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Potential for Conduit Hydropower at NYC's Newtown Creek Wastewater Treatment Plant

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ABSTRACT

The Newtown Creek facility is New York City's largest wastewater treatment plant, with the capacity to treat up to 2.65 billion liters of combined sewage (rainfall and raw sewage) each day. After treatment at the plant, clean water flows out to the nearby East River via an outfall pipe. On average, the plant treats 810 million liters of combined sewage per day, which means there is potential to extract significant amounts of energy from the water flowing through the outfall. This paper first verifies that hydropower is a viable option at the plant by calculating the theoretical amount of power available from the running water, then determines what type of turbine would be the most appropriate for the outfall, and finally calculates how much electricity could realistically be generated by a turbine in the outfall. The bulb turbine was identified as the most appropriate type of turbine, and it was approximated that a bulb turbine in the outfall could produce, on average, 263 kilowatts of power. Considering that the plant runs year-round, a total of 2.24 gigawatt hours of clean electricity could be generated annually, which could be used to help power the energy-intensive wastewater treatment process or be fed back into New York City's electrical grid, where it could power up to 211 homes annually.

Introduction

Over the past ten years, New York City has received an average of 129 centimeters of rainfall, well above the global average of 100 centimeters ("Monthly & annual precipitation at Central Park," 2021; Wells et al., 2023). Because New York City's landscape consists mainly of concrete and asphalt, this rainfall is not absorbed by soil and vegetation as it would be in other areas, and therefore must be transported off of streets by drains and sewers. Considering that New York City has a total area of 790 square kilometers, this means that 1.019 trillion liters of rainfall is dropped on New York City annually, and must be transported off the streets quickly and effectively by the sewer system (Lankevich, 2023).

However, rainfall is not the only water that flows through New York City's extensive sewer system. It is generally assumed that the average American living in a modern residence generates 151-227 liters of wastewater per day, and the wastewater from New York City's 8.5 million residents must also be transported out of homes by the sewers ("Residential Flow Rates," 2002; "U.S. Census Bureau Quickfacts," 2021). This means that between rainfall and wastewater, there are significant amounts of water flowing underneath New York City, and thus significant amounts of hydropower can most likely be reclaimed from the sewer system.

In order to determine how much hydropower can be extracted from the system, it must first be determined where this water is flowing. 60% of New York City has a combined sewer system, with raw sewage and rainwater flowing together through the same sewers to wastewater treatment plants, where the water is treated and then dumped into nearby water bodies like the East River ("Sewer System," n.d.). This means that NYC's wastewater treatment plants are where the majority of this water flows, and would therefore be ideal sites for conduit hydropower systems.

Putting hydropower in wastewater treatment plants is not a new concept, and many wastewater treatment plants around the world are already using hydroelectric turbines in their effluent pipes to generate clean electricity.

These systems range in size from 4.2 megawatts to 15 kilowatts, and use a wide variety of turbines depending on specific conditions present at the plant ("North Head Wastewater Treatment Plant technical data sheet," 2020; O'Connor & Torrey, 2011). Wastewater treatment plants have already been identified as strong candidates for future hydroelectric developments, as hydropower could lower the high electrical bills that many plants receive, and because of the sheer number of plants and the amount of water that flows through them, with 15,000 plants processing 129 billion liters per day in the United States alone (O'Connor & Torrey, 2011).

In New York City there are fourteen of these plants, which treat a daily total of 4.92 billion liters of combined sewage ("Sewer System," n.d.). The largest of NYC's fourteen plants is the Newtown Creek wastewater treatment plant, which serves a total population of 1.068 million citizens, and a total drainage area of 15,656 acres across Brooklyn, Queens, and Manhattan ("Wastewater Resource Recovery Facilities," n.d.). During wet weather, the plant can treat up to 2.65 billion liters of combined sewage per day ("Wastewater Resource Recovery Facilities," n.d.). Because of the raw power that these significant amounts of water contain, it was determined that this plant would be the most appropriate for a hydropower system. This paper aims to verify that the plant is a viable site for hydropower by calculating the total power available, determining an appropriate turbine type, and then approximating how much electricity could realistically be generated and discussing how this electricity could be used. Although this paper only assesses the potential for hydropower at Newtown Creek, it is important to recognize that this same assessment could be done for the thirteen other wastewater treatment plants in New York City in order to reduce emissions from fossil fuel-based energy production and ultimately create a more sustainable future for the city.

Potential for Hydropower

Data

Once wastewater at the Newtown Creek plant has been treated, it flows through an outfall pipe from a couple of feet above sea level to the East River below. The pipe itself is 3.66 meters in diameter, and made out of reinforced concrete (Sadeghi, 2023). This is where the conduit hydropower system would be installed, and in order to verify that hydropower is a viable option for the plant, the total amount of power available from the water flowing through this pipe must be calculated. In order to perform this calculation, two main values are needed: the head of the pipe (also known as vertical run, which is how far the water will be falling as it travels through the pipe), and the flow rate through this pipe. While not available online, both of these values were provided by Demian Sadeghi, an engineer that works at the plant, via email.

According to Mr. Sadeghi, the approximate head of the pipe is about 3.26 meters, although it varies slightly with the tide levels and flow levels of the plant (Sadeghi, 2023). The value of 3.26 is obtained when assuming the mean tide level and average flow rate (Sadeghi, 2023). Mr. Sadeghi also provided a large dataset from the flowmeter at the mouth of the outfall with hourly average flow rates throughout the year. The overall average flow rate was 2477 liters per second, or 9.38 cubic meters per second (Sadeghi, 2023). For the entire raw dataset, see the Appendix.

Calculations

The following hydropower formula can be used to calculate the amount of power in the water flowing through the outfall, where P is power in watts, p is the density of water (which is a constant at 998 kg/m^3), g is acceleration due to gravity (which is constant at 9.81 m/s/s), h is the head in meters, and Q is the flow rate in cubic meters per second:

Equation 1: Total hydropower available in watts (not incorporating efficiency):

$$P = p \cdot g \cdot h \cdot Q$$

Plugging in the given values for head and flow in Equation 1, as well as the constants, we get:

$$P = 998\,kg/m^3 \cdot 9.81\,m/s/s \cdot 3.26\,m \cdot 9.38\,m^3/s$$
$$P = 299000\,kg \cdot m^2/s^3$$
$$P = 299000\,W$$
$$P = 299\,kW$$

Based on these calculations, there is an average of 299 kilowatts of power in the water flowing through the Newtown Creek outfall. This translates to roughly 7 megawatt hours per day, and 2.5 gigawatt hours per year. Although this value does not factor in the efficiency of the turbine, it demonstrates that there is a significant amount of power available to be harnessed from the outfall, and that further investigation into the potential for hydropower is warranted.

Proposed System

Flow Analysis

Although the plant has an average flow rate of 810 million liters per day (MLD), the flow is somewhat variable, which must be considered when determining what type of turbine is the most appropriate for the site. There are two main factors which influence the flow at the plant, which are rainfall and time of day, as more water is used by citizens at certain times of the day than others. The dataset for flow given by Mr. Sadeghi (the engineer at the plant) contained hourly average flow rates for each month of the year, and the standard deviation for the entire dataset was 129 MLD (Sadeghi, 2023). The maximum range between data points was 572 MLD, demonstrating that the flow at the plant is highly variable (Sadeghi, 2023).

Thus, the turbine needed for the Newtown Creek plant should be designed to handle low head and high flow situations (as the outfall has only 3.26 meters of head but an extremely high flow rate), as well as highly variable flows while maintaining a high efficiency. In order to find the most appropriate turbine, a systematic review was conducted with a decision matrix, where a total of five turbines were reviewed.

Turbine Options

When narrowing down what types of turbines could potentially be appropriate for the outfall, impulse turbines (turbines that use the kinetic energy of water to generate torque) can immediately be ruled out, as they require high heads to generate strong jets of water, and this is an extremely low head, high flow site. This leaves reaction turbines, which use a combination of pressure and the kinetic energy of the water to generate torque. The following figure can be used to determine which types of reaction turbines would be appropriate for the outfall (when referencing the figure, note that the head in feet of the outfall is approximately 10.7 and the flow rate in cubic feet per second is 331):

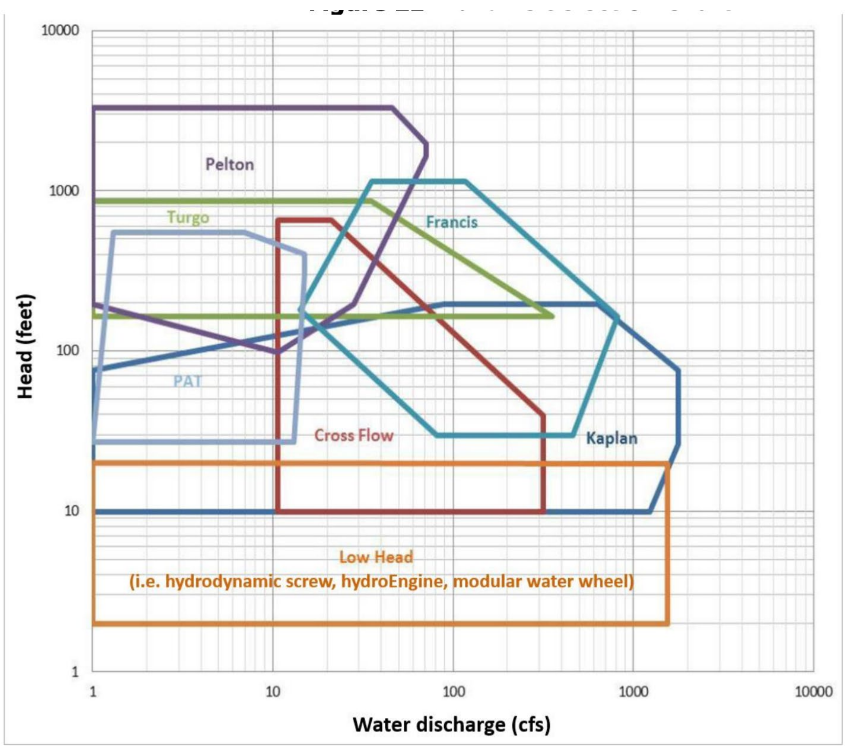

Figure 1. Appropriate turbine type based on flow rate and head (Badruzzaman et al., 2020).

Based on the above figure, it seems that crossflow, Kaplan, and low head turbines could all be appropriate for the outfall. Of the low head turbines, some of the most commonly used in conduits are bulb turbines, Archimedean screw turbines, and axial-type propeller turbine generator units, and thus these will be considered as well (Badruzzaman et al., 2020).

For context, crossflow turbines are conventional turbines which use gutter-shaped blades to harness the energy of flowing water (Badruzzaman et al., 2020). Meanwhile, Kaplan turbines were invented in the early 1900s, and use inlet guide vanes to direct water to adjustable, propeller-like blades (Badruzzaman et al., 2020). Bulb turbines use a very similar operating principle to the Kaplan turbine, except that the generator, runner, and wicket gate are all housed inside a "bulb" (hence the name) and the full device is placed inside the conduit (Badruzzaman et al., 2020). Archimedean screw turbines are a much newer technology, and essentially are large Archimedean screws which rotate as the water pushes on their helical flights (Badruzzaman et al., 2020). Finally, axial type propeller turbine generator units are similar to bulb turbines in that the entire apparatus is placed inside the conduit, but use a conventional propeller design instead of a Kaplan design like the bulb turbine (Badruzzaman et al., 2020).

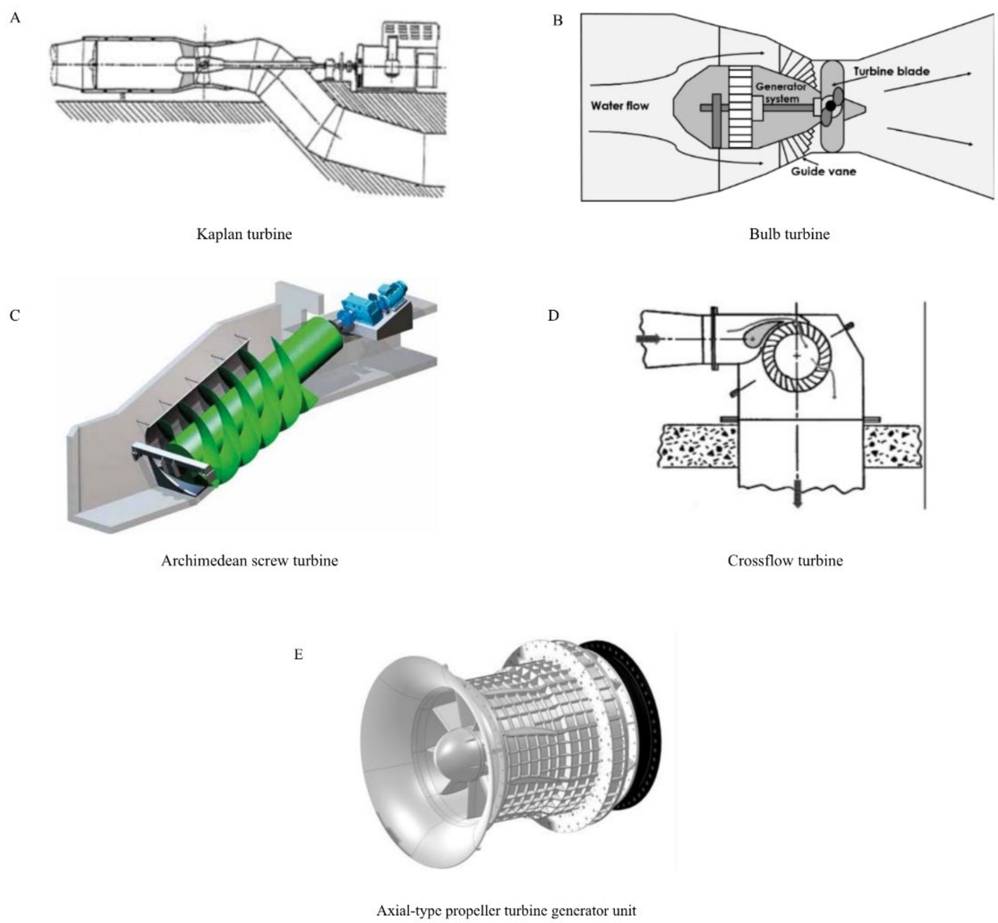

Figure 2. Diagram of each type of turbine (Badruzzaman et al., 2020).

Choosing a Turbine

When considering which of the above turbines is most appropriate for Newtown Creek, three main factors will be considered: how well they can handle varying flows, their maximum efficiency, and build viability (whether it can be installed in a 3.66 meter underground concrete tube). The turbines' ability to handle varying flows will be analyzed using their efficiency curves, which compare the turbine's efficiency to the percentage of its rated flow (the flow it was built to operate at). Turbines that can handle variable flows well will have flatter efficiency curves, as their efficiency will stay high no matter what the flow is at, and turbines that cannot handle variable flows will have steep efficiency curves, as their efficiencies will drop significantly once the flow starts to change from its ideal rated flow.

Cost will not be analyzed in this paper, as cost of installation is highly variable for unique conduit sites like this, and a more in-depth, onsite investigation would be needed for a truly accurate estimate. However, past conduit hydropower systems at wastewater treatment plants with similar capacities to this one have had total costs hovering near $2 million, but a payback period of just eight years (Badruzzaman et al., 2020).

For efficiency curves and build viability, each turbine was given a rating on a scale of 1-10, where 10 was most appropriate and 1 was least. The total score was then calculated by adding the maximum efficiency (in decimal form) to its two ratings for efficiency curve and build viability to get a comprehensive total score. To give a score for efficiency curve, the following efficiency curves were used. In this case, the bulb turbine has roughly the same curve

HIGH SCHOOL EDITION
Journal of Student Research

as the Kaplan, as they use the same mechanism of action (Badruzzaman et al., 2020). There is not any publicly available data about the efficiency curves of axial-type propeller turbine generator units, as they are still being researched and developed, but it is logical to assume its efficiency curve will be similar to the propeller turbine, as it uses the same mechanism of action as well (Badruzzaman et al., 2020).

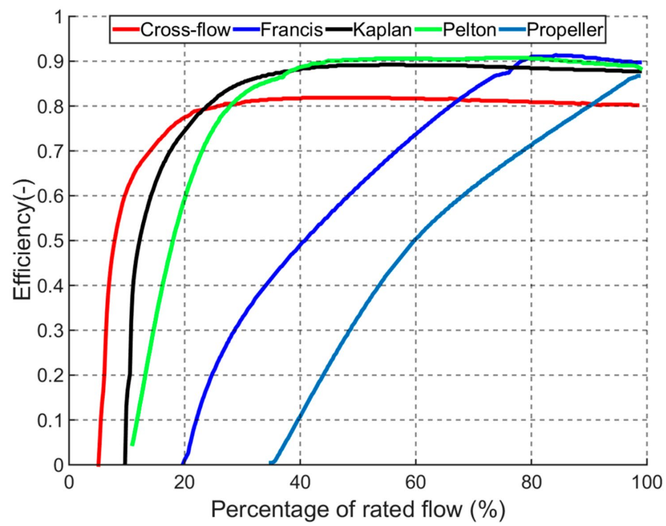

Figure 3. Efficiency curves for crossflow, Francis, Kaplan, Pelton, and propeller turbines (Woldemariam et al., 2018).

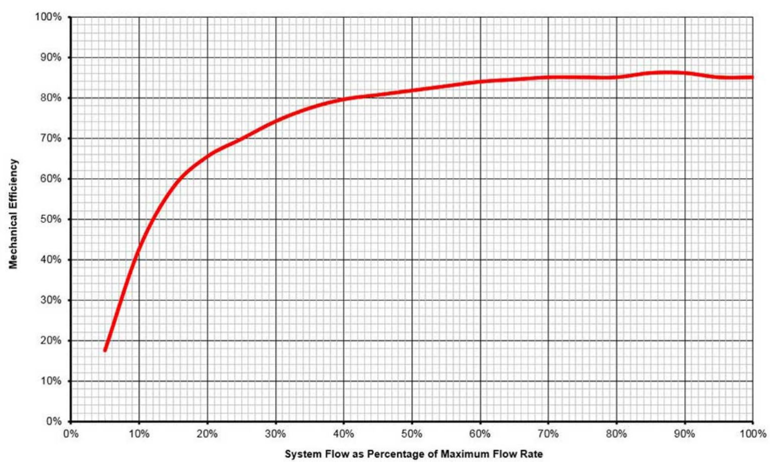

Figure 4. Efficiency curve for Archimedean screw turbine ("Archimedean screw hydro turbine," 2017).

Table 1. Decision matrix to determine the most appropriate type of turbine.

Turbine Type	Maximum Efficiency	Efficiency Curve (score on a scale of 1-10)	Build Viability (score on a scale of 1-10)	Total (max efficiency + efficiency curve score + build viability score)
Kaplan	94% (Abeykoon & Hantsch, 2017)	8 (flat efficiency curve up until 40% of rated flow)	5 (would require an external generator)	13.94

Bulb	95% (Darsono et al., 2022)	8 (similar to that of Kaplan)	7 (would not require an external generator, has a modular design)	15.95
Crossflow	74% (Costa Pereira & Borges, 1996)	9 (flat efficiency curve up until 20% of rated flow)	5 (would require an external generator)	14.74
Axial-type propeller turbine generator unit	92% ("Hydromatrix - Innovative Hydropower Solutions," n.d.)	3 (similar to propeller turbine, efficiency drops steeply at just 80% of rated flow)	7 (would not require an external generator, has a modular design)	10.92
Archimedean screw	90% (Johnson, 2018)	8 (efficiency doesn't start dropping steeply until 40% of rated flow)	4 (would require above-ground generator, pipe may not have appropriate slope)	12.9

Based on the total scores presented above, it seems that a bulb turbine would be most appropriate for this application. It has a high potential efficiency of 95%, can deal well with varying flows without significant decreases in efficiency (since it uses the same mechanism of action as a Kaplan turbine), and would not require an external generator house, since the entire generator is housed inside the bulb.

The Archimedean screw turbine was also a contender, with a good maximum efficiency and efficiency curve, and in recent years has become a common turbine used in wastewater treatment plant outfalls, but it was simply not viable for two main reasons (Badruzzaman et al., 2020). First of all, Archimedean screw turbines generally require a steep slope in the pipe, reaching their highest efficiencies at slopes between 20 and 24.5 degrees, and, based on the head of the pipe and how far it must run from the plant to the river, the Newtown Creek outfall is simply not steep enough (Sadeghi, 2023). Secondly, Archimedean screw turbines require a generator station above the pipe, and because in this case, the pipe is underground, it would be hard and expensive to build (Badruzzaman et al., 2020).

Traditional crossflow and Kaplan turbines had high total scores as well, but simply were not viable because they would also require an external generator, which would be very difficult to build considering that the pipe is underground. Thus, the Kaplan-based bulb turbine would be the most appropriate turbine for the outfall.

Discussion and Analysis

Efficiency Analysis

As was calculated in the "Potential for Hydropower" section above, there is an average of 299 kilowatts of power available in the water flowing through the outfall of the Newtown Creek plant. However, this figure did not factor in the efficiency of the turbine. If the bulb turbine were operating at a maximum efficiency of 95%, then a theoretical average of 284 (0.95 times 299) kilowatts could be generated (Darsono et al., 2022). But as was mentioned above with the efficiency curves, the flow at the plant is highly variable, and thus the actual flow rate will almost never be at the turbine's exact rated flow, and the turbine will almost never be running at maximum efficiency.

The average daily flow at the plant is 810 million liters per day, and using Mr. Sadeghi's dataset, a standard deviation of 129 MLD was calculated (Sadeghi, 2023). Theoretically speaking, the turbine should be built with a rated flow of 810 MLD, and if the standard deviation is 129 MLD, the actual flow will usually be about 129 MLD away from this rated flow. Thus, using some simple math, it can be calculated that the actual flow will generally be at 84% - 115% of the turbine's rated flow. This lower value (84%) is calculated by subtracting the standard deviation from the average, and the upper value (115%) is calculated by adding the standard deviation to the average, as shown below:

$$810\,MLD\ (rated\ \ flow) - 129\,MLD\ (StDev) = 681\,MGD$$
$$681\,MLD\ (realistic\ \ flow)\ /\ 810\,MLD\ (rated\ \ flow) = 0.84 = 84\%$$

$$810\,MLD\ (rated\ \ flow) + 129\,MLD\ (StDev) = 939\,MGD$$
$$939\,MLD\ (realistic\ \ flow)\ /\ 810\,MLD\ (rated\ \ flow) = 1.15 = 115\%$$

Using the efficiency curve for a Kaplan turbine above (which the bulb turbine is based on), and additional resources, it was found that the general efficiency of bulb turbines at 84% of rated flow is about 88%, and at 115% of rated flow, it is 92% (Tuhtan, 2007; Stople, 2011). Thus, based on this standard deviation, the turbine will generally be operating at efficiencies between 88% and 92%.

Total Electricity Generation

Assuming a conservative efficiency of 88% based on the above calculations, an average flow of 810 MLD, and that the turbine is running 355/365 days per year (to allow maintenance checks, etc), it can be calculated how much electricity would be generated annually. First, the amount of power generated assuming an 88% efficiency is calculated by multiplying the raw power available in the water by 0.88:

$$299\,kW \cdot 0.88 = 263\,kW$$

Then, the amount of energy generated each day can be calculated:

$$263\,kW \cdot 24\,h = 6312\,kWh$$

After that, the annual amount of electricity generated can be calculated, and then converted into more reasonable units:

$$6312\,kWh \cdot 355 = 2240760\,kWh$$
$$2240760\,kWh\ /\ 1000 = 2240\,MWh$$
$$2240\,MWh\ /\ 1000 = 2.24\,GWh$$

Based on these calculations, a total of 2.24 gigawatt hours of electricity could realistically be generated annually by a bulb turbine in the Newtown Creek wastewater treatment plant outfall.

Applications

As shown in the above calculations, while 263 kW may not seem like much power, over time it truly adds up, amounting to an annual total of 2.24 gigawatts of electricity. According to the US Energy Information Administration, the average American home uses just 10.632 MWh of electricity per year ("Green Power Equivalency Calculator," 2022). This means that annually, this hydroelectric system could power roughly 211 homes with clean, sustainable energy.

In order to get this power to homes, the electricity generated by the system could be fed directly back into the local community electrical grid and distributed to homes from there. This electricity could also be used to power technologies such as electric cars, and provide additional power to the grid during peak usage hours. Under the 2015 Community Distributed Generation order passed by New York state, local residents on the community's grid could also subscribe to receive this community-based clean hydropower and receive credits and compensation in return ("Community Distributed Generation," 2023).

However, the wastewater treatment process is also very energy-intensive, and thus the power generated by the hydro system could also be used locally at the plant ("Energy Data Management Manual," 2017). The Newtown Creek plant already has its own off-grid electric system, as they are planning on harvesting and using biogas from the solid waste that is collected to generate electricity for the plant ("DEP, EPA, and National Grid celebrate," 2023). Thus the energy from the turbine could also be fed into that same off-grid system and help power the plant itself.

Conclusion

Overall, this paper has demonstrated that there is a significant amount of energy just waiting to be harvested from the water flowing through the Newtown Creek plant, and that there are existing technologies that are appropriate for the job. Based on flow data provided by a plant engineer, an average of 263 kW of power could be generated, which translates to 2.24 GWh of electricity annually. Although more data and analysis is needed for a complete assessment of the site, this is a significant early sign that Newtown Creek has potential for hydropower.

It seems that the bulb turbine would be the most appropriate for the given site, and although an accurate price estimation cannot be given because of the unique nature of the situation (as it is an underground pipe, variable flow, uncommon type of turbine) without a more in-depth onsite analysis, bulb turbines are typically affordable because of their modularity, and conduit hydropower systems with similar capacities in wastewater treatment plants have been shown to have a payback period of just eight to ten years (Badruzzaman et al., 2020).

Newtown Creek could also potentially serve as a prototype location for this type of system, and if positive results are received, conduit hydropower could be installed at NYC's thirteen other wastewater treatment plants. Although there is very little data available about the other plants online, and Newtown Creek has the highest flow capacity, more research can be done into these other plants to investigate their potential for hydropower and ultimately move New York City towards a more sustainable future.

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