{m}^3} \times 9.81 \ \frac{\text{m}}{\text{s}^2} \times 4 \text{ m} \times 0.59 \ \frac{\text{m}^3}{\text{s}} = 20840 \text{ W} \tag{3}$$

For this configuration (labeled Configuration 1), the estimated average power rating of the micro-hydro system is **20.84 kW**, based on 2016 stream gauge data. This corresponds to an average annual energy production of **183 MWh**. Note that the estimated power of the system would be larger if a different stream discharge data set were used, as the drought conditions significantly decrease the performance of the system. This estimate is also heavily dependent upon the value of head, h, used. If we instead consider an arbitrary site, one without a dam or waterfall, and one with the average rate of change of elevation shown in §3.2 of 0.021 m/m, then the system power capacity is highly dependent upon the length of the penstock. The length would have to be sufficiently long to generate the head necessary for significant power output. If we consider a penstock 25 meters in length, the average power rating of the system is:

$$P_{Sys2} = 0.90 \times 1000 \ \frac{\text{kg}}{\text{m}^3} \times 9.81 \ \frac{\text{m}}{\text{s}^2} \times \left(0.021 \ \frac{\text{m}}{\text{m}} \times 25 \text{ m}\right) \times 0.59 \ \frac{\text{m}^3}{\text{s}} = 2735 \text{ W} \tag{4}$$

For this low head configuration (labeled Configuration 2), the average power rating is **2.73 kW**, with an annual energy generation of **24 MWh**.

Note that the two estimates above assume no losses in the system (frictional or otherwise), assume constant rated operating conditions of the system, and assume a constant penstock inlet conditions. Micro-hydro systems typically have a capacity factor of 50%, due to system shutdowns for maintenance and variable conditions of the host stream/river [16]. This capacity factor results partially from maximum water diversion constraints, such as those given by the DEC. Another contributing factor are stream flow conditions that cannot be handled by the turbine as they fall beyond the operating limits of the turbine.

The power and energy estimates are subject to the strong assumption of a constant water volumetric flow rate. The USGS gauge data shown in Figures 10 and 11 is highly variable, with sharp peaks created by large rainfall events. Thus, the system is subjected to highly variable operating conditions, some of which may fall beyond the system's operation limits. A load controller would be needed to maintain allowed and optimal operating conditions, or to shut off the system during times of excessive or insufficient fluid flow. Finally, Figure 11 indicates large portions of the year, especially during the drought of the summer, where no flow can be diverted to the system due to the DEC regulation. Thus, system power and energy output are not only highly variable, but they may be non-existent for periods of time in the year. The specific operating conditions of a Kaplan turbine are unknown. As a

more conservative estimate of the energy potential, we assume only one half of the available kinetic energy in the fluid can be converted to electricity, resulting from suboptimal operating conditions of the turbine, required system outages, or other factors that may decrease the turbine performance. This serves to halve the annual energy production estimates given above - **91.5 MWh** for Configuration 1, and **12 MWh** for Configuration 2.

5.2 Turbine Estimate

The analysis below estimates the power output of an individual turbine, and considers frictional losses incurred by fluid flow through the penstock, which we assume to be circular with diameter D and length L.

For this analysis we consider a modified Equation 1:

$$P \approx \eta \times ke_{\text{Turbine Inlet}} \times \dot{q}_{\text{Turbine Inlet}} \tag{5}$$

$\dot{q}_{\text{Turbine Inlet}}$ refers to the volumetric flow rate of water through the turbine, which is not the same as $\dot{q}$, the volumetric flow rate of water through the entire section of the stream. In Equation 5, $ke_{\text{Turbine Inlet}}$ represents the density of kinetic energy delivered to the turbine, in J/m^3, given by:

$$ke_{\text{Turbine Inlet}} \approx \frac{\rho U_{avg}^2}{2} + \rho g h - \rho g h_L \tag{6}$$

Equation 6 shows the kinetic energy density to be a function of the kinetic energy density of the penstock inlet fluid, the change in potential energy of the fluid over the distance of the penstock as a function of head h, and frictional losses in the penstock, represented by h_L, referred to as the head loss. Equation 1 assumes quiescent penstock inlet conditions (achieved with the use of a forebay, see Figure 1), and no frictional losses. Thus, Equation 6 provides a more accurate estimate of the turbine power.

The analytical expression for h_L is given by:

$$h_L = f \frac{L}{D} \frac{U_{avg}^2}{2g} \tag{7}$$

In Equation 7, f is the Darcy friction factor, L is the length of the penstock, and D is the diameter of the penstock. The determination of f requires the knowledge of the Reynolds number, Re, of the flow, given by:

$$\text{Re} = \frac{U_{avg} D}{\nu} \tag{8}$$

In Equation 8, ν is the kinematic viscosity of the fluid. The value of Re indicates the operating conditions of the flow - either laminar or turbulent conditions. Traditionally, Re values above 4,000 for circular pipes indicate fully turbulent flow. Values of Re for our penstock flow are on the order of magnitude of 10^5 to 10^6, thus we consider fully turbulent flow. For turbulent flow, f is given by the Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2.0 \log \left[\frac{\epsilon/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}} \right] \tag{9}$$

In Equation 9, ϵ represents the roughness of the pipe, a function of the pipe material, and given in units of length. Values of ϵ are available in textbooks on fluid mechanics. We assume our penstock to be stainless steel, with a corresponding ϵ value of 0.002 mm.

Equation 9 is implicit in f. Traditionally, f is evaluated using the Moody Chart, which plots f as a function of Re for different level curves of relative roughness, ϵ/D. However, S. E. Haaland developed an explicit relation for f in 1983:

$$\frac{1}{\sqrt{f}} \cong -1.8\log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\epsilon/D}{3.7}\right)^{1.11}\right] \tag{10}$$

The value of f given by Equation 10 is accurate to within 2% of the value given by the implicit Colebrook equation [17]. We use Equation 10 to evaluate f for this analysis.

The average fluid velocity, U_{avg}, is estimated using the USGS gauge data and the estimated width and depth of the stream noted at Site 1 (6.75 m and 0.6 m, respectively) and is given by:

$$U_{avg} = \dot{q}wd \tag{11}$$

$\dot{q}_{\text{Turbine Inlet}}$ is directly proportional to the penstock diameter, D. The selection of the penstock diameter is crucial, as it sets the volumetric flow rate of water through the turbine, which is directly proportional to the power produced by the turbine. For our analysis, we define D as a function of the stream conditions and subject it to the stream flow constraints set by the DEC. In the summer, the stream discharge must be at least 70% of the median discharge of the year. In the winter, the discharge must be at least 80% of the median stream discharge. If the discharge at a given time is below these thresholds, no water can be drawn from the stream. We consider the more stringent condition and assume that the instantaneous stream discharge must not fall be 80% of the 2016 median value of 19.3 ft^3/s, approximately 15.4 ft^3/s. We refer to this as $\dot{q}_{median}$. We then assume $\dot{q}_{\text{Turbine Inlet}}$ to be the maximum permitted stream discharge:

$$\dot{q}_{\text{Turbine Inlet}} = \dot{q} - \dot{q}_{median} \tag{12}$$

The penstock diameter is then computed by:

$$D = \sqrt{\frac{4\dot{q}_{\text{Turbine Inlet}}}{\pi U_{avg}}} \tag{13}$$

In this way, we compute the maximum permissible penstock diameter as a function of instantaneous stream discharge conditions. Note that for the high head configuration, the value of L is rather arbitrary. However, for the low head configuration, L is critical, as it directly impacts the head of the system.

Figure 10 indicates the high variability of the instantaneous stream discharge Thus, the power output of the turbine is highly variable. Furthermore, this variability introduces a constraint of the penstock diameter. D increases with $\dot{q}$; however, if the value of D were selected based upon maximum stream discharge conditions, then the DEC regulations will

be violated for sub-maximum stream discharge conditions. One way to work around this constraint is to have a penstock inlet valve that could adjust the intake. The numerical results for different conditions are given below, found using Equations 5 thorugh 13.

Table 2: Turbine Power Estimates

Configuration	L (m)	$\dot{q}$ (ft^3/s)	$\dot{q}_{\text{Turbine Inlet}}$ (m^3/s)	D (m)	h (m)	**P (kW)**
1	10	20	0.13	1.09	4	**4.6**
1	10	40	0.70	1.79	4	**24.6**
1	10	60	1.26	1.97	4	**44.75**
1	10	80	1.83	2.06	4	**64.94**
1	10	100	2.40	2.10	4	**85.24**
2	25	20	0.13	1.09	0.525	**0.60**
2	25	40	0.70	1.79	0.525	**3.25**
2	25	60	1.26	1.97	0.525	**5.95**
2	25	80	1.83	2.06	0.525	**8.73**
2	25	100	2.40	2.10	0.525	**11.62**

Table 2 presents power output of a turbine in either Configuration 1 or Configuration 2 for different $\dot{q}$ values. Recall that Configuration 1 is the high head configuration possible with Sites 1 and 2, whereas Configuration 2 is a low-head configuration that relies on a long penstock with gradual change in elevation (h is determine by multiplying the average slope of the stream by the length of the penstock). The values of $\dot{q}$, the instantaneous stream discharge, were selected based upon the data shown in Figure 10, which indicates the maximum median stream discharge to be about 100 ft^3/s. Note that for stream discharge values below 15.4ft^3/s that no water can be diverted from the stream.

The quantity P in Table 2 represents the instantaneous power of a single turbine. The large variability is a function of the large variability in stream discharge. Given their large variability, and the difficulty to quantify a period of time for which these conditions apply, no energy production estimate is made. Given the large variability in power output, micro-hydro turbines may be better suited for part-time operation, where the turbine is only used for periods of time when there is large stream discharge.

6 Project Economic Analysis

As seen in the previous sections, a significant amount of construction and machinery goes into developing a micro-hydro scheme. First we calculate the number of households that can obtain electricity from this scheme as that will be crucial in determining the costs associated with laying down distribution works and constructing household connections.

The energy output from the system is $= 20.84 \times 8760 \times 0.50 = 91.5$ MWh (The capacity factor of the plant is assumed as 50% [16])

The average electricity consumption of a US. Household is about 10,812 kWh [24].

Thus the number of households benefited = 91,500/10,812 = 9 (Approx.)

Thus distribution works and household connections need to be constructed for these 9 households in addition to the machinery and the powerhouse of the micro-hydro scheme. All of these have significant costs attached to them which can be analyzed as follows:

6.1 Capital Expenditure (CAPEX)

The capital expenses associated with this 21kW (approx.) project can be divided as follows:

Table 3: Direct Costs - Micro-hydro Scheme [20]

Description	Formulae	Cost ($)
CIVIL WORKS (C)		
Penstock	$106 \times D^{0.571} \times$ L	1500
Power House Foundation	$672 \times P^{0.456}$	2700
Power House Building	338 × P + 139,900	10,000
ELECTROMECHANICAL WORKS (E)	$10{,}410 \times (P/\sqrt{He})^{0.56}$	40,000
DISTRIBUTION WORKS (D)	$2 \times (HH \times X)^{0.5541}$	300
HOUSEHOLD CONNECTION (H)	58 × HH +4,386	5000
PREPARATORY WORKS	(C+E+D+H) × 10%	6000
CONTINGENCY COSTS	(C+E+D+H) × 15%	10,000
Total		**75,500**

where,

- Q - Turbine Discharge = 0.59 m^3/sec
- L - Length of Penstock = 10 m
- D - Diameter of Penstock = 1.75 m
- P- Maximum Power Output (kW) = 20.84 kW
- H_e - Effective Head (m) = 4 m
- X - Average Distance of House from the plant = 10 m
- HH - Number of Households = 9

The following sections list the items of direct cost in greater detail:

Electro Mechanical Works

- Turbine
- Controller
- Generator

- Dummy Load
- Accessories, Spare Parts and Tools

Distribution Works

- Transmission Pole
- Cable
- Transformer
- Accessories

Household Connection

- Cable
- Switch
- Accessories

Preparatory Works

- Location Setting Out
- Filling and Measurement
- Equipment and Materials Mobilization

6.2 Operating Expenditure (OPEX)

Akin to a conventional hydro system, the operating expense of a micro-hydro system depends on the size of the system, the head and the type of the turbine. Micro-hydro systems are quite reliable in the long term as compared to solar photovoltaic systems and wind turbines and the only maintenance required is to keep the intake filter clean of debris. Smaller systems generally have manually raked intake screens, while the larger capacity systems might deploy a automatically raked system or a self-cleaning coanda intake screen. These also include the refurbishment of mechanical and electrical equipment like turbine overhaul, generator rewinding and re-investments in communication and control systems.

The annual operational costs are about 4% of the total capital expenses [21] and amount to around **$3000** for the 21 kW system.

It is important to note that the cost of replacement of electromechanical equipment has not been taken into account since these are infrequent.

6.3 Net Present Value and Payback Period

The micro-hydro project would enable the community to reduce its dependence on the electricity obtained from the power grid and this would lead to potential economic savings. These economic savings form the revenue stream for this project and are used to compute the Net Present Value (NPV) of the project below using the following assumptions:

- Project Lifetime (N) = 50 years
- Minimum Attractive Rate of Return (i) = 5%

6.3.1 Annual Cost Savings

Average price of electricity in Ithaca = 9 cents/kWh.

Annual Cost Savings = 0.09 $\times$ Annual energy output from the turbine

Annual Cost Savings = 0.09 $\times$ 20.84 $\times$8760 $\times$ 0.5, where 0.5 is the capacity factor

Annual Cost Savings = $8250

6.3.2 Net Present Value

Net Cash Flow = Annual Cost Savings - OPEX

Discounted Cash Flow = Net Cash Flow $\times$ $\frac{(1+i)^N-1}{i(1+i)^N}$

Net Present Value = Discounted Cash Flow - CAPEX

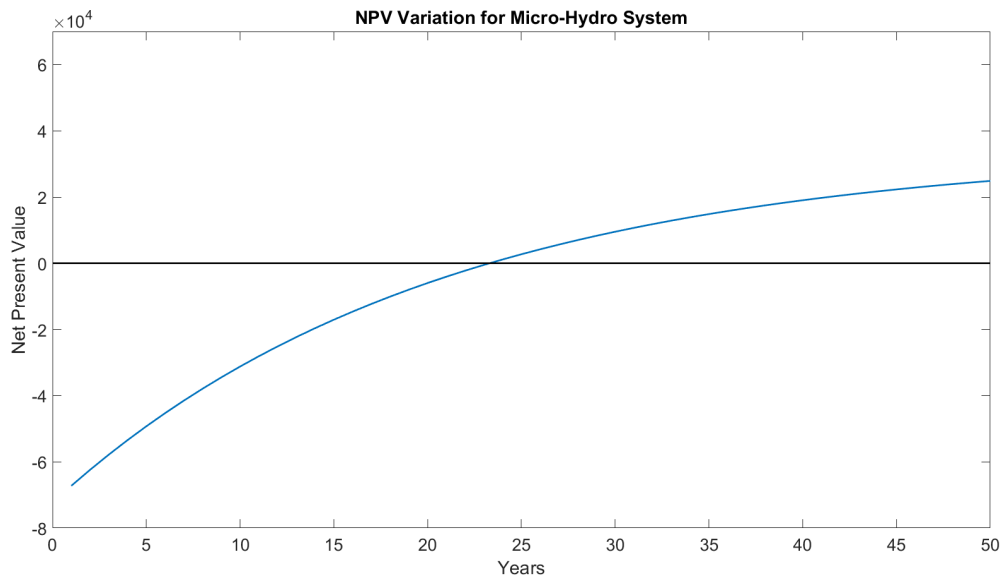

Figure 12: NPV Variation for a Micro-Hydro System

The NPV at the end of the project lifetime is approximately **$25,000**. This also gives us the upper limit of the cost that can be allocated for obtaining the DEC permit(s) necessary for implementing this project. If the cost of the permit is above $25,000, the project becomes infeasible over its lifetime.

6.3.3 Payback Period

The payback period is obtained when the Net Present Value becomes 0, which occurs when the original investment in the project is recovered by the net revenue stream from the project. In the Figure 12, this corresponds to the point where the NPV curve (blue) intersects the horizontal line (black).

Thus, for the micro-hydro scheme proposed in the earlier sections the payback period is **24 years**

6.4 Sensitivity Analysis

A basic sensitivity analysis is also conducted to apportion the uncertainty in NPV to the different sources of uncertainty in its inputs. The sensitivity is performed by varying the parameters as shown in Table 4 below with the baseline NPV as $25,000:

Table 4: Parameter Variation for Sensitivity Analysis

Factor	Base	Low	High
Electricity Price	\$0.09/kWh	\$0.08/kWh	\$0.10/kWh
System Capacity	21 kW	19 kW	23 kW
Electro Mechanical Works Cost	\$40,000	\$36,000	\$44,000
Civil Works Cost	\$14,200	\$12,800	\$15,600

Varying the above parameters yields the following tornado diagram:

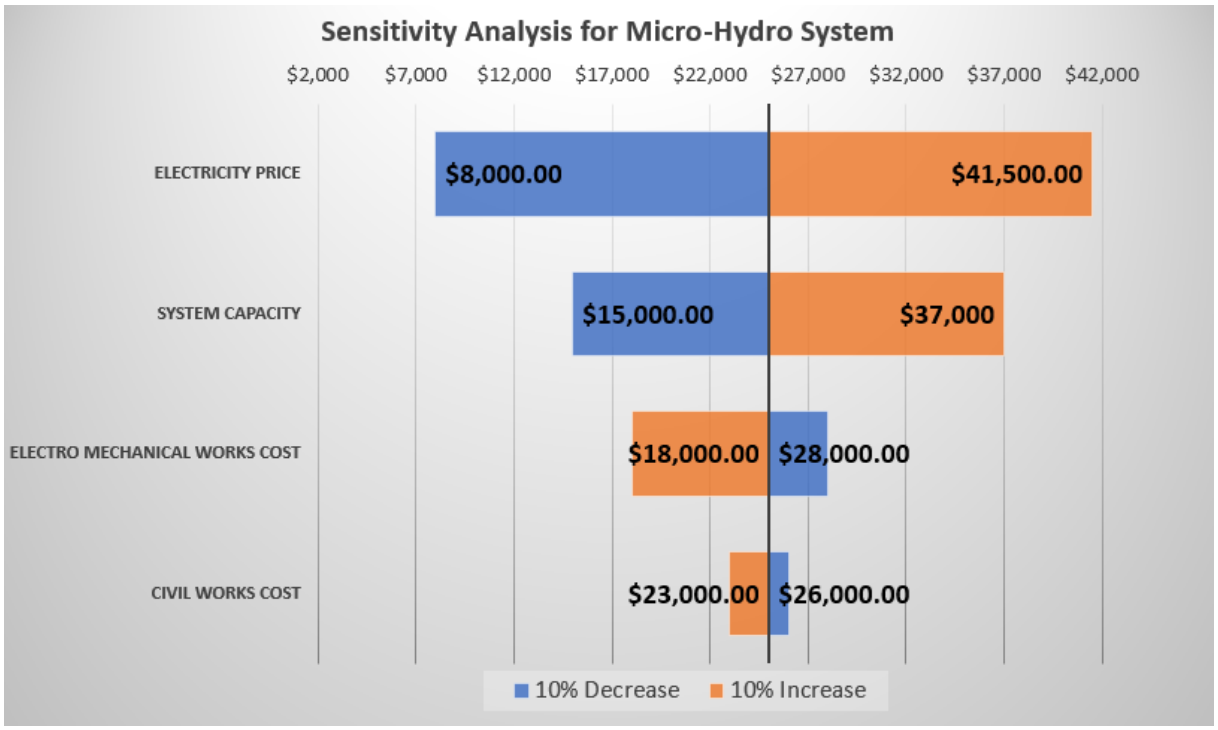

Figure 13: Sensitivity Analysis for Micro-Hydro System

From the above analysis, it is quite evident that the cost of electricity has a major role to play in Net Present Value of the project. The system capacity is the next most important parameter and a lower power output than the one estimated can result in negative NPV over the lifetime of the project. Again it needs to be kept in mind that the cost of the DEC permit has not been included in the sensitivity analysis presented above.

7 Solar Power for Caroline, NY

We discuss briefly the potential of a solar power system, such as a solar panels mounted on the top of homes or businesses, to serve as a comparison to the micro-hydro resource.

7.1 Energy Production

We consider here a system with a DC rating of 20 kW that can serve the community in Caroline, comparable in capacity to the estimated micro-hydro system of 20.84 kWW. We utilize the National Renewable Energy Laboratory (NREL) PV Watts Calculator to determine the energy output of a residential solar system [18]. We assume a standard module type with no tracking control, solar azimuth of 180°, and a panel tilt angle of 20°. Note that these latter two quantities vary from site to site. The standard module type has an efficiency of 15%, and system losses are assumed to be 14%, the calculator default. The calculator uses data collected at a weather station in Binghamton, NY, approximately 20 miles southeast of Caroline, NY. Given these input setting, the calculator estimates an annual energy output of approximately **24 MWh**.

7.2 Project Economics

In this section we calculate the NPV of the 20 kW solar photo voltaic system considered above and consider the following cost parameters as obtained from NREL [19]:

- CAPEX ($3500/kW) = $70,000
- New York State Incentives ($0.40/W) = $8000
- CAPEX after incentives = $62,000
- OPEX ($19/kW/year) = $380/ year
- Annual Cost Savings = $2160
- Net Annual Revenue = $2160 - $380 = $1780
- Project Lifetime = 33 years

We again consider a MARR of 5% for computing our discounted cash flow.

The NPV analysis yields then following graph:

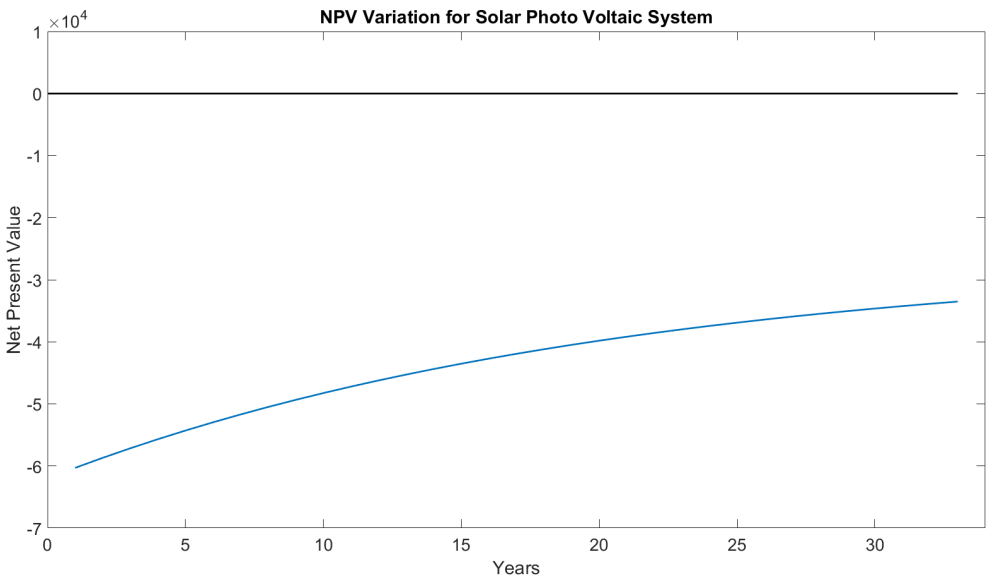

Figure 14: NPV Variation for a Solar Photo Voltaic System

The NPV of the solar photo voltaic system over its lifetime is obtained as **-$33,500** which makes this project infeasible. Thus, it is better to go with a 20 kW micro-hydro scheme rather than a 20 kW solar photo voltaic scheme as the former is feasible and yields a positive NPV over its lifetime.

8 Reduction in Carbon Emissions

Apart from obtaining economic benefits, the adoption of a micro-hydro system will also reduce the carbon footprint of the town and will be in line with the goal of EIC to achieve energy independence from fossil fuels on a residential level. This reduction in carbon footprint is quantified through the following calculations.

The energy mix of the Tompkins County is given below [23].

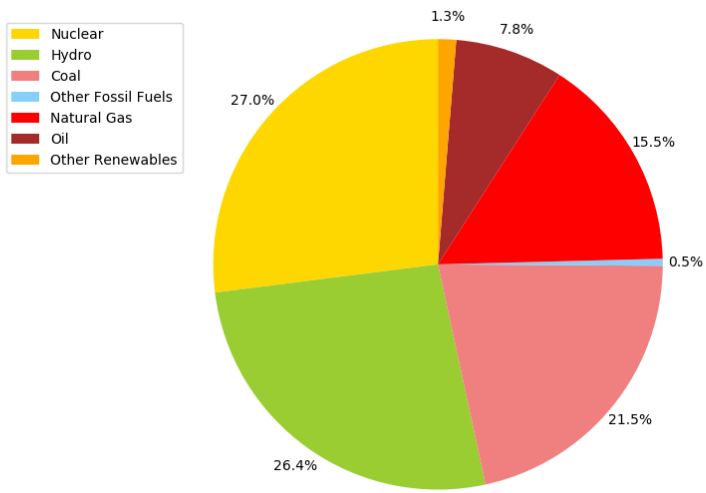

Figure 15: Energy Mix of Tompkins County

We also know the CO_2 emissions from generating 1 kWh of electricity from the following primary sources of energy:

- Coal - 1.2111 kg of CO_2
- Natural Gas - 0.4185 kg of CO_2
- Oil - 0.7653 kg of CO_2

Therefore, as per the energy mix of Tompkins County, the total carbon emissions per kWh of electricity produced is = 0.385 kg CO_2/kWh.

Since the annual power output from our micro hydro system is 91,500 kWh, the annual reduction in CO_2 emission would be 91,500 kWh $\times$ 0.385 kg CO_2/kWh $\approx$ **35 tons**. This carbon reduction analysis assumes that less electricity would be produced by other energy sources when the micro-hydro system is in operation. This is not in general true, however. In order to ensure that other energy sources would produce less electricity because of a micro-hydro system in Caroline, it would be necessary to purchase Renewable Energy Credits (REC's) or Zero-Emission Credits (ZEC's) from the New York State Energy Research & Development Authority (NYSERDA). One REC or ZEC may be purchased per MWh of electricity produced. REC's cost $21.16 per credit and ZEC's cost $17.5394 per credit. This corresponds to an estimated yearly REC cost of $1,930 or an estimated yearly ZEC cost of $1,570 given our estimated yearly energy production for a site. Prices will vary year to year and are to be purchased at the beginning of the year. By purchasing REC's or ZEC's, Caroline would be committing to producing the amount of electricity that corresponds to how many credits it purchased [25].

9 Conclusion

The sites visited along Six Mile Creek in Brooktondale show genuine micro-hydro potential. With even a modest head of 4 meters with the fluid volumetric flow rate variation given in Figure 10, an average power output of **20.84 kW** per system can be achieved. While only two sites were visited along Caroline, other sites with man made or natural head likely exist, and an effort should be made by the members of EIC to quantify the number of these sites. While run-of-the-river configurations without a dam or waterfall could be implemented, leveraging the gradual change in elevation along the river, their average power rating is a fraction of the high head configurations, only **2.73 kW**. We then make this estimate more conservative by halving it to account non-optimal operating conditions of the turbine (a capacity factor of 50%). Thus, we estimate the former configuration (Configuration 1) to produce **91.5 MWh** of electricity, and the latter configuration (Configuration 2) to produce **12 MWh** of electricity. In 2015, the average annual electricity consumption of a residential utility customer was 10.812 kWh [24]. Thus, one Configuration 1 system could produce enough electricity for 8 to 9 homes. One Configuration 2 system could produce sufficient electricity for about 1 home. Note that the capacity factor may not be this low in reality and that losses may not be so significant. Additionally, energy output for a year without a significant drought would be larger than the figures presented here.

Table 2 enumerates the instantaneous power output of a turbine subject to instantaneous stream discharge conditions. A Kaplan turbine is recommended for the Six Mile Creek stream conditions. Instantaneous power will vary on different time scales. Power will be high in winter months (provided there is no significant freezing of the stream water) and will be lower in the summer months. Within seasons there may be large rainfall events, causing large peaks in power for only short duration (on the order of a day to a week in time). During the summer months there is often insufficient flow for water extraction (see Figure 11), so power production may drop to zero in the summer months. Thus, the micro-hydro power resource along Six Mile Creek is a highly variable one. The system should be equipped with a means of energy storage, either via a battery or a connection to the grid, such that significant energy can be harvested on days of peak stream discharge. Solar power systems may be able to close the gap of energy production in the summer when solar irradiation is high, providing the opportunity of a symbiotic relationship between solar and micro-hydro power.

The terrain of Sites 1 and 2 prove a distinct challenge for construction of the system. The power house would be located within the banks of the creek and would require a containment structure to protect against flood events. A permit from the DEC would be required for the project, which would increase the project cost. The low-head sites would be more easily retrofitted with a micro-hydro system.

The viability of the project hinges upon the cost of any permits, DEC issued or otherwise. We estimate that a permit cost below $25,000 will allow for the project to break even (the project lifetime is taken to be 50 years). The cost of the permit will only be known after an

initial application has been reviewed and approved by the relevant agency. If we assume no cost for this permit, the break even point occurs after 24 years of system operation. Thus, the system requires at minimum 24 years to break even. If the permit costs do not exceed $25,000, then the project is viable. Underestimates of energy production would decrease the minimum break even period and would allow for larger permit costs, while overestimates of the energy production would make the minimum break even period larger and decrease the allowed range of permit costs.

Caroline stands to benefit from micro-hydro energy. Further project planning of the system, and knowledge of the specifications of the Kaplan turbine, will eliminate uncertainties in the analysis. If after submitting the project plan the costs of permits fall below the threshold of $25,000, the project will achieve a positive NPV at the end of the project lifetime. Finally, we find that a solar PV system of comparable capacity, 20 kW, is less economically feasible than our projected micro-hydro site of approximately 20 kW.

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