Energy Harvesting from Water Pressure Regulation

EGR 424L - Energy and Environment Capstone - Spring 2013

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1 Abstract

The goal of the Delta P project was to design and construct a device that reduces water pressure while harvesting energy released during the associated pressure drop. The final design utilizes a Francis turbine with connected shaft as both the pressure-reducing and energy-harvesting device. Prototype testing results showed turbine shaft rotational speed of 70 rpm. At production scale, the device is viable in the municipal water system market and has carbon and other air pollutant emission offset potential.

2 Project definition

Americans produce over 5 billion metric tons of carbon dioxide per year.[1] However, much of that number accounts for energy inefficiencies; thirty percent of energy used in commercial buildings could be reduced through increased energy efficiency.[2] The water pressure regulators that are currently used universally throughout the country are energy inefficient. Traditional water pressure regulators, used in both residential and industrial applications, reduce incoming high water pressure to a lower pressure that can be used in a safe and functional manner. Through the process of reducing the water pressure, energy, in the form of heat and mechanical vibration, is released to the surrounding environment. By harvesting this energy rather than allowing it to dissipate, it is possible to use this previously wasted source of energy productively.

The goal of Delta P is to prove that harvesting energy through a water pressure regulator is possible and may be used in a constructive manner. Our product will harvest energy while still maintaining the pressure regulation that is required. City-wide scales potentially generate the largest power output, so while a scale model was created, it was designed to scale up to a larger application. In addition to harvesting energy, the pressure regulator must be cost-efficient, allowing cities to enjoy a low payback period. By creating a cost-efficient and energy-efficient pressure regulator, Delta P can compete on the open market and lower America's carbon footprint and reduce other air pollutant emissions.

[1] http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8

[2] http://www.edf.org/energy/energy-challenge-numbers?s_src=ggad_control_012012&gclid=CL-DtK_l8rYCFYpQOgodvy8AFQ

2.1 Items critical to quality (CTQ)

The following parameters were determined to be critical to quality:

Parameter	Value
Change in Pressure	50 psi
Power Output	0.6 W
Cost	Competitive with existing technologies

Table 1: Items Critical to Quality

3 Concept Generation

3.1 Existing technologies

Currently, various turbine systems have been installed at the industrial scale to harvest energy from water pressure reduction. Rentricity, a company based in New York City, has designed a turbine system called "Flow-to-Wire." For the public works of Keene, New Hampshire, Rentricity's system features twin 40 kW and 22 kW turbines in parallel, which receive water from an upstream reservoir. The turbines act as reverse action pumps and reduce water pressure by about 80 psi.[3] The turbine impeller drives a generator for on-site electricity generation.

Similarly, SOAR Technologies, based in Washington State, has developed energy recovery systems for water pressure regulation operations in Hawaii, Vermont, Oregon, and other locations in the United States. Through a research project conducted in conjunction with the California Energy Commission and San Diego State University, SOAR developed designs for a generating pressure reducing valve (GPRV). The company has produced several iterations of the GPRV, including a Pelton turbine system installed in Hawaii and reactive versions using Francis and reverse-pumps, which are fully immersed in water but constrained to a much narrower operating range for changes in flow.[4] Table 2 compares the designs of Rentricity and SOAR Technologies on several key parameters.

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[3] http://www.rentricity.com/about_overview.html
[4] http://www.canyonhydro.com/news/SOAR_IWPDC.pdf

Parameter	Rentricity	SOAR Technologies
Power [kW]	22 & 40	35
Flow rate [gpm]	700-2000	400-900
Pressure drop [psi]	80	50
Simplicity	Multiple chambers	Single chamber
Turbine	Twin Pelton, reverse-pump	Pelton and Francis

Table 2: Comparison of Rentricity and SOAR Technologies designs

3.2 Market research

In the United States, there is tremendous potential for sustainable technologies to penetrate the public infrastructure market in the future. Our specific market opportunity is directly related to how water is transported throughout the country. Pipelines transport over 400 billion gallons of water per day in the US. Due to the nature of water transportation, pressure changes are always a component when dealing with efficiency and elevation changes and thus they present myriad windows for implementation in the public water infrastructure.

To address the need for renovation in the near future, it is important to understand the age of our current water distribution system. Of the pipes that distribute water to populations of more than 100,000 people, 30% of them are between 40 and 80 years old and about 10% of them are older than 80 years. It is important to emphasize that the system is not only old but, due to regular failure, it is also in need of repair and updating. On average about 700 water main breaks occur across the United States each day.

Our team focused our efforts on an industrial scale energy harvesting water pressure regulator for implementation in public utility and waste water management systems. In searching for customers, we identified Duke University as a great starting point. As an institution, Duke prides itself on being environmentally friendly and relatively self-sufficient. Examples of this include their independently owned and operated chilled water plants, water reclamation facilities, and natural gas based steam plants. Furthermore, Duke operates at a large scale that includes not just an entire student body but also a nationally lauded medical center. Our presumption was that Duke might also operate its own water pressure regulation in some parts of campus and would be very interested in an energy harvesting system like this one.

After speaking with Steve Palumbo, Energy Manager and head of Utilities & Engineering Services at Duke University, it turns out that Duke works with the water pressure that is provided by the city of Durham rather than managing anything internally. Although larger state institutions might still be an interested customer, we decided to focus specifically on public water distribution systems. After discussing this avenue with the President and Founder of Rentricity Frank Zammataro, who was very careful not to provide too much information to a competitor, we grew to understand the complexity of installations. Each turbine and pressure regulating system is designed uniquely for each installation site. The main driver is how complicated and different each water distribution system is; in fact, some are so complicated that it does not make sense even to consider them for a potential installation.

Considering that our customers are in the government sector and that they will be using taxpayer dollars to purchase and to install the devices, it will be most important to demonstrate the benefits of their investment. We used a simple model to predict, based on population, the number of devices that each town in Duke Energy's territory (VA, NC, and SC) would need. Then based on the corresponding installation costs (Rentricity's was $500,000), amount of power generated, and cost of electricity in that state, we calculated how many years it would take to recover the costs of initial investment. The results of this model can be found in the table below.

Included in our analysis was an efficiency assumption that larger towns would need fewer devices due to increased population density, thereby decreasing the initial capital costs.

City Size	Average Payback Years
Large	9.00
Medium	11.08
Small	13.74

Table 3: Average payback years after installation of device

Overall, we believe that large towns (population greater than 100,000) will be our best targets. Even though the water distribution systems may be more complicated, we have the potential for higher revenue capture in selling more devices and the ability to pitch the quickest payback schedules. It is important to emphasize how our device fits in the broader picture: the water infrastructure in our country needs updating. We have the opportunity to involve ourselves with the wave of renovations and ultimately reduce the emission levels from power generation in the surrounding community.

3.3 Concept selection

Given the prevalence of turbine systems in the market, we chose to use a turbine as the energy-harvesting and pressure-reducing device in our design. We consulted a SOAR Technologies analysis that identified head (pressure) and flow duration (variability) as parameters critical to the feasibility of a potential project.[5] Pressurized output and variable flow, which occur in water pressure regulation settings, present competing challenges when selecting an appropriate turbine for a system. While impulse turbines such as Pelton or turgo have broad efficiency curves and

[5] http://www.canyonhydro.com/news/SOAR_IWPDC.pdf

can perform well down to 10% of design flow, they operate in open air and therefore are not easily pressurized. On the other hand, reactive turbines such as Francis and Kaplan are effective in pressurized environments but do not perform well under variable flow, and below 50% of design flow, experience significant drops in efficiency. Additionally, given the presence of downstream customers, water must continue to flow unimpeded in the event of device failure. As a result of this issue, all SOAR energy harvesting systems are installed in parallel with existing water systems, allowing the turbine and generator to be taken offline for maintenance without disrupting water supply to the community.

Pelton turbines do not work in flooded cavities and require a high-pressure nozzle, in addition to a free flow draft outlet. This is not useful for our goals as it raises pressure and then releases the water at very low pressure. Kaplan turbines generally rely on high gravitational flow. Francis turbines work well with low-flow and low-pressure applications and can run in either horizontal or vertical orientations. The specific speed of the application also matched with the recommended range of Francis turbines. Ultimately, the team chose the Francis turbine as the pressure-reducing and energy-harvesting device in the design. Table 4 presents a decision matrix used for evaluating the Pelton, Kaplan, and Francis turbines.

Parameter	**Pelton**	**Kaplan**	**Francis**
Flow rate	-1	0	0
Head range	0	1	1
RPM	-1	0	1
Specific speed	1	-1	0
Efficiency	-1	1	1
Total	**-2**	**1**	**3**

Table 4: Decision matrix for turbine selection

4 Prototype architecture

The main prototype consists of three main components: the volute, the impeller, and the shaft. Figure 1 shows the exploded view of the prototype. Figure 2 shows a better view for visualizing components. The pulley for the Prony brake press fit onto the left end of the shaft and protruded out from the main body in final assembly. The first bearing pressed into the hole in the lid, which slipped over the shaft and allowed free movement. A spacer between the lid and press fit impeller kept the components from touching or rubbing against each other. The impeller had a locational fit on the shaft to allow accurate location on the shaft and torque transfer. The second spacer had the same role; to keep the impeller and volute from interfering. The second bronze bearing pressed into a supported ring in the volute outlet. The volute itself has an inlet at the top and a drafted outlet, which connect to flexible hose. The base supports the entire assembly and rigidly secures it to the Prony brake base.

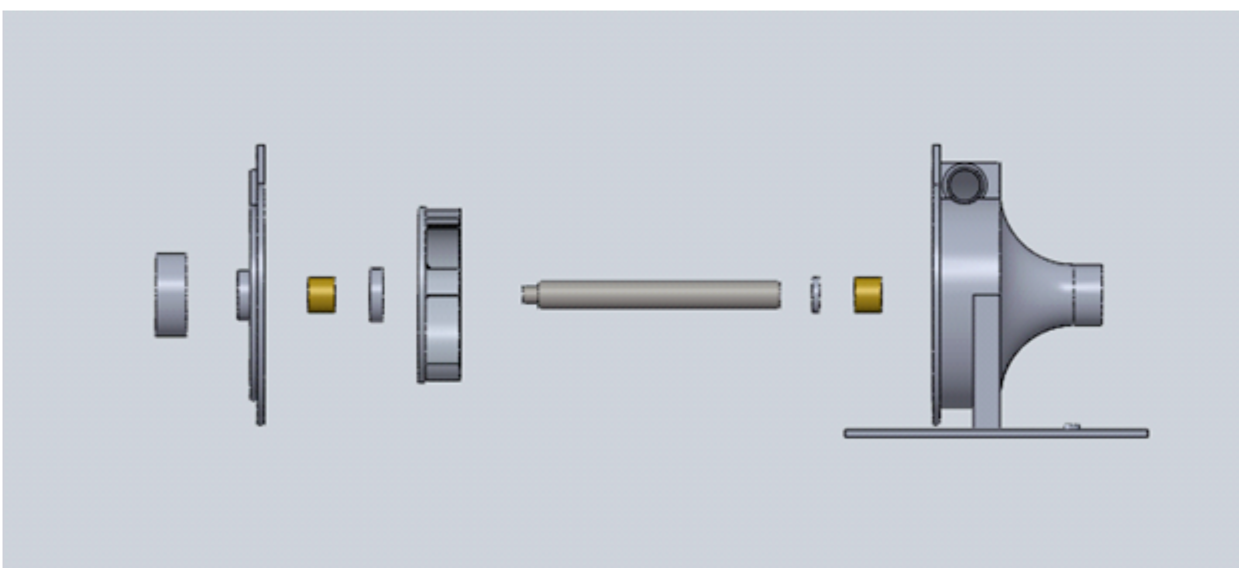

Figure 1: Side profile of exploded prototype. From left to right, the components are as follows: pulley wheel, volute lid, PTFE bronze bearing, spacer, impeller, shaft, spacer, PTFE bronze bearing, and volute with base.

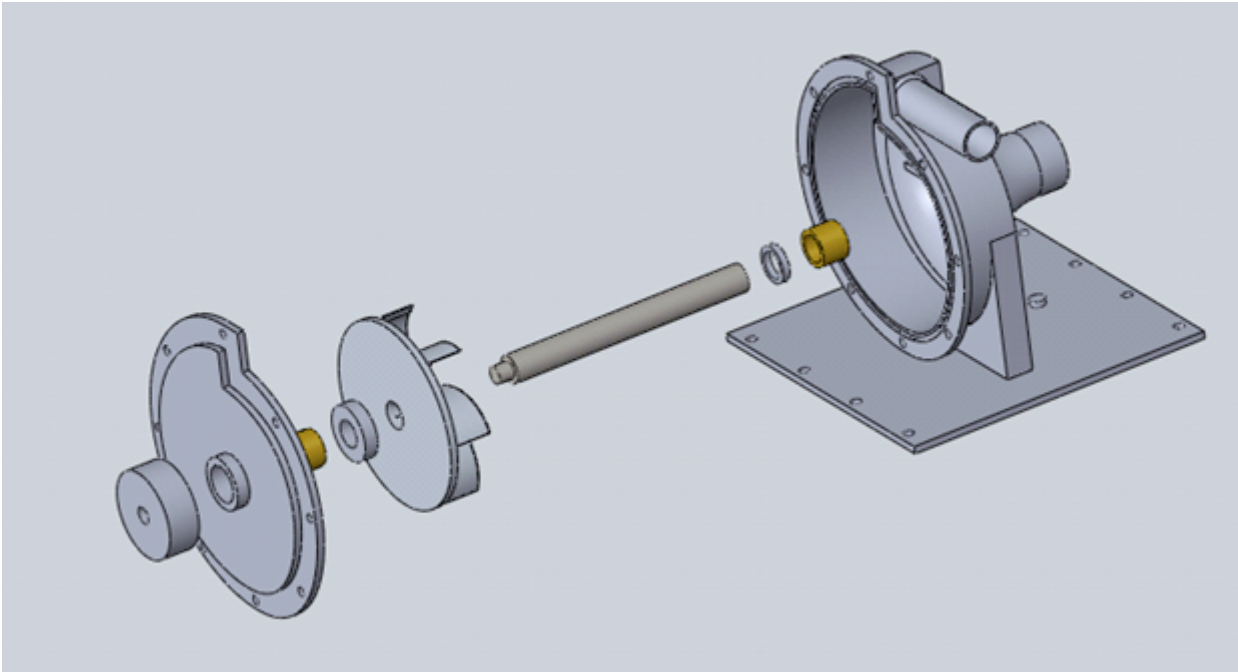

Figure 2: Alternate exploded view

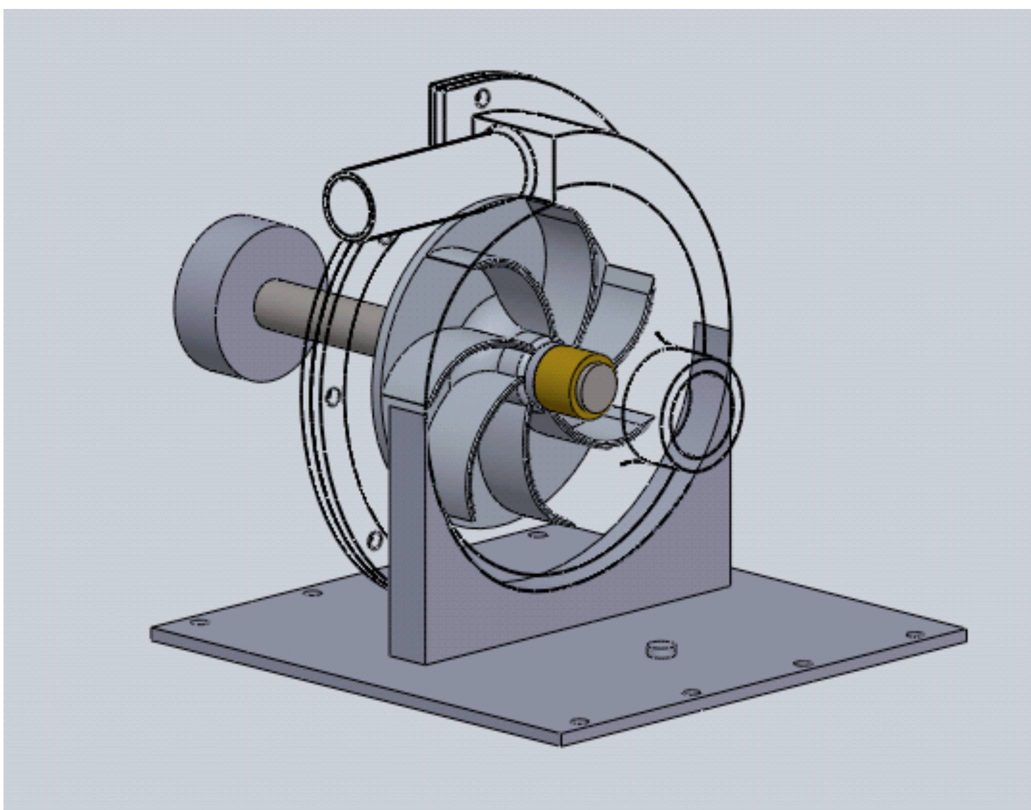

Figure 3: Semi-transparent view of the assembly

4.1 Design components

Impeller

The impeller is based off of a Francis turbine design, simplified for modeling and printing constraints. It is basically a circular base with seven extruded blades and an extruded collar for the shaft. The collar is sized to have a 1.2” long locational fit for the shaft. The blade angles are vital to design; they affect the radial flow component of the fluid, relative to the blades. The guide for designing blades is to have the fluid enter with almost all radial velocity and exit with little to no radial velocity. This is achieved by minimizing the blade angle at the outer diameter formed with the line tangent to the outer circle, so that the fluid enters nearly totally radially. At the inner diameter, the blade should be as normal to the inner circle as possible. The constraint of the blade shape is that there should not be any fluid flow separation from the blade, so the curvature of the spline should not have any discontinuities and be as smooth as possible. For an impeller this small, only five or seven blades are necessary.

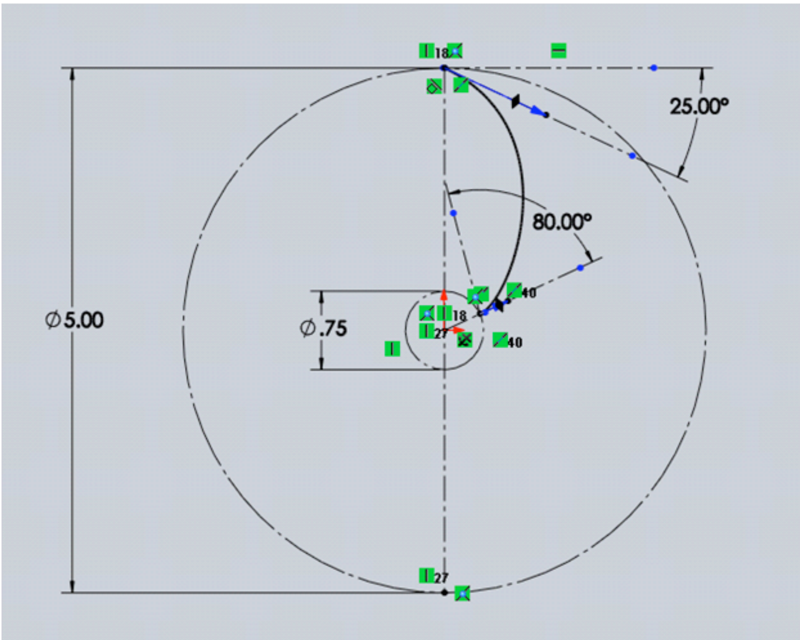

Figure 4: SolidWorks sketch view of the impeller as seen from a top view. The solid spline was constructed using the reference circles of the inner and outer impeller diameters and angles relative to the tangents.

Shaft

The shaft has a simple design. The small diameter press fits onto the pulley on which the belt for the Prony brake slides. The shoulder provides locational security for the pulley. The shaft otherwise can slide easily on the bearings at the uniform 0.75" diameter. The impeller's locational fit also transfers torque. The shaft is stainless steel for strength and corrosion resistance.

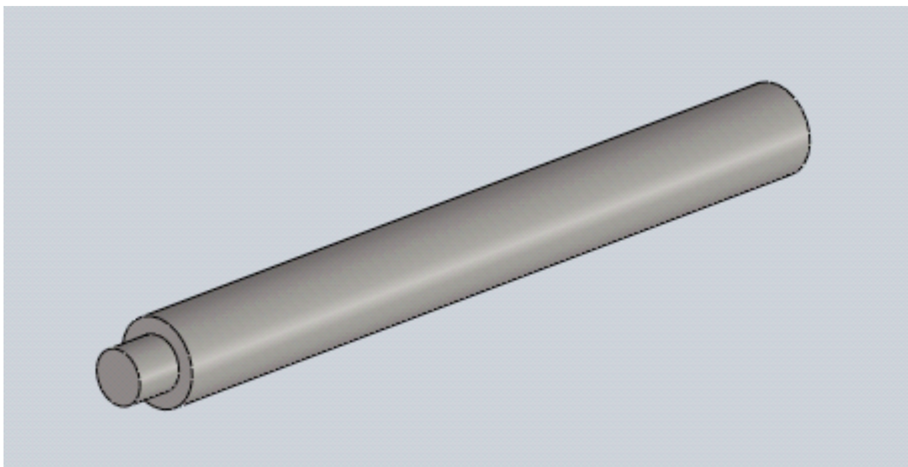

Figure 5: Isometric view of stainless steel shaft

Volute

The volute shown in Figure 6 was another critical component. The top straight pipe is the inlet to be connected to 1" hose. The shape of the volute is a spline fit to have a decreasing radius around the impeller. This would force the water to flow into the impeller radially all around the circumference. Considering the horizontal orientation of the shaft and impeller, the water enters at top to flow down into the impeller. The supports and ring hold the bearing for the shaft. The drafted shape of the outlet allows water to smoothly flow out and around the shaft. The groove on the flange is for the o-ring to create a seal. The o-ring fit in the groove without any need for splicing and created a tight seal with the fastened lid.

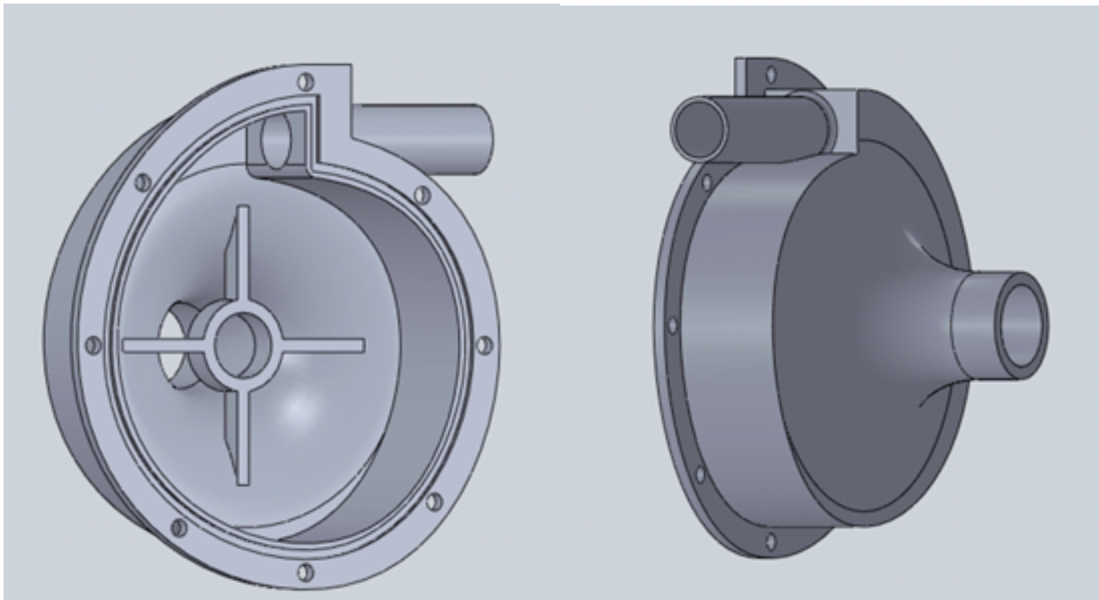

Figure 6: Two views of the volute, showing the inner details and shape

5 Design analysis

In order to size the prototype, a design analysis was performed comparing a prototype to Rentricity's industrial scale. Figure 7 shows a diagram of Rentricity's system:

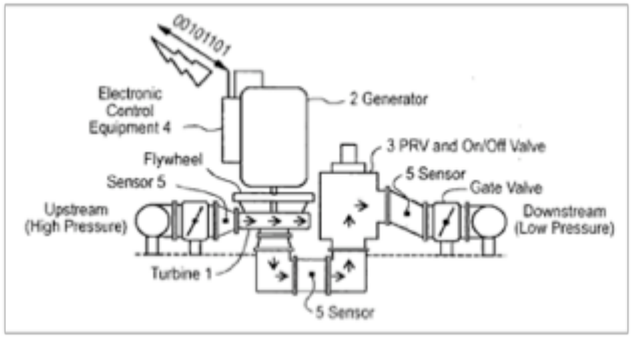

Figure 7: Diagram of Rentricity pressure regulation system

Once the conceptual design was drawn, the parameters that needed to be calculated were the inner and outer turbine radius, as well as the tangential velocity of the water coming in and the radial speed. The comparison of the Rentricity model with the prototype's size and output can be seen below.

Parameter	Rentricity (Model)	Prototype
Flowrate	2.5 MGD	2.9 GPM
Pressure drop	50 psi	50 psi
Inlet pipe diameter	8 in	1 in
Inner turbine diameter	8 in	0.75 in
Outer turbine diameter	3 ft	5 in
Power output	30 kW	0.76 W

Table 5: Flowrate, pressure drop, diameter, and power output parameters for model and prototype

In order to calculate these numbers, dimensional analysis was used as a means to compare the two models. First, some assumptions had to be made. The inner and outer diameters of the Rentricity model were unknown, so they had to be approximated using photographs of the model. Second, tangential velocity had to be approximated using flow rate and cross-sectional area. Third, the exit velocity was designed to be 5% of the entrance velocity.

The dimensionless number used can be calculated as follows, where Q is the flow rate of the water, A_0 is the outlet cross-sectional area, R_0 is the outer turbine radius, and ω is the angular velocity.

$$\text{Flow}, \phi = \frac{Q}{A_0 R_0 \omega}$$

Parameter	Rentricity (Model)	Prototype
Flow [m^3/s]	0.11	0.0002
Outlet area [m^2]	0.032	0.001
Outlet radius [m]	0.102	0.016
Angular velocity (rpm)	3500	1500
φ	0.181	0.185

Table 6: Flow, area, radius, and angular velocity parameters for model and prototype

First, this dimensionless number was calculated for Rentricity's model. Next, the variables for the prototype were changed until a similar dimensionless number could be calculated for the prototype. The numbers calculated are in the table above. Next, in order to estimate the expected torque and power, the following equations were used:

$$\tau_{shaft} = (r_1 V_T - r_2 V_{T,2})\dot{m}$$

$$\text{Mechanical Power} = \dot{W}_m = \omega\tau = \omega(r_1 V_T - r_2 V_{T,2})\dot{m}$$

The values calculated for these two parameters are as follows:

Parameter	Rentricity (Model)	Prototype
Torque [Nm]	167	0.004
Power [W]	30,652	0.76

Table 7: Torque and power parameters for model and prototype

6 Prototype construction

The construction of the prototype began with the 3-D printing of the volute, lid, impeller, and base. Team members then cut the shaft to a 7.72" length and machined on the lathe to create the ~0.45" smaller diameter shoulder. The team also partially bored out the shaft to reduce mass and weight. The printed lid and volute had bearings press fit into the holes, and the team made sure that the shaft could slide and run easily in the PTFE bearings. The base was fastened to the Prony brake base, which was taken from another test set-up and had its own base to accurately locate the pulley. Using epoxy, we secured the volute to the base before other components were added. The impeller was pressed onto the shaft with wood blocks to prevent damage to the components. The spacers were made of round Delrin stock, machined to washers that loosely fit on the shaft. At first, the spacers were too wide and were causing interference, so they were grinded down once on the shaft. The printed ABS lid was fastened onto the volute once all other components were assembled.

The fastening of the lid caused the shaft to jam and not turn freely. After much troubleshooting, a team member found that the lid was warped, either in manufacturing or assembly, and caused the bearing to be angled off the axis of rotation once it was fastened. An acrylic lid was laser cut and sealed with epoxy to a composite plastic tube for the bearing. The shaft components were partially disassembled and the lid was replaced. The new acrylic lid allowed the shaft to spin freely when sealed.

For the testing assembly, a 12V pump rated for max 50 psi and 3-gpm flow was connected by hose to a rotameter. We connected a 1' length of 1" schedule 40 pipe to the outlet of the rotameter to a pressure gauge. Another flexible hose followed after to connect to the inlet of the volute. The outlet similarly was connected to a semi-flexible hose, which was in turn connected to a valve, a pressure gauge and the hose exiting to the water supply bucket. All pipe connections were NPT sealed with Teflon tape and hose connections were clamped and silicon sealed where necessary.

6.1 Material Selection

The main concern in material selection was potential rusting due to contact with water. To this end, stainless steel was chosen for the shaft. The volute was 3D printed, hence made of ABS plastic. This led to problems with testing, as the ABS plastic material was porous. When the flow rate of the water was increased, water would begin to seep out of the volute itself. The lid of the volute was originally also ABS plastic. Unfortunately, it printed warped and impeded the rotation of the shaft. Acrylic was used instead to create a lid by cutting it with a laser. In addition, it allowed for viewing of the inside of the volute, which was helpful during testing.

6.2 Budget

The largest expenditures to create the prototype were the pump and the pressure gauges; in any application, there would not be a pump, as the water would already be coming in at the designed pressure and flow rate. Table 7 provides a breakdown of the prototype budget.

Product Description	Quantity	Price
Acrylic & Hose		
1’ Length Optically Clear Cast Acrylic Tube 1-1/2” OD X 1” ID	1	$29.57
5’ Length Crack-Resistant Polyethylene Tubing 1-1/8” ID, 1-3/8” OD, 1/8” Wall Thickness, White	1	$5.95
Optically Clear Cast Acrylic Sheet 1/4” Thick, 12” X 12”	1	$16.36
316 Stainless Steel Push-on Hose Fitting Adapter for 1/2” Hose ID X 1/2" NPT Male Pip	1	$25.75
2ft Length Kink Resistant Coolant Hose w/ Wire Support, 1-3/8” ID, 160 PSI, Blue	1	$35.48
1ft Length Kink Resistant Coolant Hose w/ Wire Support, 1-3/4” ID, 150 PSI, Blue	1	$19.82
Worm-Drive Hose Clamp w/ Zinc-Pltd STL Screw 1-5/16” to 2-1/4” Clamp Dia Range, 1/2” Band Width	1	$6.99
Turbine		
PTFE-Lubricated SAE 841 Bronze Sleeve Brng for 3/4” Shaft Dia, 1” OD, 3/4" Length	4	$12.80
Type 316 SS Drive Shaft 3/4" OD, 18” Length	1	$37.04
Type 304 Stainless STL Threaded Pipe Fitting 1 X 1/2 Pipe Size, Reducing Coupling, 150 PSI	1	$10.25
Std-Wall 304/304L SS Thrd One End Pipe Nipple 1 Pipe Size X 3” Length	3	$15.84
Std-Wall Type 304/304L SS Thrd Pipe Nipple 1 Pipe Size X 12” Length	1	$18.53
Stainless Steel Gauge SS Case, Dry, 2-1/2” Dial, 1/4 Bottom, 0-100 PSI	2	$82.94
Type 304 Stainless STL Threaded Pipe Fitting 1 X ¼ Pipe Size, Reducing Coupling, 150 PSI	2	$18.98
Type 304 Stainless STL Threaded Pipe Fitting 1 Pipe Size, Tee, 150 PSI	2	$37.38
Std-Wall Type 304/304L SS Thrd Pipe Nipple 1 Pipe Size X 2” Length	3	$13.29
Type 316 Stainless Steel Ball Valve with Lever and Unrestricted Flow, 1” Pipe Size	1	$60.35
Type 304 Stainless STL Threaded Pipe Fitting 1 Pipe Size, 90 Degree Elbow, 150 PSI	2	$26.14
Type 304 Stainless STL Threaded Pipe Fitting 1 X 3/4 Pipe Size, Reducing Coupling, 150 PSI	1	$10.68
Extreme-Pressure 316 SS Threaded Pipe Fitting 1 X 3/4 Pipe Size, Hex Nipple	1	$77.98
Pump		
One (1) Flojet 03526-14A 2.9 GPM 50 PSI Water Pump	1	$69.95
One (1) Quik05 Quikker Connectors	1	$41.95
	Total	**$674.02**

Table 8: Prototype budget

7 Testing

7.1 Testing apparatus

The testing apparatus was designed to measure four parameters: 1) inlet and outlet water pressure (P), 2) inlet flow rate (Q), 3) torque (T), and 4) angular velocity (ω). Parameters 1 and 2 measure the device's ability to reduce pressure at a given flow rate, a key design objective. Parameters 3 and 4 are important for calculating the power output of the device. The diagram below provides a schematic of the testing apparatus.

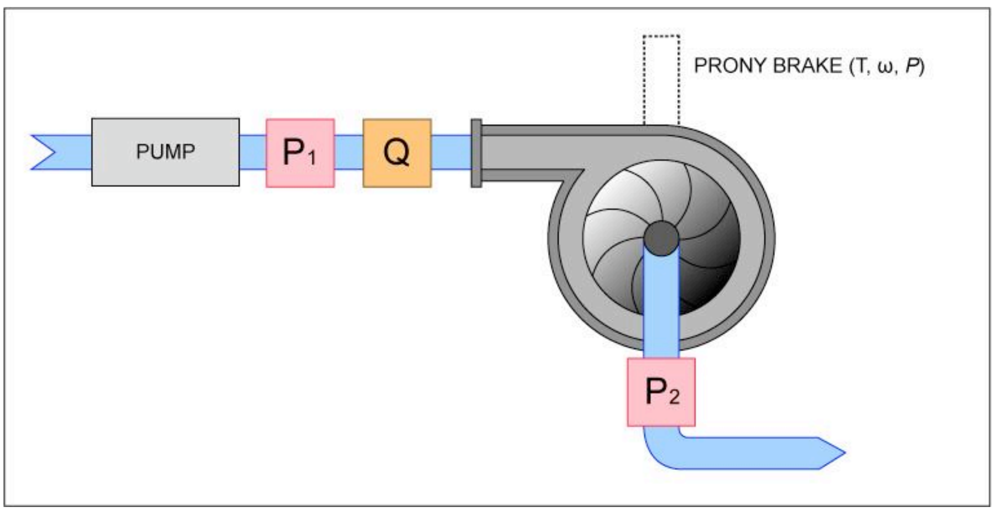

Figure 8: Schematic of testing apparatus

7.2 Testing procedure

Inlet water first flowed through a DC-powered pump. The pump can produce water pressure of 30 psi at 2 gpm. The total power available from the pump is 26 W. After flowing through the pump, the water entered a 1" pipe, and subsequent pressure gauge (P_1) and rotameter (Q) measured water pressure and flow rate, respectively. 1" plastic tubing connected the outlet pipe from the rotameter to the turbine inlet. After flowing through the turbine device and outlet tubing, the water entered a second pressure gauge (P_2) to measure outlet water pressure. Outlet water was fed into a plastic bucket via plastic tubing, and this bucket served as the source for inlet water.

A Prony brake on the shaft pulley measured torque, and a stroboscope indicated angular velocity. These measurements are used to calculate the power output of the device. Figure 9 shows the full testing apparatus.

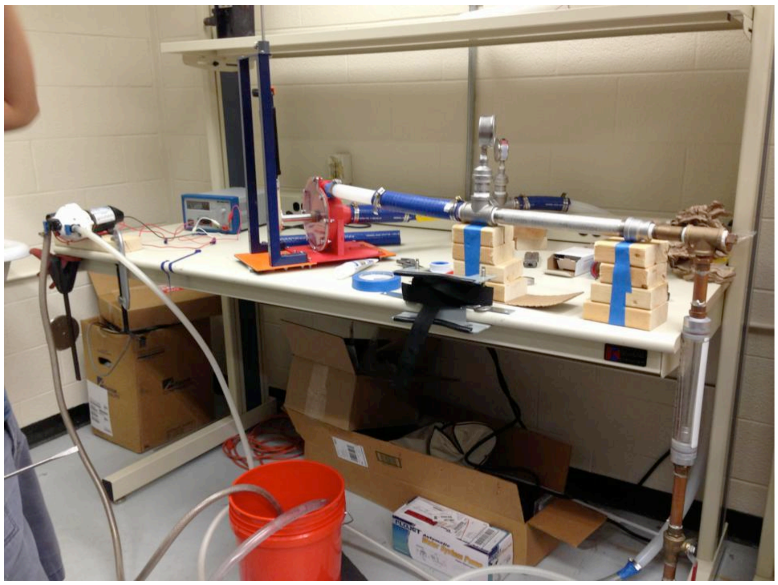

Figure 9: Testing apparatus

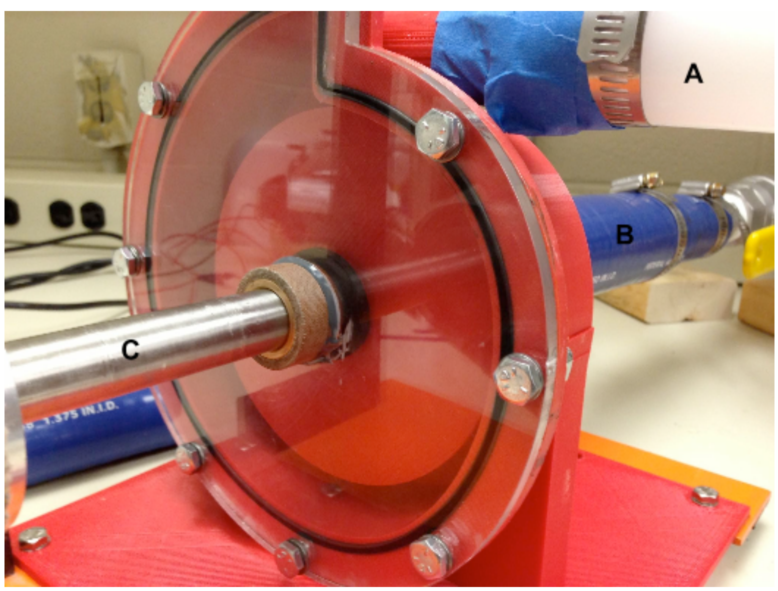

Figure 10: Turbine with inlet pipe (A), outlet pipe (B), and shaft (C)

7.3 Results

Initially, testing was attempted indoors with both a 50 psi, 2.9 GPM pump as well as faucet water. This provided enough water to flood the volute but did not cause it to turn as it did have a large enough flow through the inlet. Attempts were made to increase the pressure within the volute by closing a valve on the outlet pipe. This unfortunately made the plumbing start to leak somewhere new every time a part was sealed, including the volute due to the porous property of the plastic.

In order to increase the flow rate going through the device, we disconnected all the plumbing shown above in the testing apparatus and took it outdoors to hook it up to a hose. Once the shaft was pushed all the way inwards, and the hose was pumping approximately 9.5 gallons/minute through the volute, it began to turn. The shaft rotated at approximately 70 rpm. Although the outdoor setup did not allow for the prony brake to measure the torque, the revolutions demonstrated the proof of concept.

8 Future work

8.1 Changes to design

The volute body leaked out of pores in the ABS, so a future design would either be an epoxy-sealed thicker 3-D print, or stronger solid plastic for testing. If the prototype was meant to last, the team would send the part to be machined - the volute is an unusual shape and extremely difficult for the inexperienced. The acrylic lid worked better than the printed lid, which warped, and had the benefit of allowing observation of the impeller during testing. The shaft and pulley components were heavy for the flow available, so the next shaft iteration would be designed for smaller radii at the bearings and lower overall weight. The overall dimensions of the design could also be reduced further to reduce flow and pressure.

8.2 Prototype to production

The scaled-up version of the Francis turbine would have a more sophisticated blade design. Stainless steel material, no flat base, and many more blades at a larger diameter would account for the greater flow and pressure impacting on the impeller. The volute would also be stainless steel, and have a circular, seashell-like shape for smooth flow around the impeller. The sides of the volute would have less clearance to the top and bottom of the blades to guide most of the flow into the blades at the outermost radius.

The shaft would need to be designed for greater loads, accounting for axial loads. The bearings would be sealed if ball bearing and consistently lubricated. A more in-depth shaft analysis for radii and loads would be needed for each application. The shaft would connect to a generator instead of a pulley wheel and be constructed for great torque design. Like in SOAR Technologies operations, the industrial scale device should be built in parallel with existing water pressure regulation infrastructure so that the device may be taken offline for routine maintenance without disturbing water supply to downstream customers.

The investment cost of one turbine for 20 kw to 50 kW, not accounting for cost of labor and other costs, would be in the range of $48,000 to $115,000. All stainless steel construction, large bearings, and custom manufacturing for the unusual volute shape and blades could increase the price.

Finally, any scaled-up projects involving public utilities are subject to strict regulatory requirements. In the U.S., hydropower projects such as Delta P fall under the same regulatory category as larger scale hydro projects and thus require permitting by the Federal Energy Regulatory Commission (FERC), as well as approval by local power companies. According to SOAR Technologies, FERC permit applications generally take two months to prepare and require the agreement of multiple agencies, environmental groups, tribal leaders, and other stakeholders. Submitted applications take about six months to gain FERC approval. In the experience of SOAR Technologies, the cost of obtaining regulatory approval sometimes makes it economically unviable for a public utility company to implement such a project. However, FERC is working to streamline its approval process for energy recovery projects, thus increasing the potential for such projects to flourish.[6] Costs of obtaining regulatory approval should be factored into the overall cost of installation per turbine.

[6] http://www.canyonhydro.com/news/SOAR_IWPDC.pdf

9 Environmental impact analysis

Ignoring any potential negative environmental impacts incident to the manufacture of the device (which would be very similar to the manufacture of other components of the water system and therefore quite small), analysis of impacts caused by usage of the device are confined to reductions in emissions of pollutants caused by a displacement of conventional electricity generation by electricity produced by the device. Therefore, in order to understand the impacts, two main pieces of information must be known. First, the aggregate expected electricity produced by our turbines in a defined region must be estimated. Second, the effect on the power plant fleet in that region caused by the generated electricity must also be estimated.

To determine the first bit of information, the electricity generated by the device, Rentricity's existing turbines were examined. The company has deployed one of their turbines in the water system of the city of Keene, New Hampshire. The turbine is rated at 62 kW, and the water flowing through the turbine is intended to serve 20,000 people. Since reliable data were unavailable, and understanding that water flow in municipal systems can vary from 100% capacity in summer months to near 50% in the winter, and also that all water systems are certainly not going to produce the same profiles, the capacity factor for a theoretical turbine was reasonably estimated to be 75%. Assuming a 75% capacity factor, the Rentricity turbine in Keene would produce 407.3 MWh annually.

For reasons that will be explained later, a region consisting of Virginia, North Carolina, and South Carolina was chosen for the emissions analysis. With the estimated power output of a turbine serving 20,000 customers known, analysis turned to estimating how much power would be produced if similar turbines were deployed in similar situations in this region. Our estimates looked at what is perhaps a "best case scenario" of deployment: that is, the power generated if every city in the region at least as large as Keene installed turbines. While the decision by a municipality of whether or not to install a turbine rests on many factors analyzed above in section 3.2, this scenario of universal deployment in cities with more than 20,000 could be plausible in a number of situations, including a future of high electricity costs or a state or federal-level policy that requires or provides funding for the turbines. For cities with populations greater than 20,000, the energy produced relies on assumptions that multiple "Keene-sized" turbines would be used in the single system (ie. 2 turbines serving 40,000 people, 4 serving 80,000, etc.). While this may not be a totally realistic scaling up of the Rentricity turbine, it is the most reasonable estimation based on available hard data. Once all applicable cities in the three states were identified, the aggregate installed capacity was estimated to be 22.522 MW, and the aggregate annual power produced (assuming a .75 capacity factor) was 147,969.5 MWh.

To calculate the emissions reductions caused by the displacement of power plant generation of the turbines, we used the Environmental Protection Agency's Power Plant Emissions Calculator (P-PEC). P-PEC is a tool currently undergoing peer review that was developed in 2012 by a team at EPA's Research Triangle Park campus that included group member Ben Rakestraw. The tool, which is intended for the analysis of state and regional energy efficiency and renewable energy policies, calculates the effects on pollutant emissions caused by a reduction in electricity demand in a given region. In order to determine these effects, the tool looks primarily at a particular plant's capacity factor and pollutant emission rates. It has been determined by EPA that the lower a plant's capacity factor is, the more likely it will be that that particular plant will reduce generation when faced with a reduction in demand for electricity in the region. The regions in the P-PEC are divided based on areas set by the North American Electric Reliability Corporation (NERC). The NERC region that includes Duke essentially corresponds to the states of Virginia, North Carolina, and South Carolina, hence the choice of these states for the turbine analysis.

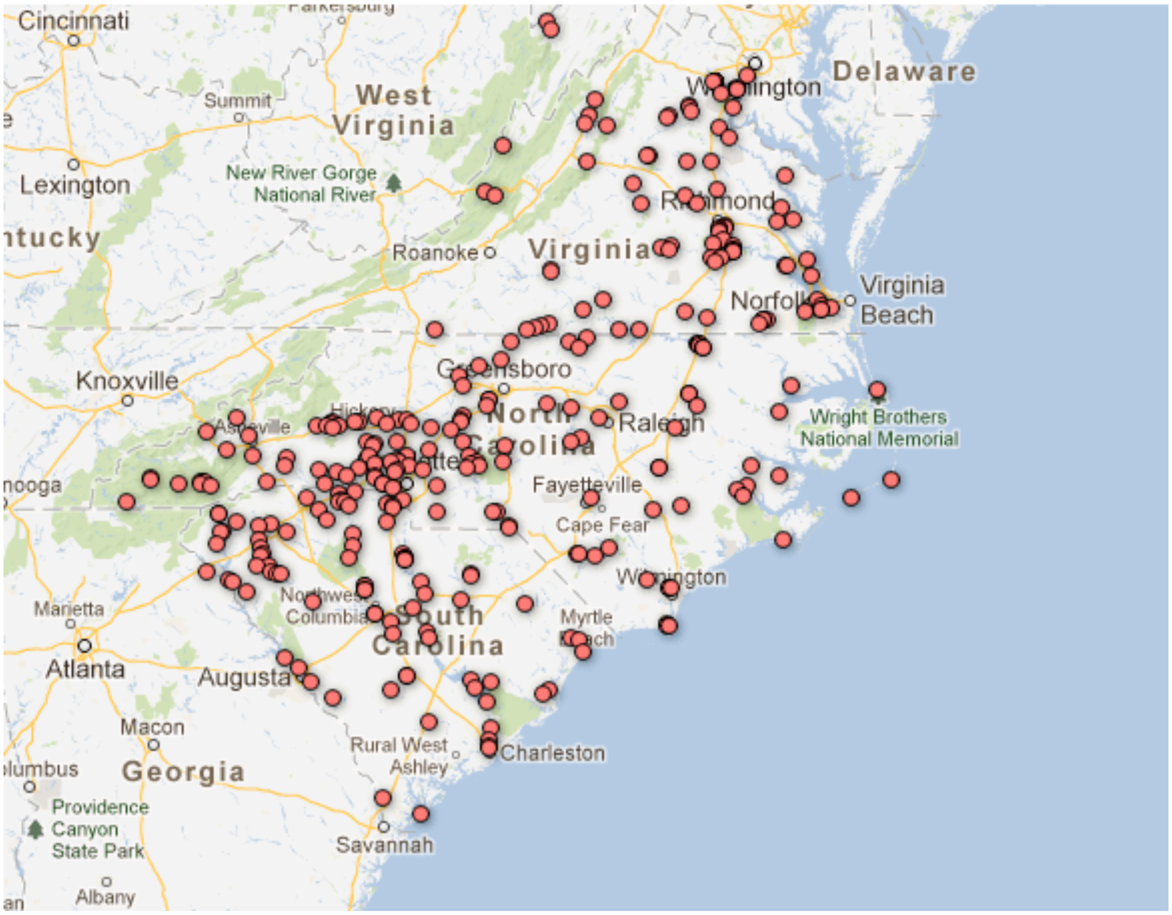

Figure 11: Map displaying all power plants in the region under analysis

To estimate the pollutant reductions in P-PEC, the aggregate annual turbine output in the region (147,969.5 MWh) was entered into the calculator. The calculator then provided information on reduction of pollutants including: Nitrogen oxides (both annually and in the “ozone season” in summer), Sulfur dioxide, and Carbon dioxide. The tool is also able to display graphs of the top ten individual power plants for reductions of each pollutant. Table 8 provides a summary of the emissions results calculated by P-PEC.[7]

Pollutant	Emissions reduction (short tons)
Nitrogen oxides (annual)	87.47
Nitrogen oxides (ozone season)	33.10
Sulfur dioxide	301.17
Carbon dioxide	103,898

Table 9: Projected emissions reductions from Delta P turbine installation

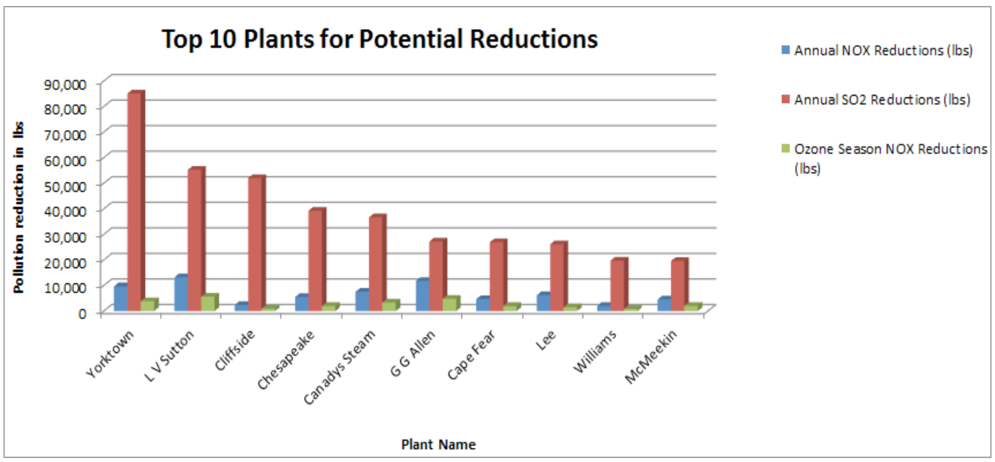

Figure 12: Top 10 plants in the region for emissions reductions of NOx and sulfur dioxide

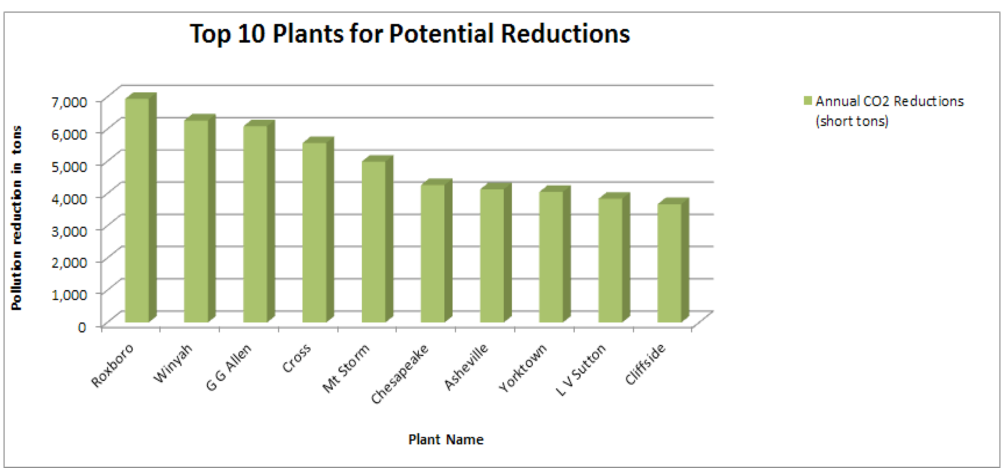

Figure 13: Top 10 plants in the region for emissions reductions of carbon dioxide

[7] For additional information on P-PEC, please consult the EPA's website at http://www.epa.gov/airquality/eere/quantify.html.

10 Conclusion

As a proof of concept, the Delta P prototype demonstrates that movement of water through the device produces rotational motion of the turbine impeller, which in turn drives the shaft torque. Further work should seek to refine the prototype by employing more resilient, non-porous materials for the volute and reducing the weight of the shaft and pulley. While the projected power output of the prototype is low (<1 W), the industrial scale model is expected to produce 20-50 kW. If employed in public utility facilities across the United States, Delta P could have significant environmental benefits as an offset of carbon and other criteria air emissions.