APPLICATION OF MICROTURBINES IN IMPROVING
THE ENERGY EFFICIENCY OF MUNICIPAL WASTEWATER
TREATMENT PLANTS IN MISSOURI.

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APPLICATION OF MICROTURBINES IN IMPROVING
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PLANTS IN MISSOURI

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ABSTRACT

Hydropower is a source of renewable energy. It is possible to combine a hydropower installation with an existing wastewater plant while ensuring it still performs its basic purpose. The multipurpose scheme would be integrated into the facility to generate hydropower while also fulfilling its primary role of treating wastewater. The wastewater plant can generate renewable energy and benefit from introducing microturbines. The turbine system is moved by the power in the flowing treated water that is transformed into mechanical energy which rotates the generator and in turn generates electrical power. In this work, the potential for power generation from the energy in the outflow along with the economics of the system in wastewater plants in the state of Missouri was investigated to improve the energy efficiency of the municipal wastewater treatment plants. Data like the daily flow rate, speed of flow, available head, etc about the wastewater plants in Missouri were collected and some interviews held with plant managers of the wastewater treatment plants. The investigation revealed that there are 127 wastewater treatment plants in the state of Missouri with 32 plants discharging less than 1 Mgd, 74 plants discharging between 1 Mgd and 5 Mgd, 13 plants discharging between 5 Mgd and 20 Mgd while just 8 plants had an outflow between 20 Mgd and 120 Mgd range. The flowrate helps in calculating and determining the theoretical and actual amount of power that can be gotten from the micro hydropower system in the wastewater treatment plant. For the actual amount of power gotten, the efficiency factor (efficiency of the turbine, and efficiency of the generator) of the generating system is considered. A brief study on the turbine system was conducted and a crossflow turbine was selected as the most suitable for the wastewater treatment plant as a vast majority of them had low head and high flow capacity. The analysis showed that out of the 127 wastewater treatment plants in the state of Missouri, only 21 treatment plants have the maximum potential to generate power and reduce operating costs. Also, two plants were selected for case studies. The operating cost is reduced because of the decrease in demand for electrical power from the grid. The 21 treatment plants have a daily outflow between 5Mgd to 120Mgd and could produce power through an axial flow turbine that utilizes the kinetic energy in the flow volume.

Chapter One

Introduction

1.1 Background

Since the dawn of civilization, there has always been a need for energy to improve humans' quality of life. This energy can be used for transportation, cooking, heating, cooling, etc. In the past, we have always depended on non-renewable sources of energy like coal, crude oil, natural gas, fossil fuels. All these when used or burned cannot be recovered again. Apart from being non-renewable, these forms of energy have the potential to be harmful to the environment. When used they can release toxins or harmful gases like carbon dioxide into the atmosphere that impact the health of human beings, animals, and plants. In recent times, there has been a need to find cleaner and reusable sources of energy for mankind's usage, in other words renewable or sustainable energy sources. Hydropower is a source of renewable energy [1]. It is naturally replenished and is a sustainable source. The energy, potential or kinetic, in the flowing water is captured and used to produce power in the form of electrical energy.

1.2 Hydropower and multipurpose scheme

Hydropower turbines can be put in municipal wastewater treatment works to generate electricity from the excess pressure in the incoming pipelines feeding the plant [2]. Beltran [3] suggested that wastewater treatment plants can generate renewable energy and benefit from introducing a micro-hydropower installation due to the low head large flow of waterfalls. As seen in Table 1, a lot of countries in the world are now installing microturbines in contemporary municipal water treatment plants. Thus, it is possible to combine a

hydropower installation to an existing wastewater plant while still ensuring it performs its basic purpose.

Table 1. Selected European case studies of multipurpose schemes [4]

Existing Infrastructure	Power plant name and country	Nominal discharge (m³/s)	Gross head (m)	Electrical Output (kW)	Electrical production (GWh/year)
Hydropower dam	Llys y Fran, Wales UK	0.16	25	29	0.22
Drinking water	Poggio Cuculo, Italy	0.38	28	44	0.36
Raw wastewater	Le Chable, Switzerland	0.10	449	380	0.85
Raw wastewater	La Louve	0.12	180	170	0.46
Treated wastewater	Seefeld, Austria	0.25	625	1192	5.50
Desalination plant	Tordera Spain	0.11	685	720	NA

European Small Hydropower Association (ESHA) [4], defines a facility that combines and incorporates a power plant into an established system or infrastructure to generate power and maintain its primary use as a multipurpose scheme. A multipurpose scheme can be a dam whose primary function is to store water for use, but a secondary function is added to the infrastructure to generate hydropower. In our case, we would be using a wastewater treatment plant. The multipurpose scheme would be integrated into the facility to generate hydropower while also fulfilling its primary role of treating wastewater. This multipurpose scheme can be done in two ways. Firstly, the hydropower can be incorporated before the wastewater reaches the treatment plant, where the wastewater from the networks flows through a penstock that has a turbine in it before reaching the wastewater treatment plant. The second option would be to install the hydropower after the wastewater plant. The treated water from the wastewater plant flows through the penstock fitted with a turbine before being disbursed into the waterworks or river. We would be using the second option as the water is free of debris and the flow rate would be higher. The flow rate would be higher because the water is free of debris. Debris or dirt make the water more viscous so it would flow less Hydropower is recovered by the turbine from the potential energy (due to change in elevation) and kinetic energy (due to velocity of the water) of the flowing water. The power used in moving the turbine system by the flowing water is transformed into mechanical energy which rotates the generator and in turn generates electrical power.

1.3 Objectives and scope of this investigation

This research thesis presents hydropower systems and formulas for calculating the amount of power and electrical energy that can be recovered from hydropower installations in wastewater treatment plants. The components and design of hydropower systems are also discussed. Turbine systems, types of turbines, and mode of operation have been reviewed.

The objective of this thesis is to improve the efficiency of municipal wastewater treatment plants in the state of Missouri through the use of microturbines to generate electrical energy. Case studies of two wastewater treatment facilities are presented and analyzed in this thesis. Furthermore, the power generation potential from municipal wastewater plants in Missouri that have a daily discharge of above 5 million gallons per day has been estimated.

Chapter 2

Literature Review

2.1 Hydropower systems

Jawahar [5] termed micro-hydropower systems as systems that generate electricity less than 100kW. Factors like water quality, reliability of flow, nearby use of generated electricity, and environmental factors are crucial when planning the installation of a low head hydropower system [2]. The flow rate of water and the pressure of the head are important parameters for hydropower; a viable hydropower source would be any facility or infrastructure that has anyone or both parameters e.g., a drinking water treatment plant, wastewater treatment plant, a dam, stormwater drainage runoff, etc. Saket [6] divided small hydropower systems into two, with micro-hydropower systems (MHPS) having a capacity less than 100kW and mini-hydropower having a capacity less than 1,000kW. In his work, he highlighted that the choice of turbine depends mainly on the head and the design flow for the micro hydropower installation. He also gave formulas to calculate and determine the theoretical and actual amount of power that can be gotten from a micro hydropower system. The theoretical amount of power is given as:

$$P_{th} = Q \times H \times g \quad (1)$$

Where:

Q = flow rate (m³/s)

H = water head (m)

g = gravitational acceleration (m/s²)

For the actual amount of power gotten, the efficiency factor (caused by frictional losses in the pipes, efficiency of the turbine, and efficiency of the generator) of the generating system is considered.

$$P_{act} = Q \times H \times g \times e \quad (2)$$

With e generally being between 50 and 70% and greater efficiency occurring in systems having a high head. Beltran [3] suggested a slightly similar formula for the calculation of hydroelectric potential but took into consideration the water density in his equation:

$$P = \eta \times Q \times \rho \times g \times H \quad (3)$$

P = power (kW)

η = efficiency of the micro-hydro installation (turbine, generator, and gearbox efficiency)

ρ = density of water (kg/m³)

From the equation, we can see that doubling the water head doubles the power generated.

Furthermore, the electrical energy that can be generated is given by:

$$E = \eta \times \rho \times g \times H \times A \times h \quad (4)$$

Where:

E = Electrical energy (kWh)

A = Annual average water flow (m³/s)

h = annual operating hours

We can classify hydro turbines into two main groups, impulse and reaction turbines [7]. The impulse works by the action of water moving the turbine runner blades. In general, the impulse turbine is adequate for high-standing water (high head) and low flow application.

Examples of impulse turbines include the Pelton turbine and the crossflow turbine. On the other hand, we have the reaction turbine which works due to changing the pressure of the water as it passes through the turbine. Reaction turbines are particularly useful in low head and high flow applications. The propeller, bulb turbine, straflo turbine, tube turbine, Kaplan turbine, and Francis turbine are examples of reaction turbines. An important criterion used in determining the right type of turbine to use is the available water head and the available flow rate: we also need to consider the position of the turbine [3].

Haidar [8] grouped turbines into three parts according to their various head, namely:

1. High head for high standing water less than 100m (Pelton wheel)
2. Medium head for high standing water between 40 and 100m (crossflow and Pelton wheel)
3. Low head for standing water of height below 40m (Kaplan turbine)

Beltran [3] appraised turbines under 10MW as smaller turbines and considered large Kaplan and Francis turbines as the most suitable for the available head because of their vertical shaft, unlike the small turbines which are mostly produced with horizontal shaft. They also discussed that due to the size of the Pelton turbine being less than the available head, a Pelton turbine can be mounted either horizontally or vertically. In research by [9], they examined the potential of split reaction water turbine and found it to be useful in low head micro-hydro-electric applications. Their analysis found the turbine to have a hydro to mechanical energy conversion efficiency of about 65 – 70% and would work better when it spins faster. Also, if the diameter of the reaction water turbine is made smaller at a continuous water head, the turbine would spin faster. Operating between a head of 2m and 40m, [10] designed four separate micro-hydro propeller turbines working at a particular rate. The turbines were designed to withstand debris and particles reaching a hydraulic efficiency greater than 68%.

The most important factor to consider in the generation of hydropower is the performance of the turbine which generates electricity by the rotating movement of the shaft [11].

We can use Bernoulli's equation to calculate the energy head of water flowing in an enclosed pipe or penstock. Bernoulli's equation brings into consideration the kinetic energy in the water, the pressure energy in the water, and also the potential energy. The equation is given by

$$H = h + \frac{P}{\gamma} + \frac{V^2}{2g} \quad (5)$$

Where:

H = the total energy head in the flowing water

h = the height or vertical distance

P = the pressure

γ = the specific weight of water

V = the velocity of water (m/s)

g = the acceleration due to gravity

The DarcyWeisbach equation gives the means to calculate the head loss due to friction of flowing water in a pipe. The formula is given by

$$h_f = f \cdot \left(\frac{L}{D}\right) \cdot \frac{V^2}{2g} \quad (6)$$

Where:

h_f = head loss due to friction

F = friction factor

L = length of pipe (m)

D = cross sectional diameter of the pipe (m)

V = velocity of flow (m/s)

g = acceleration due to gravity(m/s^2)

A decrease in the total energy head of the water can be a result of bending in pipe connections, valves, flow from a larger pipe to a smaller pipe, and friction. There can also be a loss of energy if there is a debris screen, rack, or filter before the water goes into the turbine. The total energy head in the flowing water can reduce due to the internal friction of the flowing water as it mixes at high turbulence and friction that occurs as a result of the water being in contact with the walls of the pipe. Hence, it is important to take into consideration the surface roughness of the material used in making the pipe or penstock. For screen frictional losses, the Kirschmer formula gives an estimate of the number of losses suffered [12]. The equation is given as

$$h_f = Kt \left(\frac{t}{b} \right)^{4/3} \left(\frac{V_0^2}{2g} \right) \sin \theta \quad (7)$$

Where:

h = frictional head loss due to screen

t = screen bar thickness (mm)

b = width between bars (mm)

v = approach velocity (m/s)

g = acceleration due to gravity (m/s^2)

θ = angle of inclination from horizontal

K = screen loss coefficient (differs for bars of different shapes)

As water moves from a larger pipe or penstock into a smaller pipe, there is a loss of head associated due to the sudden contraction or expansion of water in the smaller pipe. The loss of the head is due to the increase in velocity of the moving water and the increase in turbulence associated with it. The formula for the contraction head loss is given by

$$h_c = K_c \cdot \left(\frac{V_2^2}{2g} \right) \quad (8)$$

Where:

h_c = head loss due to contraction

v = velocity of flow

g = acceleration due to gravity

K_c = a coefficient given by the formula

$$K_c = 0.42 \left(1 - \frac{d^2}{D^2} \right) \quad (9)$$

d is the smaller pipe and D is the bigger pipe or conduit.

For a case of expansion, a similar formula is used with the flow momentum.

$$h_{ex} = \left(1 - \frac{d^2}{D^2}\right) \frac{V_1^2}{2g} \quad (10)$$

V_1 = speed of water in the smaller conduit

V_2 = speed of water in the bigger conduit

It is important to note that the loss of head as a result of expansion and contraction can be mitigated using conical transition like a conical diffuser for expansion and a conical confuser for contraction [13]. Some of those equations like equation [7] are used for dams or river hydropower installations. The waste water treatment plants do not need screens or filters as the turbines are installed after the water has been treated. Equation [8-10] are used if there are a lot of bends, curves, and contractions in the pipe carrying the water, most wastewater plants avoid having this situations so it only happens in outdoor cases with uneven terrains.

2.2 Design, components, and configuration of the hydropower system

1. Intake and Penstock

2. Turbine system

3. Powerhouse

2.2.1 Intake and penstock

One of the fundamental infrastructures of a hydropower system is the intake and penstock network. A penstock is a pipe that carries water from the intake or reservoir into the turbine system [14]. Penstocks are sometimes pressurized due to the flow velocity of water coursing through it. Hence, they can be subjected to flow disturbances and pressure surges caused by valve settings, water hammer surges, sudden expansion or contraction in the pipe network [15]. In a research by [16] on how mechanical power can be affected by changing penstock

parameters, they found out through MATLAB/Simulink software that the water hammer effect on the mechanical power would reduce with an increase in the length, diameter, thickness of the penstock, and the material used for the penstock. It is important to know if the penstock can accommodate the addition of a turbine due to the water hammer effect from the closing and opening of the valves. Penstock materials can include fabricated welded steel, spiral machine welded steel, ductile iron 1, polyethylene plastic (PE14), glass-reinforced plastic, and even concrete. Either fabricated steel pipes or ductile iron can be used for large heads and diameters while flow involving low heads and diameter make PVC or polyethylene plastic pipe favorable. To determine if a penstock material and thickness is suitable for a particular flow, the pressure wave speed formula is used:

$$c = \sqrt{\frac{10^{-3}k}{\left(1 + \frac{kD}{Et}\right)\rho}} \quad (11)$$

where:

c = pressure wave speed in m/s

k = bulk modulus of water in N/m²

E = modulus of elasticity of pipe material in N/m²

t = wall thickness in mm

Typically, due to the modulus of elasticity of steel and its stiffness, pipes made of steel are able to withstand more surge pressure than PVC pipes. An easy option would be to contact the pipe manufacturer and ask for the maximum working pressure or pressure rating for

which the pipe was designed, and the allowable conditions like a factor of safety and allowance for pressure surges.

2.2.2 Turbine system

The turbine system includes the Hydraulic turbine, generators, turbine control, switchgear system, and ancillary electrical equipment like plant service transformers, DC control power supply, and transmission cables.

(a) Hydraulic turbine

According to [17], hydraulic turbines act as prime movers which transform falling water's energy into rotational mechanical energy. With generators attached to the turbines, the rotational mechanical energy is then converted into electrical energy as a source of power. The hydraulic turbine is made up of a row of blades placed on a rotating shaft. The rotation of the shaft is due to the pressure of the water in contact with the blades and the difference in velocity. The hydraulic power of a turbine in watts is given by the equation:

$$P_h = \rho Q \cdot gH \quad (12)$$

Where:

ρQ = mass flow rate in Kg/s

ρ = specific density of water in kg/m³

Q = Discharge in m³/s

gH = specific hydraulic energy in J/kg

g = acceleration due to gravity in m/s² = 9.81

H = Total Head in m

In terms of the efficiency and mechanical output of the turbine

$$P_{mec} = P_h \cdot \eta \quad (13)$$

Where:

P_h = turbine hydraulic power

η = efficiency of the turbine

Generally, turbines are classified based on the difference or change in the pressure of the flowing water when it moves through the rotor. The two main classifications are impulse and reaction turbines. Figure one shows the analysis and breakdown of each classification.

Fig 1. Classification of hydraulic turbines based on the effect of the pressure of the flowing water on the turbine runner.

Impulse turbines

In impulse turbines, as water enters the turbine runner, the pressure of the water is transformed into kinetic energy with high velocity. The impulse works by the action of water moving the buckets on the turbine runner. The pressure remains constant, but the velocity of the water decreases as the kinetic energy has been recovered by the turbine. The impulse turbine includes the Pelton turbine, Turgo turbine, and Cross-flow turbine.

(i) Cross-flow turbines

The cross-flow turbine, also called the Banki Michell [18] has a peak efficiency that is less than the Pelton, Francis, and the Kaplan turbine but has a relative efficiency for a wide range of head (between 5m and 200m) that partly coincides with the Pelton, Francis, and the Kaplan turbine. [19] presents a cross-flow turbine as a simple, cheap, and efficient turbine choice for hydropower energy generation. It operates with the flowing water entering the turbine through a nozzle, the water is then guided by the vanes into the blades at an inclined angle to increase efficiency [20]. Although the Cross-flow turbines have a lower efficiency when compared to other turbines, redesigning the nozzle using an analytical model that transforms the head into kinetic energy at the inlet increases the maximum efficiency from 69% to 87% [21]. Its application across a different range of flows and heads is shown below [22]. From the figure, we can see that the Cross-flow turbine partly covers the Turgo, Kaplan, Francis, and even the Pelton turbine in a range of applications.

Fig 2. The range of flows for a cross-flow turbine as it cuts across other types of turbines.

(ii) Turgo turbine

A type of impulse turbine that is quite suitable under medium and high head application is the turgo turbine [23]. Its mode of operation is similar to a Pelton turbine as they both use the spear injector and nozzle system to modulate flow; with the turgo turbine the bucket is shaped differently and a jet of water strikes axially on an incline blade or runner [22,23]. The turgo turbine was invented by Eric Crewdson. It can operate under a head range of 50m to 300m. According to the manufacturer Gilkes [24], the turgo turbine can operate under low flow conditions, and its efficiency increases and exceeds a Francis turbine as the volume of flow of water starts to recede. The relation between power and energy with regards to the high, medium, and low flow is shown in the figure below.

	Francis		Turgo	
	Average Power (kW)	Energy (MWhrs)	Average Power (kW)	Energy (MWhrs)
High Flow	472	702	437	650
Mid Flows	221	466	242	508
Low Flows	0	0	56	144
Total	<u>N/A</u>	1,169	<u>N/A</u>	<u>1,304</u>
Average	132	11.57	147	12.91

Fig 3. Relationship between power and energy for high, medium, and low flows

The manufacturer Gilkes, also stresses that the Turgo turbine can shield the penstock from water hammer and pressure surge in the event of loss of flow load through deflectors that are installed in the turbine making it suitable for energy recovery in water treatment plants.

Fig 4. A Gilkes Turgo turbine installed in a plant

(iii) Pelton turbine

Made up of bucket and injectors, a Pelton impulse turbine operates as a result of a high-velocity jet of water from an injector hitting buckets on a disk wheel perpendicularly so that the highest torque is placed on the rotor. Like all impulse turbines, the kinetic energy in the jet of water changes as it moves through the turbine and propels the runner. This is due to the pressure in the water being converted into kinetic energy by the injector. Its defiance to pressure variation, low installation, and maintenance cost, is a result of the turbine being installed with an open casing [25,26]. Pelton turbines are mostly used in an application having high heads from 60m to up to 1000m, making them suitable for wastewater treatment plans having high heads. Although a Pelton turbine system can have a high efficiency from 30% to 100% for the highest flow from a one jet turbine system, the runner buckets, injection nozzle, seat rings can be subjected to damage as a result of cavitation, silt erosion, and failure as a result of the cyclic load or force that is applied to the runner. [26,27]. These erosion and cavitation damages can cause rotor mechanical failure, maintenance cost increase, turbine

repair downtime increase, bring about a reduction in the performance and efficiency of the turbine with time [28,29].

Reaction turbine

For reaction turbines, a force is applied on the runner blades by the pressure of the water as it moves through the turbine. This pressure reduces after the water flows through the turbine vanes while the speed of the water relative to the runner blades increases; all these bring about a change in the momentum and absolute velocity [30]. To overcome and support the operating pressure as a result of the runner immersed in water, the turbine casing of these turbines must be made strong. The Francis, Kaplan, and propeller turbines are types of reaction turbines.

(i) Francis turbines

Francis Turbines are suitable for medium heads between 25m and 350m. This reaction turbine enclosed in a spiral casing operates with guide vanes and runner blades. The spiral casing directs the water to the stay vane inlet and spreads the water across the guide vanes and stay vanes. The stay vanes connect the bottom ring and head cover and also provide the guide vanes with the flow of water at a spiral angle to reduce the loss of head and increase hydraulic torque. The flowing water is then guided by the guide vanes into the runner. The runner converts the hydraulic energy in the water to mechanical energy, then runs the water to the draft tube which recovers the remaining kinetic energy in the flowing water [31]. The placement and configuration of the Francis turbine can be in an open flume setting for low head, medium head using spiral casing, or positioned in a horizontal or vertical design [32]. The Francis turbine can be used for up to 25MW with some manufacturers like Gugler technology (see the picture in figure below) machining the turbine runner out of forged stainless steels and welding is made for large runners [32,33]

Fig 5. A Gugler Francis turbine and its generator installed in a facility

(ii) Propeller, Kaplan, and Bulb turbine

The propeller and Kaplan turbines are a type of reaction turbine that is generally used in low head and large flow capacity hydropower plants. The mode of flow is axial in these turbines. Having several blades that vary the incidence of flow angles, the adjustable runner of the Kaplan turbine can ensure optimum performance is reached [34]. If the guide plane is adjustable it is called single regulated while it is called double regulated if the guide vanes and blades are adjustable. The Propeller turbine is a fixed runner blade Kaplan turbine system [35]. The bulb unit is also a type of double-regulated Kaplan turbine that is suitable for low head applications that may vary [36]. The waterproof bulb unit contains a generator and gearbox in some cases.

Choice of turbine

The choice and criteria used in selecting a turbine for a hydropower plant or wastewater treatment plant include:

- Total Head

There is a need to take into account the total head of the plant. For reaction turbines, the head would be the vertical distance from the upper level to the lower level. Lancaster University Renewable Energy Group (LUREG) [37], gives a software evaluation tool that suggests which turbine would be suitable by simply inputting the head and the corresponding flow rate. The range of gross head for each turbine type and efficiency is shown in the table below

Table 2. Minimum and maximum head range of turbines and their efficiencies

Turbine Type	Classification	Minimum head (m)	Maximum head (m)	Efficiency (%)
Propeller and Kaplan	Reaction	2	40	92
Cross-flow	Impulse	5	200	86
Francis	Reaction	25	350	94
Turgo	Impulse	50	300	85
Pelton	Impulse	60	above 1000	90

- Flow rate and Discharge

The flow rate is an important criterion in choosing a suitable turbine as different turbines have different capacities of flow. A deviation from the required flow will bring about a decrease in the efficiency of the turbine system.

- Specific Speed

It is important to know the specific speed of a turbine from the manufacturer before installing the turbine. The specific speed of a turbine runner is given by the equation by

$$n_{QE} = \frac{n \cdot \sqrt{Q}}{E^{3/4}} \quad (14)$$

Where:

Q = Discharge in m³/s

E = Hydraulic Energy in J/kg

n = rotational speed of the turbine in t/s [turns per second, can also be in rad/s]

(b) Generators

The function of the generator is to convert and transform mechanical energy into hydraulic energy. The generator for the turbine can be synchronous or asynchronous. Synchronous generators have a direct current electric system coupled with a voltage regulator to adjust and meter the output voltage that the generator will transmit to the grid. For asynchronous generators, they use their magnetic field to absorb reactive energy and draw current from the

grid. In the event of being disconnected from the grid, asynchronous generators cannot produce their own excitation current hence generating electricity will be made impossible. Although being unable to produce their own excitement is a major demerit, asynchronous generators are inexpensive and can be used in applications requiring a low supply of electricity

(c) Turbine control system

The turbine control system is used to adjust the operating condition of the turbine in the event of loss of load or load rejection, loss of generation, faults, water hammer dynamics, etc [38]. Some of the turbine controls include wicket-gates, surge tanks in some systems to prevent water hammer, vanes, valves, speed governors to monitor and adjust speed deviations, switchgear systems to control the generators and connect them to the grid, the generator breaker to disconnect or connect the generator to the electrical grid, circuit breakers and automatic control systems.

2.2.3 Powerhouse.

The powerhouse like the name suggests houses the power components of the hydropower scheme. Its primary function is to store and protect the equipment from harsh weather conditions like rain and snow, and also prevent unwanted interactions with the hydropower equipment. Some of the components that can be in the powerhouse include the turbines, generator, control system and panels, switchgear, switchboards, transmission lines and wirings, storage equipment, etc. The size of the powerhouse building and cost depends on the size of the turbines, generators, and electromechanical equipment in it [39]. Depending on the

size, configuration, and nature of the wastewater plant, a powerhouse might not be needed if the turbine, generator, and control equipment can be enclosed in a single waterproof unit.

2.3 Evaluation of turbine for this study

Some turbines are good for small flows and others are good for high flows. In selecting a turbine, we had to consider where it will be installed, the available head, the type of flow, the cost of the turbine, and the efficiency of the turbine. We would be using the crossflow turbines in our two case studies and the other wastewater treatment plants because the crossflow turbine is a simple, cheap and efficient turbine. As shown previously in figure 2 above, the crossflow turbine denoted by a black line envelope has a range of application of flowrate from 0.2 m³/s to 10 m³/s and a hydraulic head of 2 meters to 200 meters. The two-case studies flowrate and available hydraulic head fall between this range. Joplin Turkey Creek had an average flow rate of 0.96 m³/s and an available head of 4.57 meters. St Joseph wastewater treatment plant had a flow rate of 0.96 m³/s and an available head of 20.37 meters. The highest flow rate of the wastewater treatment plants is 120 Mgd (5.26 m³/s) which is within the operating range of the crossflow turbine. With the crossflow turbine being relatively cheaper than the other turbine types and having an efficiency of between 78% to 86%. This makes the turbine type suited for the type of flow we have in the wastewater treatment plants.

Chapter 3

Methodology

3.1 Data Collection

Preliminary data was obtained from the Missouri Department of Natural Resources (MO-DNR). Data included the number of wastewater treatment plants in the state of Missouri, the location of the plants, the actual permit flow, design permit flow, and plant contact personnel. For some of the plants with omissions, the information needed (like plant contact person) was extracted from the treatment plant website. Each wastewater treatment facility is separated into 4 categories below according to the actual permit flow:

1. Less than 1 Mgd
2. 1 Mgd to 5 Mgd
3. 5 Mgd to 20 Mgd
4. 20 Mgd to 120 Mgd

Facilities with an actual permit flow from 5 Mgd to 120 Mgd were contacted. European Small Hydropower Association (ESHA) [4], suggested a feasibility study be done before deciding if installing a hydropower system in a wastewater plant would be viable. The wastewater plant managers or engineers were contacted through phone calls and email. The following key questions were asked:

1. What is the annual average flow rate? The annual average flow rate is needed to get the firm energy. The firm energy is the minimum amount of energy the wastewater plant can generate at any given time.

2. Are there seasonal variations in the flow of water?
3. Do we have the flow duration curve with daily data?
4. What is the maximum flow rate?
5. Will the microturbines impact the water quality and process in the wastewater plant?
6. What is the height or elevation of both the inflow and outflow water levels?
7. Will it be easy to get authorization for the project and will there be future public opposition?
8. Would you be interested in us visiting the wastewater treatment facility for an industrial energy audit and an onsite visual inspection?

After these questions are asked and answered, the response was used to determine if the treatment plant is feasible for us to visit and do an assessment. Of the facilities interviewed, two of them were chosen as case studies and visited for further analysis.

3.2 Data analysis and calculations

The data analysis and calculations were grouped into two tasks, namely,

- Maximum power and sustained electrical energy analysis
- The cost of implementation and economic viability.

3.2.1 Maximum power and sustained electrical energy

To get the maximum theoretical amount of power that can be recovered through the hydro turbine installation, Beltran's [3] formula for the calculation of hydroelectric potential was used. Consideration for the density of water was used in his equation. The density of water is needed and it is taken as 1000.[kg/m³]

$$P_{th} = \rho \times Q \times H \times g \quad (3)$$

Where:

P_{th} = Power (watts)

ρ = water specific density (kg/m^3)

Q = maximum flow rate (m^3/s)

H = water head (m)

g = acceleration due to gravity ($\sim 9.8 \text{ m/s}^2$)

Applying the density makes the units balanced in the final calculation to get the power.

$$P = \text{kg/m}^3 \times \text{m}^3/\text{s} \times \text{m} \times \text{m/s}^2 \times 0.71 \text{ (efficiency)}$$

$$P = \text{kgm}^2/\text{s}^3 = \text{SI unit of watts}$$

For the maximum actual amount of power that can be extracted, the efficiency factor e is considered. The efficiency factor considers the efficiency of the turbine, the efficiency of the turbine generator, the efficiency of the drive system (includes frictional loss of energy in penstock or pipe)

$$P_{act} = \rho \times Q \times H \times g \times e \quad (4)$$

For the sustained electrical energy, the formula below was used to calculate the amount that could be generated from the wastewater treatment plant.

$$E = \rho \times H \times g \times e \times A \times h$$

Where:

E = kWh

A = Annual average water flow

h = annual operating hours

3.2.2 Cost of implementation and economic viability

The cost of implementation includes parameters like the cost to purchase the turbine, turbine generator, drive system, wiring, control systems, and the powerhouse components. The engineering consultation fee and cost of installation were included. To get the cost of implementation, hydropower and turbine installation contractors were contacted for an estimate and quote. This helped us in determining the economic viability and if the project was feasible. Beltran [3] presented the methods for determining the economic viability of the project. The three methods are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Payback method (PB). Of the three methods, the payback method was used in our analysis. It is a simple method that uses the time required to get back the cost of implementation and the yearly savings accumulated because of the implemented project. The simple payback is calculated by the formula below:

$$\text{Payback} = \frac{\text{The total cost of implementation}}{\text{Annual savings}}$$

Chapter 4

Results, Data Analysis, and Conclusion

4.1 Results

From the data we got, the state of Missouri has 127 wastewater treatment plants with flows ranging from as low as 0.4 Mgd to 120 Mgd. Each facility was separated into 3 categories ranging from:

1. Less than 1 Mgd = 32 Facilities
2. 1 Mgd to 5 Mgd = 74 facilities
3. 5Mgd to 20Mgd = 13 facilities
4. 20Mgd to 120 Mgd = 8 facilities

Data like the location, permit actual flow rate, design flow rate, of the wastewater plants in Missouri, were collected. From the 127 wastewater treatment plants, 21 of them had a flow between 5 Mgd and 120 Mgd. The permit design flow and the permit actual flow of the 21 facilities are presented in table 3 below. The 21 wastewater treatment plants were contacted through phone calls and emails to get more information about the facility and the available water head. Out of the 21 wastewater treatment plants, two of them responded positively to phone calls and email correspondence. The two wastewater plants, Joplin Turkey Creek and St Joseph Water Protection facility were visited for an industrial assessment and used as case studies.

Table 3. Selected wastewater treatment plants and their permit design flow and actual flow

S/N	Facility Name	Permit Design Flow (Mgd)	Permit Actual Flow (Mgd)
1	Independence creek	10	7.3
2	Cape Girardeau	11	6.3
3	Joplin Turkey creek	28	22.0
4	Columbia WWTP	21	15.8
5	O Fallon WWTP	11	7.5
6	Jefferson City RWRF	11	8.8
7	St Joseph Water Protection facility	54	22.0
8	LBVSD Atherton	52	42.0
9	St Peters spencer creek	9.5	5.9
10	MSD Coldwater creek	40	24.0
11	St Charles Mississippi river	10	5.7
12	KC, westside	23	14.3
13	KC Birmingham	20	12.4
14	MSD lower Meramec	15	11.0
15	MSD Missouri river	38	26.0
16	MSD lemay	210	106.0

S/N	Facility Name	Permit Design Flow (Mgd)	Permit Actual Flow (Mgd)
17	KC Blue River WWTP	105	81.0
18	MSD Grand glaize	21	14.0
19	MSD Bissell Point	150	120.0
20	Springfield SW	64	32.0
21	Springfield NW	7	5.1

4.2 Data analysis

Our analysis and case studies would be from the two wastewater treatment plants (Joplin Turkey Creek and St Joseph Water Protection facility) as they were physically visited and found to process an average of 22 million gallons per day. Small axial flow turbines or cross-flow turbines could be used to generate power and there also could be gravitational potential energy change going from a higher level down to a lower level so we have additional energy due to the potential head of the water, hence more energy can be extracted. The gravitational potential energy is a result of the acceleration due to gravity, the mass of the water, and the head which is the vertical distance the water has to flow through. Each facility would receive an assessment recommendation showing the detailed calculation of the power and sustain electrical energy that could be generated. The assessment also shows how much cost could be saved and the payback period of the hydropower system. The case studies and assessment recommendations submitted to the wastewater plants are presented as follows.

4.2.1 Case study one assessment recommendation (Joplin Turkey Creek)

AR #: Use of microturbines to generate electricity

Estimated annual electric energy generated = 268,797 kWh annually

Estimated annual electric demand saving = 368 kW–Mon annually

Estimated annual electric cost saving = \$18,009

Estimated annual electric demand cost saving = \$2,937

Estimated annual total energy cost saving = \$20,946

Estimated Implementation Cost = \$306,240

Simple Payback Period = 14.62 Years

Annual CO₂ emissions reduction = 494,586 pounds

Existing Practice and Observation

Currently, the electricity requirement for the company is fulfilled by a third-party vendor. This is associated with substantial electric demand costs and electric usage costs. Based on the information provided by the company, the plant has an annual electric demand of 14,504 kW/mon and utilizes 7,384,610 kilowatt-hours of electricity annually. Currently, the company is spending \$491,964 annually on electric usage costs and \$112,100 on electric demand costs. This data is listed in Table 1 for one year starting March 2020 to March 2021. It was also observed that the plant has an average permit actual flow of 22 Mgd and an available head of about 15ft (4.57 m).

Table 1: Electricity consumption and costs per month

Month	Electric Consumption (kWh)	Electric Consumption Cost	Electric Demand (kW-month)	Electric Demand Cost	Total Electricity Cost
Mar-20	672,318	\$43,501	1,207	\$8,775	\$52,276
Apr-20	697,867	\$45,393	1,359	\$9,602	\$54,995
May-20	670,891	\$43,553	1,268	\$9,127	\$52,680
Jun-20	706,953	\$49,609	1346	\$11,378	\$60,987
Jul-20	510,994	\$36,069	927	\$8,916	\$44,985
Aug-20	549,926	\$38,996	1031	\$10,580	\$49,576
Sep-20	523,592	\$36,283	823	\$9,142	\$45,425
Nov-20	665,540	\$43,086	1379	\$9,990	\$53,076
Dec-20	595,988	\$38,530	1046	\$8,749	\$47,279
Jan-21	627,776	\$40,710	1157	\$8,252	\$48,962
Feb-21	646,485	\$42,246	1334	\$9,228	\$51,474
Mar-21	516,280	\$33,988	1177	\$8,361	\$42,349
Annual Totals:	7,384,610	\$491,964	14,054	\$112,100	\$604,064

Recommended Action

Since the utility costs associated with contracting and buying electricity from the utility provider is significant, it is recommended to integrate a multipurpose scheme within the facility. The multipurpose scheme involves the wastewater treatment plant incorporating a hydro turbine after treating the water and before it is discharged into the river. This multipurpose scheme enables the plant to reduce the electricity usage and demand cost or

even be self-sustainable and still perform its primary function of treating water [Ref 1]. Cost will be saved by the plant as it will generate its renewable energy in the form of hydropower. By considering the information provided by the company (such as flow rate and available head), the facility will require axial or crossflow turbines due to the high flow rate and low head of the plant.

Analysis

The hydropower system generates electricity using the energy in the flowing water. The power used in moving the turbine system by the flowing water is transformed into mechanical energy which rotates the generator to generate electricity. The maximum flow rate is 28 Mgd while the annual average flow rate is 22 Mgd. The plant has an available head of about 15ft (4.57 m). The available head or hydraulic head is a vertical drop in height from the point where the water was treated to the discharge outflow or river.

The maximum theoretical amount of power [Ref 2-3] is given as:

$$P_{th} = \rho \times Q \times H \times g \quad (1)$$

Where:

P_{th} = Power (watts)

ρ = water specific density (kg/m³)

Q = maximum flow rate (m³/s)

H = water head (m)

g = acceleration due to gravity (m/s²)

For the maximum actual amount of power that can be extracted, the efficiency factor e (efficiency of the turbine) is considered. The efficiency factor takes into account the

efficiency of the turbine (crossflow 80%), the efficiency of the turbine generator (typically 93% for small hydropower system), the efficiency of the drive system i.e rotor and gearbox (95%). All these bring the total efficiency to 71%

$$P_{act} = \rho \times Q \times H \times g \times e \quad (2)$$

$$\rho = 1000 \text{ kg/m}^3$$

$$Q = 28 \text{ Mgd} = 1.23 \text{ m}^3/\text{s} \text{ [Ref 4]}$$

$$H = 15 \text{ ft} = 4.57 \text{ m}$$

$$g = 9.81 \text{ m/s}^2$$

$$e = 0.71 \text{ (Total efficiency of the system)}$$

$$P_{act} = 1000 \text{ kg/m}^3 \times 1.23 \text{ m}^3/\text{s} \times 4.57 \text{ m} \times 9.81 \text{ m/s}^2 \times 0.71$$

$$P_{act} = 39,151.52 \text{ kgm}^2/\text{s}^3 = 39,151.52 \text{ W}$$

$$P_{act} = 39.2 \text{ kW}$$

Since the plant operates for 8,760 hours per year and the annual average flow rate is 22 Mgd (0.964 m³/s), the sustained electrical energy that can be generated annually is given by:

$$E = \rho \times H \times g \times e \times A \times h$$

Where:

$$E = \text{kWh}$$

A = Annual average water flow

h = annual operating hours

$$E = 1000 \text{ kg/m}^3 \times 4.57 \text{ m} \times 9.81 \text{ m/s}^2 \times 0.71 \times 0.964 \text{ m}^3/\text{s} \times 8,760 \text{ hours}$$

$$E = 268,797.2 \text{ kWh}$$

The annual electric demand savings (AEDS) is:

$$\text{AEDS} = \frac{\text{Annual electric energy generated}}{\text{Annual hours of operation}} \times 12 \text{ Months}$$

$$= \frac{268,797.2 \text{ kWh}}{8,760 \text{ hr}} \times 12 = 30.7 \text{ kW} \times 12 \text{ mon} = 368 \text{ kW-Mon}$$

The annual electric cost saving (AEUCS) is:

$$\text{AEUCS} = \text{Electrical energy generated} \times \text{Cost per kWh}$$

$$= 268,797.2 \text{ kWh} \times \$0.067/\text{kWh}$$

$$= \$18,009$$

The annual electric demand cost saving (AEDCS) is:

$$\text{AEDCS} = \text{AEDS} \times \text{Cost per kW-Mon}$$

$$= 368 \text{ kW-Mon} \times \$7.98 \text{ kW-Mon}$$

$$= \$2,937$$

The annual total electric energy cost saving (ATECS) is:

$$\text{ATECS} = \text{AEUCS} + \text{AEDCS}$$

$$= \$18,009 + \$2,937$$

$$= \$20,946$$

Implementation Cost and Payback

The wastewater treatment plant will require a turbine, a generator, and powerhouse components (including wiring, drive system, switchboards, etc.). A bypass piping or system should also be put in place to redirect the flow of water when the turbine system is not in use. A company (Canyon Hydro) that builds custom hydroelectric systems according to specification was contacted for a cost estimate of the whole hydropower system, however, we recommend getting price quotes from other potential vendors. An estimate of \$400,000 was given for the implementation of the system [5]. The system includes the turbine, turbine generator, and powerhouse components.

The initial project cost is \$400,000. The Federal Renewable Electricity Production Tax Credit (PTC) allowable at \$0.013 per kWh for a period of 10 years [6]. Thus, the credit would be $268,797 \text{ kWh} \times 10 \text{ yr} \times \$0.013 / \text{kWh} = \$34,944$. Another federal tax credit available is the Business Energy Investment Tax credit (ITC) of 10% of project cost and a maximum of \$200/kW [7]. Thus, for a 30.7 kW generation, the credit would be 10% of \$400,000 which is \$40,000. Additionally, Evergy provides a rebate of \$0.07/kWh with pre-approval, potentially the rebate would be $268,797 \text{ kWh} \times \$0.07 / \text{kWh} = \$18,816$. Thus, the final project cost would be $\$400,000 - \$34,944 - \$40,000 - \$18,816 = \$306,240$

The simple payback period is $\$306,240 / \$20,946 = 14.62$ years

Typically, most hydro turbine manufacturers give an estimated quote of at least 25 years for the average lifespan of a turbine but the turbines are known to still operate efficiently at over 50 years. The hydropower installation itself can last up to a 100 years with regular maintenance like lubricating the turbine bearings, periodic replacement of oil and bearings in the drive system [ref 6 - 8]. So, a simple payback period of 14.62 years is economically

feasible. Additionally, it may be noted that the production of 268,000 kWh of electric power is from a sustainable source.

Emissions Analysis

At these 268,797.2 kWh usage savings the annual reduction in carbon dioxide is:

494,586 pounds (pounds of CO₂ per kWh = 1.84)

-The Source of emission coefficients is the Energy Information Administration.

Case Study 1 References

1. European Small Hydropower Association (ESHA), 2010, Energy recovery in existing infrastructures with small hydropower plants: multipurpose schemes – overview and examples, e-book.
2. European Small Hydropower Association (ESHA), 2004, Guide on How to Develop a Small Hydropower Plant
3. Beltran, H., Vidal, R., Basiero, L., Santos, J.M., Basiero, J.A, and Belenguer, E., 2014, “Micro Hydro Installation Analysis in a Wastewater Treatment Plant,” Renewable Energy and Power Quality Journal, 1(12).
4. [https://www.convertunits.com/from/million+gallon/day+\[US\]/to/cubic+meters/second](https://www.convertunits.com/from/million+gallon/day+[US]/to/cubic+meters/second)
5. Personal communication with a sales representative of the turbine and turbine generator supplier
6. <https://programs.dsireusa.org/system/program/detail/734/renewable-electricity-production-tax-credit-ptc>
7. <https://programs.dsireusa.org/system/program/detail/658/business-energy-investment-tax-credit-itc>

8. <https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-long-will-hydropower-systems-last/>
9. <https://www.nrel.gov/docs/fy04osti/34916.pdf>
10. https://www.vgb.org/en/hydropower_fact_sheets_2018.html?dfid=91646

4.2.2 Case study two assessment recommendation (St Joseph WPF)

AR #: Use of microturbines to generate electricity

Estimated annual electric energy generated = 1,198,118 kWh annually

Estimated annual electric demand saving = 1,641 kW-Mon annually

Estimated annual electric cost saving = \$68,293

Estimated annual electric demand cost saving = \$15,032

Estimated annual total energy cost saving = \$83,325

Estimated Implementation Cost = \$120,377

Simple Payback Period = 1.44 Years

Annual CO2 emissions reduction = 2,204,537 pounds

Existing Practice and Observation

Currently, the electricity requirement for the company is fulfilled by a third-party vendor. This is associated with substantial electric demand costs and electric usage costs. Based on the information provided by the company, the plant has an annual electric demand of 9,011 kW-Mon and utilizes 4,938,632 kilowatt-hours of electricity annually. Currently, the company is spending \$281,811 annually on electric usage costs and \$82,562 on electric demand costs. This data is listed in Table 1 for one year starting April 2020 to March 2021. It was also observed that the plant has a permit actual flow of 22 Mgd and an available head of 802 inches (20.37 m)

Table 1: Electricity consumption and costs per month

Month	Consumption (kWh)	Consumption Cost	Demand Consumption (kW-month)	Demand Cost	Total Cost
Apr-20	415,879	\$23,826	816	\$6,054	\$29,880
May-20	353,076	\$20,398	768	\$6,064	\$26,462
Jun-20	349,500	\$21,409	580	\$8,587	\$29,996
Jul-20	409,935	\$25,388	709	\$8,669	\$34,057
Aug-20	369,468	\$23,315	655	\$8,656	\$31,971
Sep-20	397,029	\$25,262	889	\$8,663	\$33,925
Oct-20	410,421	\$22,093	707	\$5,985	\$28,078
Nov-20	414,278	\$22,502	781	\$6,003	\$28,505
Dec-20	466,067	\$24,616	734	\$6,003	\$30,619
Jan-21	478,424	\$25,061	851	\$5,958	\$31,019
Feb-21	504,474	\$27,031	803	\$5,970	\$33,001
Mar-21	370,081	\$20,910	718	\$5,950	\$26,860
Annual Totals:	4,938,632	\$281,811	9,011	\$82,562	\$364,373

Recommended Action

Since the utility costs associated with contracting and buying electricity from the utility provider is high, it is recommended to integrate a multipurpose scheme within the facility. The multipurpose scheme involves the wastewater treatment plant incorporating a hydro turbine after treating the water and before it is discharged into the river. This multipurpose scheme enables the plant to reduce the electricity usage and demand cost or even be self-

sustainable and still perform its primary function of treating water [Ref 1]. Cost will be saved by the plant as it will generate its renewable energy in the form of hydropower. By considering the information provided by the company (such as flow rate and available head), the facility will require axial turbines due to the high flow rate and low head of the plant.

Analysis

The hydropower system generates electricity using the energy in the flowing water. The power used in moving the turbine system by the flowing water is transformed into mechanical energy which rotates the generator to generate electricity. The maximum flow rate is 54 Mgd while the annual average flow rate is 22 Mgd. The plant has an available head of about 802 inches (20.37 m). The available head or hydraulic head is a vertical drop in height from the point where the water was treated to the discharge outflow or river.

The maximum theoretical amount of power [Ref 2-3] is given as:

$$P_{th} = \rho \times Q \times H \times g \quad (1)$$

Where:

P_{th} = Power (watts)

ρ = water specific density (kg/m^3)

Q = maximum flow rate (m^3/s)

H = water head (m)

g = acceleration due to gravity (m/s^2)

For the maximum actual amount of power that can be extracted, the efficiency factor e (efficiency of the turbine) is considered. The efficiency factor takes into account the efficiency of the turbine (crossflow 80%), the efficiency of the turbine generator (typically

93% for small hydropower system), the efficiency of the drive system i.e. rotor and gearbox (95%). All these bring the total efficiency to 71%

$$P_{act} = \rho \times Q \times H \times g \times e \quad (2)$$

$$\rho = 1000 \text{ kg/m}^3$$

$$Q = 54 \text{ Mgd} = 2.37 \text{ m}^3/\text{s} \text{ [Ref 4]}$$

$$H = 802 \text{ inches} = 20.37 \text{ m}$$

$$g = 9.81 \text{ m/s}^2$$

$$e = 0.71 \text{ (Total efficiency of the system)}$$

$$P_{act} = 1000 \text{ kg/m}^3 \times 2.37 \text{ m}^3/\text{s} \times 20.37 \text{ m} \times 9.81 \text{ m/s}^2 \times 0.71$$

$$P_{act} = 336,253.4 \text{ kgm}^2/\text{s}^3 = 336,253.4 \text{ W}$$

$$P_{act} = 336.3 \text{ kW}$$

Since the plant operates for 8,760 hours per year and the annual average flow rate is 22 Mgd (0.964 m³/s), the sustained electrical energy that can be generated annually is given by:

$$E = \rho \times H \times g \times e \times A \times h$$

Where:

$$E = \text{kWh}$$

$$A = \text{Annual average water flow}$$

$$h = \text{annual operating hours}$$

$$E = 1000 \text{ kg/m}^3 \times 20.37 \text{ m} \times 9.81 \text{ m/s}^2 \times 0.71 \times 0.964 \text{ m}^3/\text{s} \times 8,760 \text{ hours}$$

$$E = 1,198,118 \text{ kWh}$$

The annual electric demand savings (AEDS) is:

$$\text{AEDS} = \frac{\text{Annual electric energy generated}}{\text{Annual hours of operation}} \times 12 \text{ Months}$$

$$= \frac{1,198,118 \text{ kWh}}{8,760 \text{ hr}} \times 12 = 136.7 \text{ kW} \times 12 \text{ mon} = 1,641 \text{ kW-Mon}$$

The annual electric cost saving (AEUCS) is:

$$\text{AEUCS} = \text{Electrical energy generated} \times \text{Cost per kWh}$$

$$= 1,198,118 \text{ kWh} \times \$0.057/\text{kWh}$$

$$= \$68,293$$

The annual electric demand cost saving (AEDCS) is:

$$\text{AEDCS} = \text{AEDS} \times \text{Cost per kW-Mon}$$

$$= 1,641 \text{ kW-Mon} \times \$9.16 \text{ kW-Mon}$$

$$= \$15,032$$

The annual total electric energy cost saving (ATECS) is:

$$\text{ATECS} = \text{AEUCS} + \text{AEDCS}$$

$$= \$68,293 + \$15,032$$

$$= \$83,325$$

Implementation Cost and Payback

The wastewater treatment plant will require a turbine, a generator, and powerhouse components (including wiring, drive system, switchboards, etc.). A bypass piping or system should also be put in place to redirect the flow of water when the turbine system is not in use. A company (Canyon Hydro) that builds custom hydroelectric systems according to specification was contacted for a cost estimate of the whole hydropower system, however, we recommend getting price quotes from other potential vendors. An estimate of \$400,000 was given for the implementation of the system [5]. The system includes the turbine, turbine generator, and powerhouse components.

Initial project cost is \$400,000. The Federal Renewable Electricity Production Tax Credit (PTC) allowable of \$0.013 per kWh for a period of 10 years [6]. Thus, the credit would be $1,198,118 \text{ kWh} \times 10 \text{ yr} \times \$0.013 / \text{kWh} = \$155,755$. Another federal tax credit available Business Energy Investment Tax credit (ITC) of 10% of project cost and a maximum of \$200/kW [7]. Thus, for a 1,641-kW generation the credit would be 10% of \$400,000 which is \$40,000. Additionally, Evergy provides a rebate of \$0.07/kWh with pre-approval, potentially the rebate would be $1,198,118 \text{ kWh} \times \$0.07 / \text{kWh} = \$83,868$. Thus, the final project cost would be $\$400,000 - \$155,755 - \$40,000 - \$83,868 = \$120,377$

The simple payback period is $\$120,377 / \$83,325 = 1.44 \text{ years}$

Typically, most hydro turbine manufacturers give an estimated quote of at least 25years for the average lifespan of a turbine but the turbines are known to still operate efficiently at over 50 years. The hydropower installation itself can last up to a 100years with regular maintenance like lubricating the turbine bearings, periodic replacement of oil and bearings in the drive system [ref 6 - 8]. So, a simple payback period of 1.44 years is economically

feasible. Additionally, it may be noted that the production of 1,198,118 kWh of electric power is from a sustainable source.

Emissions Analysis

At these 1,198,118 kWh usage savings the annual reduction in carbon dioxide is:

2,204,537 pounds (pounds of CO₂ per kWh = 1.84)

-The Source of emission coefficients is the Energy Information Administration.

Case Study 2 References

1. European Small Hydropower Association (ESHA), 2010, Energy recovery in existing infrastructures with small hydropower plants: multipurpose schemes – overview and examples, e-book.
2. European Small Hydropower Association (ESHA), 2004, Guide on How to Develop a Small Hydropower Plant
3. Beltran, H., Vidal, R., Basiero, L., Santos, J.M., Basiero, J.A, and Belenguer, E., 2014, “Micro Hydro Installation Analysis in a Wastewater Treatment Plant,” Renewable Energy and Power Quality Journal, 1(12).
4. [https://www.convertunits.com/from/million+gallon/day+\[US\]/to/cubic+meters/second](https://www.convertunits.com/from/million+gallon/day+[US]/to/cubic+meters/second)
5. Personal communication with a sales representative of the turbine and turbine generator supplier
6. <https://programs.dsireusa.org/system/program/detail/734/renewable-electricity-production-tax-credit-ptc>

7. <https://programs.dsireusa.org/system/program/detail/658/business-energy-investment-tax-credit-itc>
8. <https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-long-will-hydropower-systems-last/>
9. <https://www.nrel.gov/docs/fy04osti/34916.pdf>
10. https://www.vgb.org/en/hydropower_fact_sheets_2018.html?dfid=91646

4.2.3 Potential for power and energy extraction from other facilities in Missouri

Using the permit design flow and the permit actual flow of the 21 wastewater treatment facilities listed in table 3, the power and sustainable electrical energy were estimated for all the facilities. The formulas used in the case studies were used for the other facilities with the water head assumed to be just one meter. It should be noted that facilities with a higher hydraulic head would give a value higher than the one presented in table 4 below. The facility with the lowest amount of power to be extracted was Springfield NW wastewater treatment plant with just 2 kW minimum actual amount of power and sustainable energy of 13,633 kWh. This is because Springfield NW had a permit design flow of just 7 Mgd and a permit actual flow of 5.2 Mgd. On the other hand, MSD Lemay in Saint Louis Missouri had a permit design flow of 210 Mgd and could generate a minimum actual power of 64 kW. It could also generate sustainable electrical energy of 283,361 kWh as the permit actual flow was 106 Mgd. The largest sustainable electrical energy was from MSD Bissell point also in Saint Louis Missouri. The facility has a permit actual flow of 120 Mgd and could produce sustainable electrical energy of 320,786 kWh. From the data collected, it was observed that a vast majority of the wastewater treatment in Missouri that has high flows where from Saint Louis Missouri and the wastewater plants in that region have tremendous potential for sustainable electrical energy using microturbines for hydropower. The data for the actual amount of power and sustained electrical energy that can be generated from each of the selected 21 wastewater treatment facilities in the state of Missouri are presented in table 4 below.

Table 4. Power and sustainable electrical energy capabilities of the selected wastewater treatment plants

S/N	Facility Name	Permit Design Flow (Mgd)	Permit Actual Flow (Mgd)	Power Generated (kW)	Sustainable Energy Generated (kWh)
1	Independence creek	10	7.3	3	19,514
2	Cape Girardeau	11	6.3	3	16,841
3	Joplin Turkey creek	28	22.0	9	58,811
4	Columbia WWTP	21	15.8	6	42,237
5	O Fallon WWTP	11	7.5	3	20,049
6	Jefferson City RWRf	11	8.8	3	23,524
7	St Joseph Water Protection facility	54	22.0	16	58,811
8	LBVSD A.	52	42.0	16	112,275

S/N	Facility Name	Permit Design Flow (Mgd)	Permit Actual Flow (Mgd)	Power Generated (kW)	Sustainable Energy Generated (kWh)
9	St Peters spencer creek	9.5	5.9	3	15,772
10	MSD Coldwater creek	40	24.0	12	64,157
11	St Charles Mississippi river	10	5.7	3	15,237
12	KC, westside	23	14.3	7	38,227
13	KC Birmingham	20	12.4	6	33,148
14	MSD lower Meramec	15	11.0	5	29,405
15	MSD Missouri river	38	26.0	12	69,504
16	MSD lemay	210	106.0	64	283,361
17	KC Blue river	105	81.0	32	216,531

S/N	Facility Name	Permit Design Flow (Mgd)	Permit Actual Flow (Mgd)	Power Generated (kW)	Sustainable Energy Generated (kWh)
18	MSD Grand glaize	21	14.0	6	37,425
19	MSD Bissell Point	150	120.0	46	320,786
20	Springfield SW	64	32.0	20	85,543
21	Springfield NW	7	5.1	2	13,633

4.2.3 Electric usage savings and demand savings of the other Missouri facilities

Joplin turkey creek from case study one has an electricity usage cost of \$0.067 per kWh and a demand cost of \$7.98 kW-Mon. Case study two, St, Joseph wastewater treatment plant had an electricity usage cost of \$0.057 per kWh and a demand cost of \$9.16. Analyzing utility data from five other wastewater treatment plants also, the electric demand cost variations are from \$3.70 to \$9.16 per kW. The average demand cost of the seven facilities is estimated to be \$7.82 per kW. For the electric usage cost, the variations were from \$0.06 to \$0.09 per kWh. The average electricity cost is estimated at \$0.072/kWh. We can use these average variations to estimate the potential annual electricity usage cost savings (AEUCS) and the demand cost savings of the selected wastewater treatment plants. The result of this estimate is presented in table 5. From the table, we can see that facilities with higher electric

energy generated produced higher annual electricity usage cost savings (AEUCS) and high demand cost savings.

Using the rebates that were used in the two case studies such as the Federal Renewable Electricity Production Tax Credit (PTC) that allows \$0.013 per kWh for a period of 10 years [40], the federal tax credit available Business Energy Investment Tax credit (ITC) of 10% of project cost or a maximum of \$200/kW [41], and the utility suppliers generally have a rebate program, such as by Evergy company a rebate of \$0.07/kWh, the installation cost can be determined for the remaining facilities. For example, for independence creek the implementation cost would be $\text{Project cost} - \text{PTC rebates} - \text{ITC rebates} - \text{Evergy rebates}$, which gives us $\$400,000 - (19,514 \text{ kWh} \times 10 \text{ yr} \times \$0.013/\text{kWh}) - \$40,000 - (\$0.07/\text{kWh} \times 19,514 \text{ kWh}) = \$356,097$. For a facility with higher electric energy generated like MSD Bissell point the implementation cost would be $\$400,000 - (320,768 \text{ kWh} \times 10 \text{ yr} \times \$0.013/\text{kWh}) - \$40,000 - (\$0.07/\text{kWh} \times 320,768 \text{ kWh}) = \$295,843$. It is observed that facilities with higher electric energy generated have a lower cost of implementation due to the higher rebates accumulated. The result of this estimate is presented in table 5. From the table, we can see that facilities with higher electric energy generated produced higher annual electricity usage cost savings (AEUCS) and high demand cost savings.

Table 5. The estimated savings for the selected wastewater treatment plants

S/N	Facility Name	AEUCS (\$)	Demand Cost Savings (\$)	Total Cost Savings (\$)	Installation Cost (\$)
1	Independence creek	1,405	211	1,616,	356,097
2	Cape Girardeau	1,213	180	1,393	356,631
3	Joplin Turkey creek	4,234	633	4,867	348,238
4	Columbia WWTP	3,041	454	3,495	351,553
5	O Fallon WWTP	1,444	211	1,655	355,990
6	Jefferson City RWRf	1,694	250	1,944	355,295
7	St Joseph Water Protection facility	4,234	633	4,867	348,238
8	LBVSD Atherton	8,084	1,204	9,288	337,545
9	St Peters spencer creek	1,136	172	1,308	356,846

S/N	Facility Name	AEUCS (\$)	Demand Cost Savings (\$)	Total Cost Savings (\$)	Installation Cost (\$)
10	MSD Coldwater creek	4,619	688	5,307	347,169
11	St Charles Mississippi river	1,097	164	1,261	356,953
12	KC, westside	2,752	407	3,159	352,355
13	KC Birmingham	2,387	352	2,739	353,370
14	MSD lower Meramec	2,117	313	2,430	354,119
15	MSD Missouri river	5,004	743	5,747	346,099
16	MSD lemay	20,402	3,034	23,436	306,478
17	KC Blue river WWTP	15,590	2,323	17,913	316,694
18	MSD Grand glaize	2,695	399	3,094	352,515
19	MSD Bissell Point	23,097	3,433	26,530	295,843
20	Springfield SW	6,159	915	7,074	342,891

S/N	Facility Name	AEUCS (\$)	Demand Cost Savings (\$)	Total Cost Savings (\$)	Installation Cost (\$)
21	Springfield NW	982	149	1,131	357,273

4.3 Conclusion

This research thesis presented hydropower systems and formulas for calculating the amount of power and electrical energy that can be recovered from installing microturbines in the municipal wastewater treatment plants. The turbine converts the energy in the water to functional electrical energy. In selecting a turbine, we had to consider where it will be installed, the available head, the type of flow, the cost of the turbine, and the efficiency of the turbine. In a study of wastewater treatment plants by the advanced energy conversion, LLC, about 25 to 40% of the total operating budget of a wastewater plant goes into electricity to power the wastewater. Making electricity the second largest operating cost of a wastewater treatment plant. The objective which is to create a hydropower system that could recover the energy in the flowing water and convert it into electrical power which can be used to power the wastewater plant, thereby offsetting operational cost, and saving money for the municipal wastewater plants in Missouri was achieved. The efficiency of the facilities was improved and the power generation potential from the wastewater treatment plants in Missouri were estimated.

Including the two case studies, a minimum total sustainable electrical energy of 2,924,084 kWh could be gotten from the selected 21 wastewater treatment plants. The minimum total annual electricity usage cost of wastewater plants amounts to \$191,220, while

the minimum demand cost that can be saved is \$33,571. The minimum total cost that can be potentially saved amounts to \$224,791. This figure is the minimum as a available head of one meter was assumed in the estimation of the other facilities. Facilities with higher available head would generate more sustainable electrical energy and hence generate more cost savings. The money saved can be used for areas in the wastewater treatment plant that need attention. Apart from the money saved, clean, environmentally friendly, and sustainable energy would have been produced. The estimated total annual reduction in carbon dioxide is 5,380,315 pounds (Pounds of CO₂ per kWh = 1.84). We considered the payback period for the installation of the microturbines and determined it to be economically feasible. The payback period for both case studies was determined to be 14.62 years and 1.44 years. Typically, most hydro turbine manufacturers give an estimated quote of at least 25years for the average lifespan of a turbine but the turbines are known to still operate efficiently at over 50 years. The hydropower installation itself can last up to 100 years with regular maintenance like lubricating the turbine bearings, periodic replacement of oil and bearings in the drive system. Future potential work can be conducted for the wastewater treatment plants in the Saint Louis region of the state as it was observed that most plants in that region have high permit design flow and permit actual flow.

References

- [1] Panwar, N.L, Kaushik, S.C., Kothari S., 2011, “Role of renewable energy sources in environmental protection: A review,” *Renewable and Sustainable Energy Reviews*, 15, pp 1513-1524
- [2] Loots, I., van Dijk, M., Barta, B., van Vuuren, S.J., Bhagwan, J.N., 2015, “A Review of Low Head Hydropower Technologies and Applications in a South African Context,” *Renewable and Sustainable Energy Reviews*, 50, pp 1254-1268
- [3] Beltran, H., Vidal, R., Basiero, L., Santos, J.M., Basiero, J.A, and Belenguer, E., 2014, “Micro Hydro Installation Analysis in a Wastewater Treatment Plant,” *Renewable Energy and Power Quality Journal*, 1(12).
- [4] European Small Hydropower Association (ESHA), 2010, Energy recovery in existing infrastructures with small hydropower plants: multipurpose schemes – overview and examples, e-book.
- [5] Jawahar, C.P., Michael, P.A., 2017, “A Review on Turbines for Micro Hydro Power Plant,” *Renewable and Sustainable Energy Reviews*, 72, pp 882-887.
- [6] Sakeet, R.K., 2008, “Design, Development and Reliability Evaluation of Micro Hydro Power Generation System Based on Municipal Waste Water,” *IEEE Electrical Power and Energy Conference*.
- [7] “Types of Hydropower Turbines,” Office of Energy Efficiency and Renewable Energy, from <https://www.energy.gov/eere/water/types-hydropower-plants>

- [8] Haidar, A. M., Senan, M. F., Noman, A., and Radman, T., 2012, "Utilization of Pico Hydro Generation in Domestic and Commercial Loads," *Renewable and Sustainable energy reviews*, 16(1), pp 518-524.
- [9] Date, A., Date, A., Akbarzadeh, A., & Alam, F., 2012, "Examining the Potential of Split Reaction Water Turbine for Ultra-low Head Hydro Resources," *Procedia Engineering*, 49, 197-204.
- [10] Alexander, K. V., Giddens, E. P., & Fuller, A. M., 2009, "Axial-flow Turbines for Low Head Microhydro Systems," *Renewable energy*, 34(1), pp 35-47.
- [11] Zainuddin, H., Khamis, A., Yahaya, M. S., Basar, M. F. M., Lazi, J. M., & Ibrahim, Z., 2009, "Investigation on the performance of pico-hydro generation system using consuming water distributed to houses," *International Conference on the Developments in Renewable Energy Technology (ICDRET)*, 1, pp. 1-4
- [12] Botero, L., Woodley, M., Knatz, C. and Topa, T., 2010, Hydraulic Similarity of Head loss Predictions Derived Using Commonly Used Methods Versus Actual Results as It Relates to Wastewater Screen Elements.
- [13] ARET 3400, Fluid flow, Chap. 4
- <https://faculty.tru.ca/eahmed/Chapters/ARET%203400%20-%20Chapter%204.pdf>
- [14] Kumar, R. and Singal, S.K., 2015, "Penstock material selection in small hydropower plants using MADM methods," *Renewable and Sustainable Energy Reviews*, 52, pp.240-255.
- [15] Triki, A., 2016, "Water-hammer control in pressurized-pipe flow using an in-line polymeric short-section," *Acta Mechanica*, 227(3), pp.777-793.

- [16] Mishra, S., Singal, S.K. and Khatod, D.K., 2012, "Effect of variation of penstock parameter on mechanical power," *a A*, 10, p.4.
- [17] Dincer, I., 2018. *Comprehensive energy systems*. Elsevier.
- [18] Khosrowpanah, S., Albertson, M.L. and Fiuzat, A.A., 1984, "Historical overview of cross-flow turbine," *Int. Water Power Dam Constr.;*(United Kingdom), 36 (10).
- [19] Sinagra, M., Sammartano, V., Aricò, C., Collura, A. and Tucciarelli, T., 2014. "Cross-Flow turbine design for variable operating conditions," *Procedia Engineering*, 70, pp.1539-1548.
- [20] Jordan, H., Kailyn, S., and Jason, D., 2020, "Energy Education - Crossflow turbine" from https://energyeducation.ca/encyclopedia/Crossflow_turbine [Accessed: March 4, 2021].
- [21] Adhikari, R.C., and Wood, D.H., 2017, "A new nozzle design methodology for high efficiency crossflow hydro turbines," *Energy for Sustainable Development*, 41, pp.139-148.
- [22] Benzon, D.S., Aggidis, G.A. and Anagnostopoulos, J.S., 2016. "Development of the Turgo Impulse turbine: Past and present" *Applied Energy*, 166, pp.1-18.
- [23] Benzon, D., Židonis, A., Panagiotopoulos, A., Aggidis, G.A., Anagnostopoulos, J.S. and Papanonis, D.E., 2015, "Impulse turbine injector design improvement using Computational Fluid Dynamics," *Journal of Fluids Engineering*, 137(4).
- [24] Gilkes, 2014, "Gilkes Turgo Impulse Hydro Turbine," from http://www.gilkes.com/user_uploads/turgo%20paper2.pdf
- [25] Jeon, H., Park, J.H., Shin, Y. and Choi, M., 2018, "Friction loss and energy recovery of a Pelton turbine for different spear positions," *Renewable energy*, 123, pp.273-280.

- [26] Egusquiza, M., Egusquiza, E., Valentin, D., Valero, C. and Presas, A., 2017, "Failure investigation of a Pelton turbine runner," *Engineering Failure Analysis*, 81, pp.234-244.
- [27] Messa, G.V., Mandelli, S. and Malavasi, S., 2019, "Hydro-abrasive erosion in Pelton turbine injectors: A numerical study" *Renewable energy*, 130, pp.474-488.
- [28] Rossetti, A., Pavesi, G., Ardizzon, G., and Santolin, A., 2014, "Numerical analyses of cavitating flow in a Pelton turbine," *Journal of Fluids Engineering*, 136(8).
- [29] Padhy, M.K., and Saini, R.P., 2011 "Study of silt erosion on performance of a Pelton turbine" *Energy*, 36(1), pp.141-147.
- [30] Date, A., Date, A. and Akbarzadeh, A., 2013, "Investigating the potential for using a simple water reaction turbine for power production from low head hydro resources," *Energy Conversion and Management*, 66, pp.257-270.
- [31] Flores, E., Bornard, L., Tomas, L., Liu, J. and Couston, M., 2012, November. "Design of large Francis turbine using optimal methods," In *IOP Conference Series: Earth and Environmental Science* (Vol. 15, No. 2, p. 022023). IOP Publishing.
- [32] Gugler Water Turbines from www.gugler.com/produkt/francis-turbines
- [33] Geppert Hydropower Francis Turbine from <https://www.geppert.at/en/produkt/francis-turbines/>
- [34] Zhang, M., Valentín, D., Valero, C., Egusquiza, M. and Egusquiza, E., 2019, "Failure investigation of a Kaplan turbine blade," *Engineering Failure Analysis*, 97, pp.690-700.
- [35] Shukla, R.S. and Parashar, C., 2017, "Design of Propeller Turbine for Micro Hydro Power Station Using CFD" *International Journal of Scientific Engineering and Science*, 1(7), pp.37-41.

- [36] Guénette, V., Houde, S., Ciocan, G.D., Dumas, G., Huang, J. and Deschênes, C., 2012, November. "Numerical prediction of a bulb turbine performance hill chart through RANS simulations" In IOP Conference Series: Earth and Environmental Science (Vol. 15, No. 3, p. 032007). IOP Publishing.
- [37] Lancaster University Renewable Energy Group (LUREG), 2014, "Hydro Resource Evaluation Tool: Engineering Options," from <http://www.engineering.lancs.ac.uk/lureg/nwhrm/engineering/index.php?#tab>
- [38] Mover, W.G.P. and Supply, E., 1992, "Hydraulic turbine and turbine control models for system dynamic studies," IEEE Transactions on Power Systems, 7(1), pp.167-179.
- [39] Ogayar, B., Vidal, P.G. and Hernandez, J.C., 2009, "Analysis of the cost for the refurbishment of small hydropower plants" Renewable Energy, 34(11), pp.2501-2509.
- [40]<https://programs.dsireusa.org/system/program/detail/734/renewable-electricity-production-tax-credit-ptc>
- [41]<https://programs.dsireusa.org/system/program/detail/658/business-energy-investment-tax-credit-itc>