New York State Energy Research and Development Authority

# Hydropower from Wastewater

Final Report

December 2011

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# Hydropower from Wastewater

Final Report

Prepared for the

**New York State Energy Research and Development Authority**

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# NOTICE

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# EXECUTIVE SUMMARY

This project designed, prototyped, and evaluated a 15kW integrated turbine/generator system for application to capturing flow energy contained within the effluent stream at wastewater treatment plants. The specification for the prototype system was based on a survey of wastewater treatment plants in New York State; it is expected that plants of similar size and diversity exist in other states and countries. The prototype system was designed to deliver 15kW of electric power to the utility grid when supplied with a flow of 12 million gallons per day (MGD) and a head of 12 feet.

This project was undertaken through the collaborative efforts of Advanced Energy Conversion, LLC (prime contractor), Turbo Solutions Engineering LLC, and Clark Engineering & Surveying, P.C., all small businesses. The objective of the project was to develop and demonstrate technology that could address capturing energy from flowing water and converting that energy into electricity that could be used to offset operating expenses or create an untapped revenue stream.

Using concurrent design, the turbine design was integrated into the design of a permanent magnet generator. Consistent with the head and flow of the prototype turbine, a propeller-type turbine was selected. This choice was also consistent with the relatively low heads available at wastewater treatment plants. The rotor of the generator was integrated into the outer rim of the turbine rotor.

Design of the turbine rotor was supported by one- and three-dimensional flow analysis that was subsequently verified using computational fluid dynamics (CFD) analysis. The generator design was based on a fractional slot stator winding that minimized end turn length and simplified the construction of the stator. The stator of the generator was integrated into the mechanical design of the turbine/generator support structure. This support structure included a tapered inlet section that allowed the entire turbine/generator to be housed within a section of pipe that was of standard size. Mounting the turbine generator within a section of pipe allows for turbine/generator maintenance without putting personnel at risk or requiring the flow at the WWTP outfall to be shut down, even temporarily.

Fabrication and test showed that the integrated system operated largely as designed. The significance of the turbine efficiency curve on system performance was underestimated during the design process. In hindsight, it might have been appropriate to select a different type of turbine with a broader efficiency curve. Selecting another style of turbine, however, would have substantially complicated the system design because of the challenges associated with routing the fluid through the turbine and generator.

An analysis of the potential turbine/generator market within wastewater treatment plants suggests a potential United States market size of $50 -- $100 million by serving the 2,600 wastewater treatment plants that are viable candidates for the technology. Accessing this market will require modest cost reductions in the turbine/generator system that should be achievable.

Extending the turbine/generator to other markets is possible. Nevertheless, these markets are likely characterized by requiring higher head. Operating at higher head allows the possibility of increased energy capture without substantially increasing the size of the turbine/generator. Operation at higher head would require the selection of a different type of turbine, which might improve overall system operation over varying speeds. It would be vital to maintain as much simplicity in system design as possible.

## Introduction and Overview

There are more than 15,000 publicly owned wastewater treatment facilities in the United States. These facilities process in excess of 34,000 million gallons of water per day (34,000 MGD). There is energy of increasing value contained in the effluent stream, representing an emerging business opportunity. It is worthy of note that there are similar applications with substantially larger amounts of energy available. These applications include: raw water transmission lines, run of river hydro, water-intensive industrial processes, and gravity fed public water supplies.

The project described in this report evaluates the potential for building a business around harvesting energy in wastewater effluent streams. This business could easily grow into other markets, notably the potable public water supply in which pressure reduction valves are used to throttle (reduce) the pressure by dissipating energy rather than capturing it. Industrial processes that are heavy users of water are also likely candidates. This project focuses on wastewater because:

- Wastewater treatment plants (WWTPs) are large consumers of electrical energy, thereby creating a ready use for any energy captured from the effluent stream. Electricity is the second largest operating cost at WWTPs, representing 25 to 40% of the total operating budget. Pressure reduction valves distributed throughout the public water supply do not necessarily have the same natural load present where the energy is harvested.

- Wastewater treatment plants are hungry to reduce their energy consumption, making them open to trying new technology with an acceptable risk mitigation plan.

- There are no licensing requirements as with many water flows.

A business to serve the wastewater treatment industry must be based on:

- Developing an integrated turbine/generator that can be installed in effluent flows, converting flow power into electrical power. The turbine/generator must be able to be easily customized to the available head and flow at each facility. Each installation cannot represent a custom design.

- Developing the associated power and control electronics that simplifies the interface of the captured energy into the wastewater treatment plant electricity grid through a motor control center or other appropriate interconnection point.

- Developing a generic installation approach that minimizes interruption to the operation of the wastewater treatment plant. In addition, the ability to bypass the turbine/generator must be incorporated, as well as a means for maintaining the equipment without interrupting the operation of the balance of the plant.

- Developing a business model for deploying the technology that respects the purchasing practices/requirements of municipalities, avoids capital construction projects for the wastewater treatment plant, and goes beyond a simple equipment purchase to provide sustained cash flow.

The following sections of this report address the technical development and demonstration of an integrated turbine/generator system that was designed to support application in a wastewater treatment plant. The business case is considered also, with the technology case and the business case converging to support the project conclusions.

# Design of the Prototype Turbine/Generator System

The design of the prototype turbine/generator system was driven by a review of requirements for various wastewater treatment facilities. Emphasis was placed on New York State plants, with the expectation that plants in other states and countries would have similar requirements.

## Specification Development

A review of data from the NYS Department of Environmental Conservation indicates that there are 78 WWTPs with a rated flow of 5 MGD, broken down as follows:

- 28 in the range of 5 to 10 MGD
- 29 in the range of 10 to 40 MGD; and
- 21 above 40 MGD.

The plants having flow rates in the range of 10 to 40 MGD was selected for further analysis. Seven of these plants were visited. Detailed flow data were collected from 15 plants. Survey data and interviews were conducted with 25 plants. Subcontractor Clark Engineering & Surveying, P.C. assisted with this effort.

Key findings from the interviews include:

- An intense interest and desire to use the technology
- There is a diverse range of operating conditions, physical designs, and economics
- The equipment must be designed suitably for installation: it cannot interfere with operations or EPA data requirements; it must be low maintenance; and, it must have a 10 – 30 year life
- A payback of five years is needed, but plants have widely varying electricity costs ranging from $0.06 to $0.16 / kWh plus varying demand charges
- Over 50% of the plants are suited to installation of standardized intake structure at outfall after final process. Other designs are also possible
- For a target power yield of 10 – 20 kW, an installed cost of less than $50k meets interest level.

It was concluded by the design team that critical factors for commercial success include:

- The available head or velocity at the plant
- The ability of the turbine/generator unit to be tolerant of submergence

- Ease of installation access
- Ease of maintenance access
- Absolutely no backwater impact on the process or EPA testing; and
- Proximity to power usage is an important factor in the installation cost.

Figure 1 depicts the possible locations of the turbine/generator equipment. From the survey, it was clear that the equipment needed to be downstream of the last process. Beyond that, location is driven by energy capture, ease of installation, ease of maintenance, and minimizing installation cost. Given that cable lengths are minimized by locating the turbine/generator equipment close to the final outfall, Figure 2 suggests the preferred placement of the equipment.

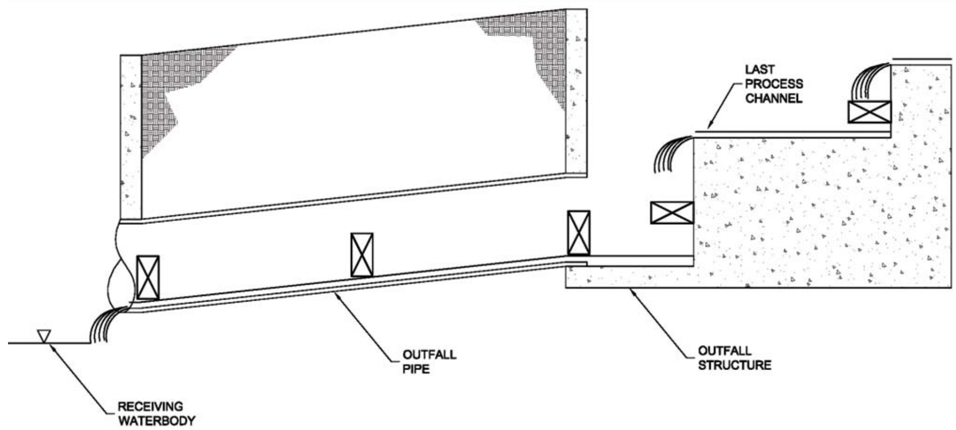
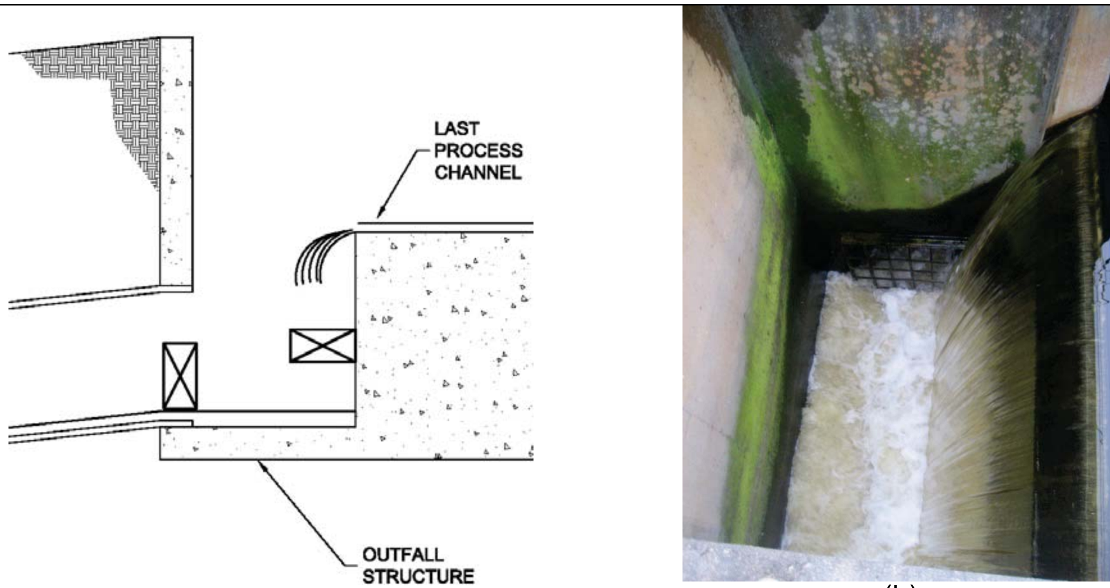



Figure 1: Possible locations of the turbine/generator system.




(a) (b)

Figure 2: The most desirable locations of the turbine/generator system: (a) schematically at the outfall following the final process; (b) a picture showing the flow can either be caught at the outfall, or in the pit where the flow is directed into the output channel.

Figure 3 provides a distribution of the head and flow for the surveyed plants. The plants with the highest product of head and flow represent the best opportunities. For the prototype system, emphasis was placed on average daily flows in excess of 10 MGD and heads of 10 ft or more.

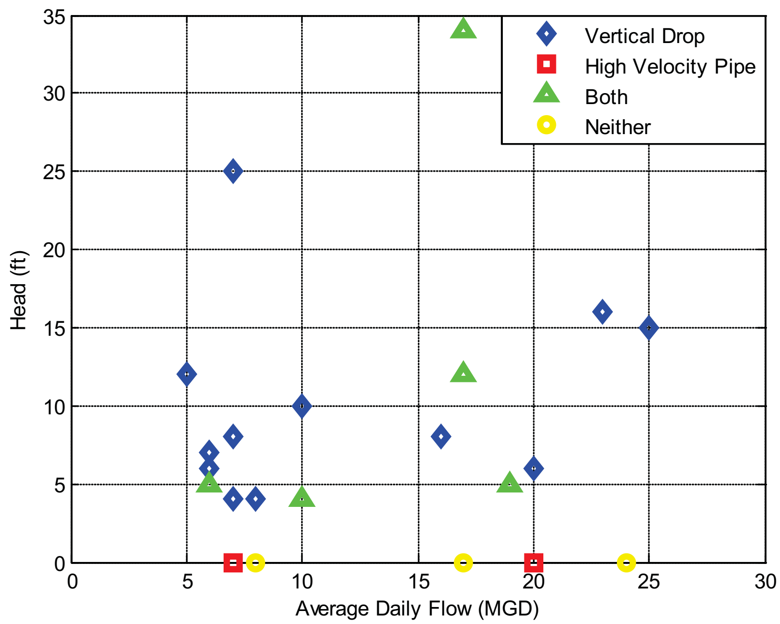



Figure 3: The distribution of head and flow for the surveyed WWTPs.

A summary of operator data collected during the interviews includes:

- 75% of the WWTPs have suitable hydraulic drop for energy recovery, with over 50% in "ideal" range
- 30% of the WWTPs have pipes with significant velocity head; some have both pipes and outfall opportunity
- 25% of the WWTPs could accommodate 2 or more units
- Only 15% of the WWTPs have neither suitable hydraulic drop nor significant velocity head
- Two thirds of the operators expressed a very strong interest in the project and are willing to provide additional review and feedback
- 80% of the operators have a 480V MCC and/or equipment for power utilization in close proximity to the outfall; and
- A 5 year return on investment is essential for energy saving capital budget approval.

Specifications elements driven by market research include:

- Intake design must be flexible to match site requirements to turbine/ generator capacity
- Allow for customization and low cost
- Ease and low cost of installation, removal, and maintenance
- The equipment must survive constant contact with the effluent; and
- Have a usable life of 10 to 30 years.

Table 1 summarizes the operational parameter range of the turbine/generator with the design target for the experimental prototype.

Table 1: A summary of turbine/generator parameters, practical ranges to address the WWTP market, and the design targets for the experimental system.

| **Parameter** | **Range** | **Prototype Design Target** | **Units** |
|---|---|---|---|
| Fluid | Water with debris, aeration, turbulence | Water with debris, aeration, turbulence | |
| Head | 1 – 20 | 10 – 12 | feet |
| Volumetric Flow Rate | 5 – 100 | 5 – 20 | MGD |
| Rotational Speed | 400 – 800 | 600 | rpm |
| Turbine Efficiency | 75 – 95 | > 90 | % |
| Output Power | 1 – 200 | 15 | kW |

## Turbine Design

Turbo Solutions Engineering assisted Advanced Energy Conversion (AEC) in the design of a turbo-generator for use in wastewater treatment plants. Figure 4 shows a turbine selection curve based on head and flow. Because of the low head in the intended application, the selected turbine runner is a fixed-pitch propeller type turbine with no wicket gates to assist in the control of the flow entering the runner. Structural struts are located just downstream of the runner. This type of hydraulic turbine tends to have an efficiency characteristic with a sharp peak because it has fixed geometry developed for a specific operating condition. As shown in Figure 5, if the turbine is operating slightly off the design condition, the efficiency will be reduced dramatically.

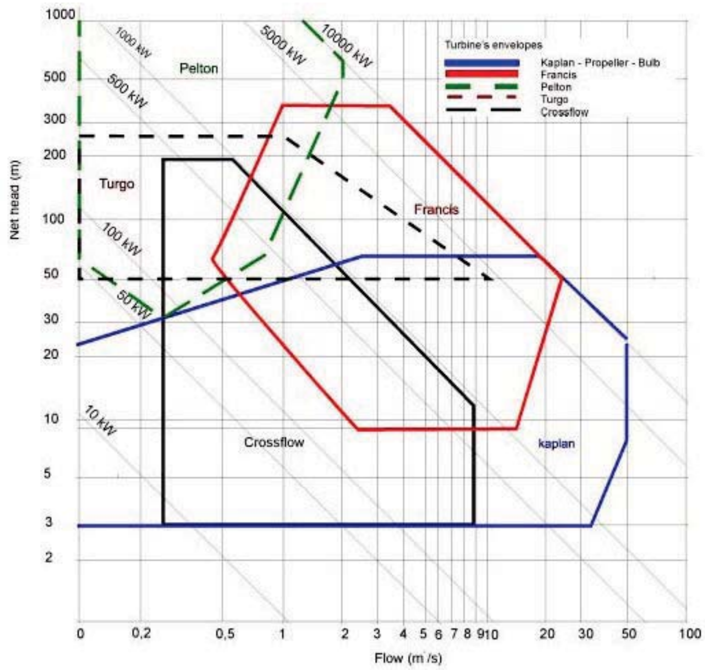



Figure 4: A turbine selection chart based on flow and head.

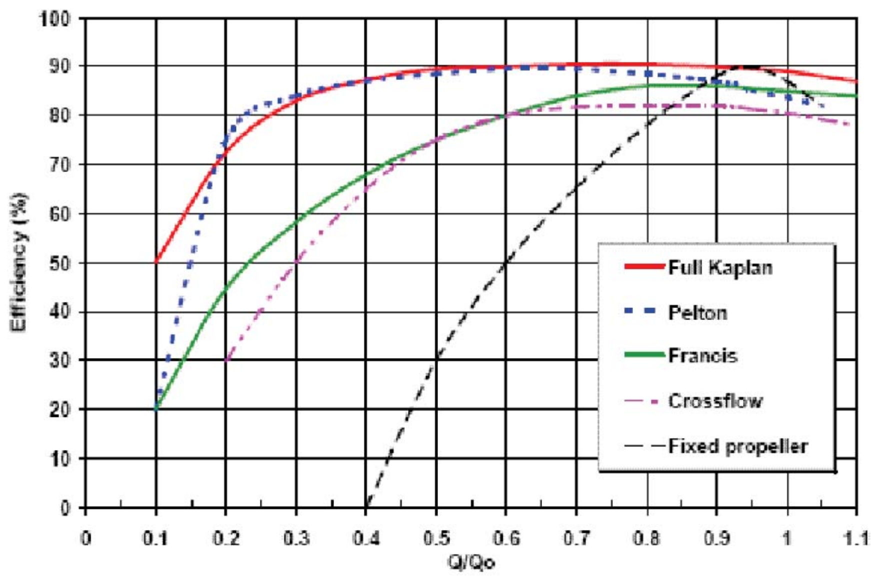



Figure 5: Efficiency characteristics as a function of normalized flow for different types of turbines.

Turbine design was based on one- and three-dimensional hydrodynamic design and analysis. Computational fluid dynamic (CFD) analysis was used to refine the design. Solid modeling of the rotor, inlet, housing, diffuser, and structural supports were developed to build a complete picture of the turbine design. Figure 6 shows the volumetric flow rate as a function of head at different turbine rotational speeds, with contours of hydraulic efficiency superimposed. Figure 7 shows the power output available as a function of head consistent with the turbine curves shown in Figure 6. To maximize power output, operation at higher turbine speed is preferable. This is also consistent with the desire to minimize generator size.

Structural analysis was performed to determine rotor steady state stresses and natural frequencies. Structural analysis was also applied to the rotor support structure.

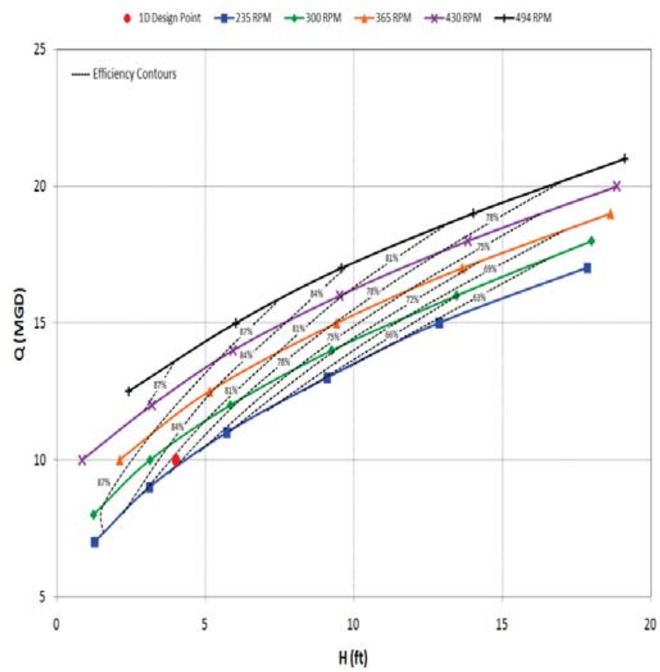



Figure 6: Volume flow rate as a function of head for turbine operation at various speeds.

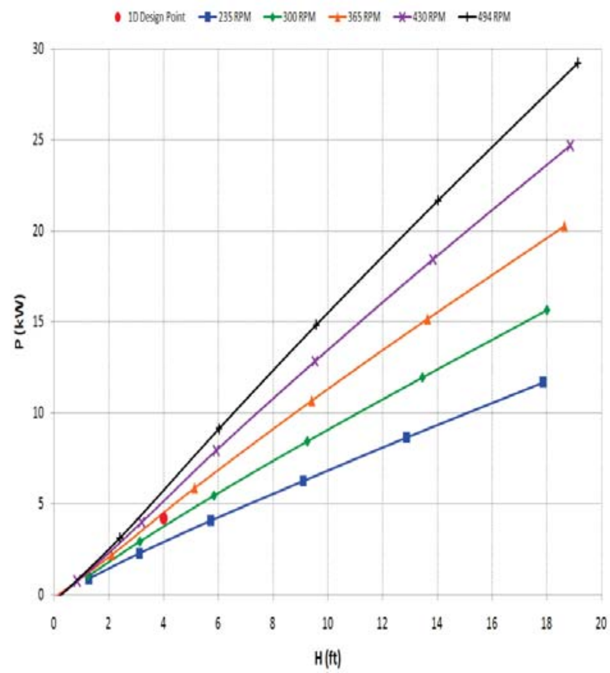



Figure 7: Turbine power as a function of head for operation at various speeds.

A summary of the turbine design is given in Table 2.

Table 2: A summary of turbine design parameters.

| | | | | |
|---|---|---|---|---|
| Hub diameter (in) | 7.200 | | Number of Blades | 5 |
| Tip diameter (in) | 18.000 | | Volumetric Flow Rate (MGD) | 23.00 |
| Solidity at hub | 1.00 | | Head (ft) | 12.00 |
| Solidity at midspan | 0.91 | | Rotational speed (RPM) | 500 |
| Solidity at tip | 0.56 | | Estimated rotor hydraulic efficiency | 0.880 |
| Max thickness-to-chord at hub | 0.150 | | Rotor Power (kW) | 31.793 |
| Max thickness-to-chord at midspan | 0.07 | | Specific speed | 146 |
| Max thickness-to-chord at tip | 0.070 | | Flow coefficient | 1.75 |
| Blade angle from tangential at hub LE | 56.77 | | Tip speed (ft/s) | 39.27 |
| Blade angle from tangential at midspan LE | 41.09 | | Inlet velocity (ft/s) | 23.97 |
| Blade angle from tangential at tip LE | 31.40 | | Tip speed/Inlet velocity | 1.64 |

During the evolution of the design of the turbine, the design conditions changed while some of the operating parameters remained fixed. The design head was increased significantly (from 4 ft to 12 ft of head), while the diameter and rotational speed of the runner were unchanged. The reason for the change was that the design team realized that more head was available at most of the potential installation sites, and the available power is directly proportional to the head, so there was good cause for the change of the design condition. The diameter was left unchanged for packaging reasons and the rotational speed was not increased for generator reliability concerns. This resulted in changes to the turbine design parameters that impact the preferred type of turbine, or result in a performance penalty for the type of turbine that had been selected. The best hydraulic efficiency that can be expected at the appropriate design conditions for a full-size, full-optimized propeller type turbine that was selected early in the design process is about 90%, as shown in Figure 5. At the size of the AEC machine, Reynolds number and clearance effects will lower the maximum attainable efficiency. In addition, the struts downstream of the runner and exit diffuser (draft tube) restrictions will further lower the peak attainable efficiency.

The power specific speed is a parameter that is used to determine the appropriate type of turbine to use for a given rotational speed, flow, and head. The equation for power specific speed is $N_s = {N\sqrt{P}}/{H^{5/4}}$. In U.S. units, the N is the rotational speed in rpm, P is power in hp, and H is head in ft. Lower head values tend to result in higher power specific speeds, and initially the design target was for a power specific speed of 160 to 180. As Figure 8 shows, higher power specific speeds lead the designer to select axial flow turbines, like a Kaplan or propeller type. As the power specific speed drops, the designer would tend to use a turbine with some radial component to the incoming flow. During the design process for this project, the change in head from 4 ft to 12 ft allowed P (power) to increase, but N remained fixed at 400 rpm, and the power specific speed dropped down to about 100. This level of power specific speed would lead the designer to favor a mixed flow (mixed radial and axial flow entering the turbine) more like a Francis type turbine rather than a propeller type turbine. Using a Francis turbine requires additional components, specifically wicket gates to control the flow entering the turbine. At the point in the design process that the design head increased it was not feasible to change from the propeller type turbine to a mixed-flow turbine. Also, although a propeller turbine at the increased head took a hit in efficiency, it is likely that the manufacturing costs are much less than they would be for a mixed-flow turbine, and the fixed propeller turbine will still generate significantly more power than it would have at the lower head value.

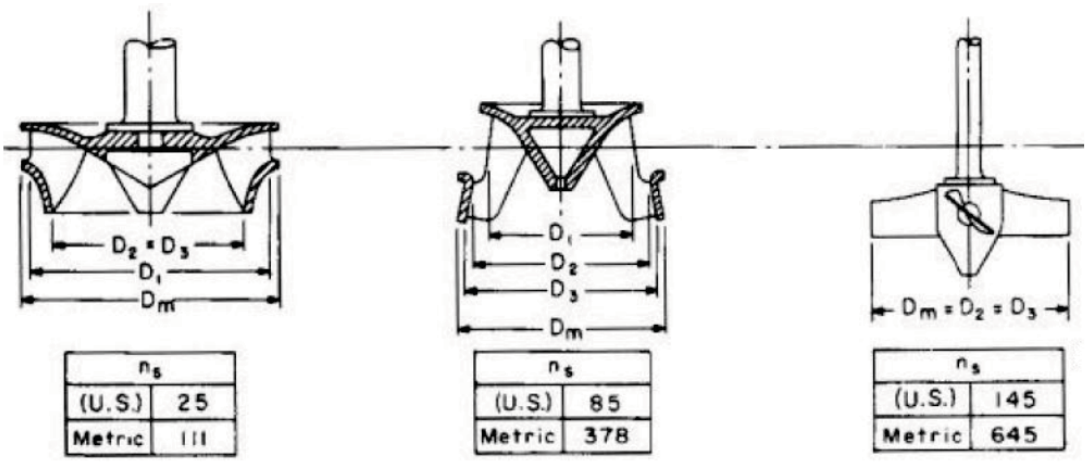



Figure 8: A guide for turbine type selection based on power specific speed.

## Generator Design

### Magnetic Design

Early in the project it was determined that the priorities of the magnetic design were to maximize generator efficiency, maximize the flatness of the generator efficiency curve, and to minimize active magnetic material. Maximizing efficiency over a wide speed range ensures that the turbine generator system would be widely applicable to a variety of flow conditions. Minimizing active magnetic material reduces system cost and weight. In addition to these three priorities, all mechanical and electrical connection constraints had to be respected. Several of the constraints are explored in more depth below.

#### Mechanical Constraints

Turbine runner design at the design point of 12 ft head indicated peak efficiency at about 400 rpm with peak power delivered at 600 rpm. These speeds were used to determine generator operation point and peak efficiency point.

The generator design was constrained by the turbine runner and the desire to make the turbine-generator unit mate with a 30” pipe bolt flange. The generator design was limited to a “pancake” aspect ratio by the diameter and axial length of the turbine runner. Thermal constraints limit the generator power rating.

#### Turbine Runaway Constraint

Further limiting design was the turbine’s runaway speed. As the electric machine was a permanent magnet machine (PMM) the voltage generated is a function of machine speed. If the electronics detected a system fault, such as a loss of grid power, the electronics would be unable to load the generator. With the turbine effectively unloaded it would speed up to its “runaway” speed; the speed at which point the turbine delivers no torque. At this speed the generator must not produce a voltage which is higher than the electronics can tolerate. As a result, the voltage which the generator produces in its operational range must be reduced in order to not exceed safe voltage during a runaway condition. This has an unfortunate effect of reducing generator efficiency in the operational range. Alternatively it can be thought of “de-rating” the generator. The generator is technically a 40 kW generator at 1200 rpm which is de-rated to a 20 kW generator at 600 rpm.

#### Design Description

The generator is a 45 slot, 40 pole, 20 kW at 600 rpm design. It is a “fractional slot” machine which implies that there are a non-integer number of slots per pole (1.125 slots per pole). Rated torque of the generator is 318.3 Nm at 600 rpm, above 600 rpm torque falls off inversely proportional to speed, maintaining 20 kW output power out to 1280 rpm. It should be noted that the torque fall off with speed is accomplished through the power electronics, the generator design does not contain any element which would limit its output power above 600 rpm. At 1200 rpm the generator produces 530 $V_{rms}$ line to line consistent with an electrical interface with a 750 V DC bus.

Finite element analysis of the generator at full torque was performed in house and by Magsoft, see Figure 9. Both analyses agreed that the peak tooth flux density near 1.6 T indicating that magnetic design is not being pushed; it is likely that the generator could produce twice rated torque by pushing additional current through the windings. A detailed thermal analysis would need to be performed, however, test results suggest the generator could tolerate increased currents.

Analytical and numerical simulations of generator operation were performed to predict and optimize efficiency. The predicted efficiency curve for the generator is given below in Figure 10. The efficiency curve uses a predicted power curve of the turbine for 12 ft of head. Low speed efficiency is limited due to insufficient generator voltage (consistent with the runaway speed constraint) while high speed efficiency is low due to insufficient power supplied by turbine. Regardless, the efficiency curve of the generator is quite flat, maintaining above 90% efficiency for over 900 rpm (75% of total speed range). Peak predicted generator efficiency was 97.3% occurring around 400 rpm.

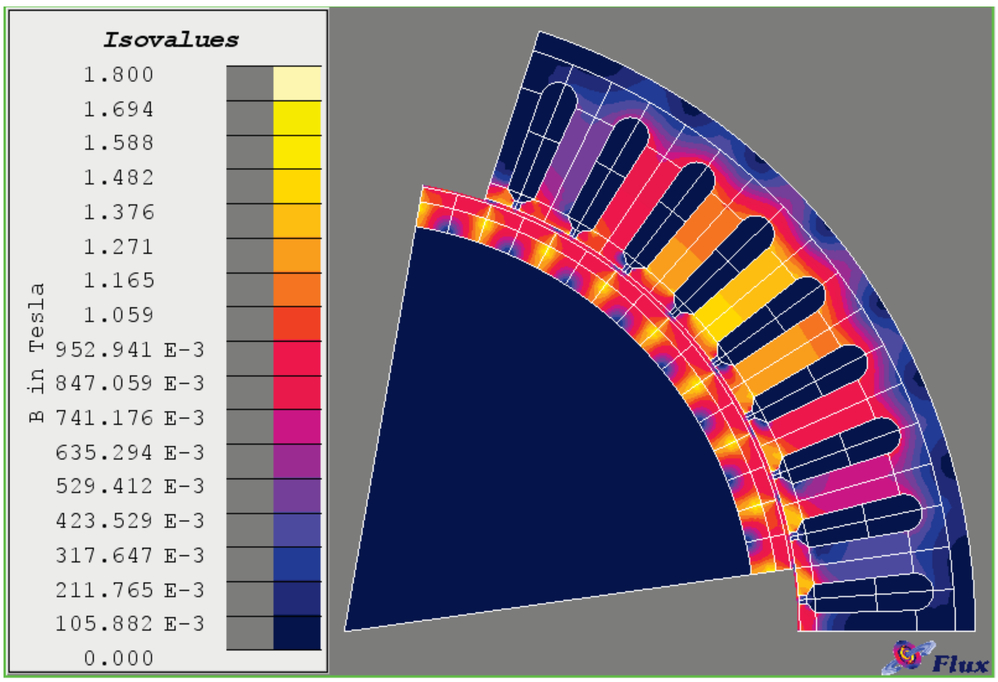



Figure 9: Magnitude of magnetic flux density in machine with machine producing rated torque.

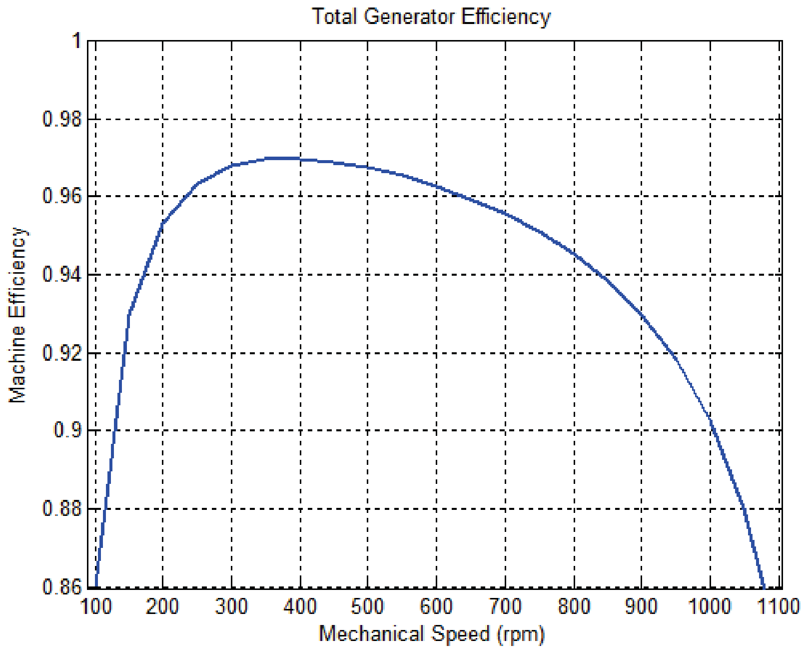



Figure 10: Analytical prediction of motor efficiency as a function of speed. Efficiency prediction relies on a predicted power curve from turbine at 12 ft head. Low efficiency at low speed is due to low motor voltage. Low efficiency at high speed is due to a reduction in the amount of power available from the turbine runner.

**Design Philosophy**

The generator design was started after preliminary turbine design was completed in order to constrain the design. In order to minimize system size, reduce cost, and meet mechanical requirements we determined that the electric machine should have a high pole count. A higher pole count allows for a thinner rotor and stator “back-iron” due to a decrease in the magnetic flux that each pole must support. This also has the benefit of reducing system weight and cost.

In order to improve system efficiency we wished to maximize the coil area which implies that we should minimize the number of teeth. An integral slot design would require a minimum of 3 slots per pole. We therefore decided a fractional slot design would be appropriate. The fractional slot design has the additional benefit of reducing cogging torque, which will push down the low speed cutoff of the generator. An 8 pole to 9 tooth ratio is a desirable ratio for a variety of reasons, which allowed us to restrict our search. We used numerical optimization methods to home in on a 40 pole, 45 slot design. A final round of magnetic optimizations was performed on the fractional slot design using finite element analysis.

## Mechanical Design

The turbine/generator was intended to integrate into a wastewater environment as seamlessly as possible. To that end, the design interfaces natively with 18-inch ductile iron pipe - a common fixture at wastewater treatment facilities. The inner and flange dimensions of this pipe style approximate the dimensions required for the generator, and the standard mounting pattern provides a common means of attachment across multiple installations. The outermost housing diameter was limited so that the final assembly could easily fit within a size 30 ductile iron pipe sleeve to provide a wider variety of installation options. Figure 11 shows a cutaway view of the turbine generator installed in a section of pipe.

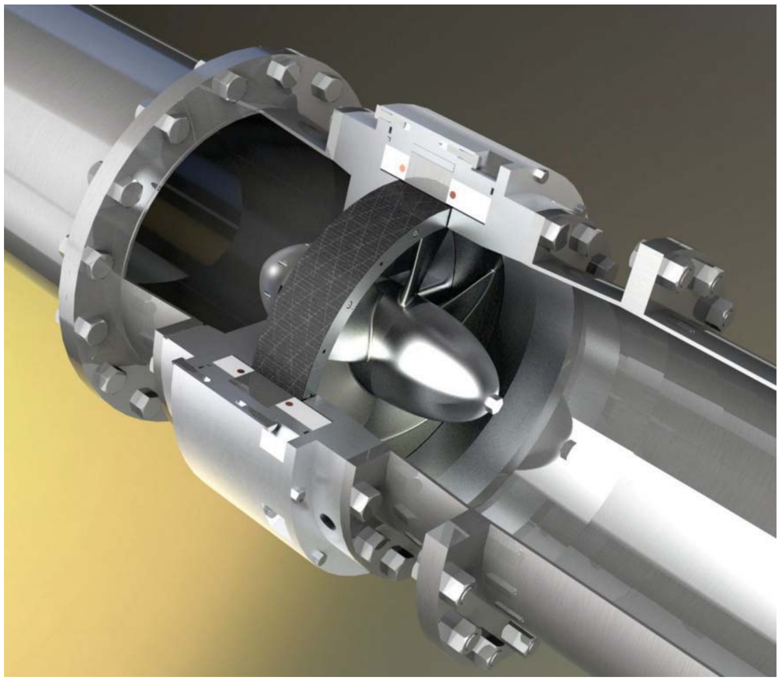


Figure 11: A cutaway view of the turbine-generator installed in a section of pipe.

The generator housing is constructed in three primary sections. O-ring seals were used between these sections to contain the flow of water. To prevent water damage, the generator windings were encapsulated with epoxy through a VPI (vacuum-pressure impregnation) process. As the particular epoxy used in this process is talc-filled, this also afforded reasonable heat conduction from the windings to the environment. Figure 12 shows a picture of the encapsulated stator in its housing.

Figure 12: The encapsulated stator in its housing.

Due to the rotor speeds and operating conditions of this machine, retention of the magnets was given special consideration. Magnets were surface-mounted to the rotor via a magnet-bonding adhesive chosen both for bond strength and for reliability. A carbon fiber wrap was also installed around the magnets. This wrap not only secures the magnets in place, but also protects them from debris and corrosion during operation.

The prototype unit was outfitted with ports for thermocouples to measure bearing temperature during dry testing, as well as three rings of four pressure taps each. The pressure taps were machined integral to the turbine/generator housing, and located at the entrance to the generator, immediately after the turbine runner, and at the generator outlet. These were intended to give a more accurate picture of turbine performance.

The turbine-generator bearing system was selected primarily for ease of installation and availability of components. As such, it is not ideally suited for long-term exposure to underwater conditions. The intention during wet testing of the machine was to determine the degree of corrosion and other degradation that could be expected of standard bearing components in a freshwater effluent environment.

## Electronic Power Conversion Design

The structure of the electronic power conversion system is shown in Figure 13. The system is comprised of a switched-mode rectifier that rectifies the generator output into a fixed dc bus voltage. The switched-mode rectifier processes the variable voltage, variable frequency output of the generator into dc. A utility interactive inverter regulates the dc bus voltage, exchanging power with the utility as required to do so. Before the generator starts producing power, the inverter will draw power from the utility to regulate the dc bus voltage. Once the generator starts to output power through the switched-mode rectifier, the inverter will send power to the utility such that the dc bus voltage is regulated. For maximum flexibility the prototype conversion electronics were designed to support 20kW even though the prototype system was intended to only generator 15kW.

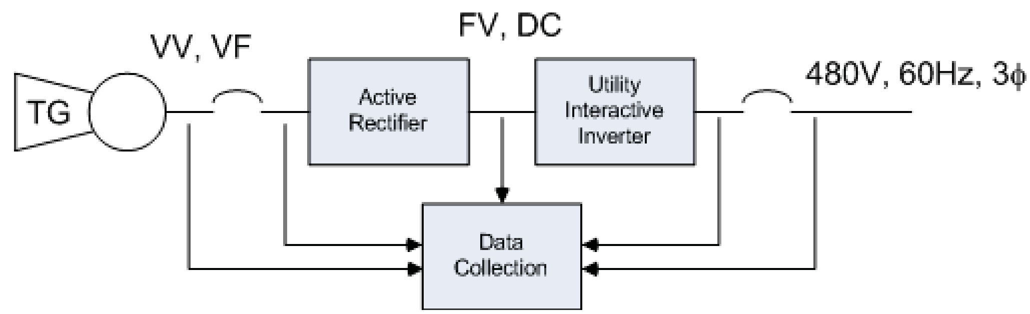



Figure 13: The structure of the electronic power conversion system.

### Switched-Mode Rectifier

A high-level schematic for the switched-mode rectifier (SMR) is given in Figure 14. Each phase of the generator is modeled as a voltage source acting behind phase resistance and inductance. The SMR is formed using three diodes in a common-anode connection connected to the positive side of the dc bus. Three fully-controllable devices with anti-parallel diodes complete the bridge, connected to the negative side of the dc bus. The three controllable devices are operated in unison. When these devices are conducting, the generator terminals are effectively shorted together. When the controllable devices are off, the generator terminals see a conventional uncontrolled rectifier. The use of the controllable devices causes the generator to operate as if the dc bus voltage were at some value that falls between zero and the actual dc bus voltage.

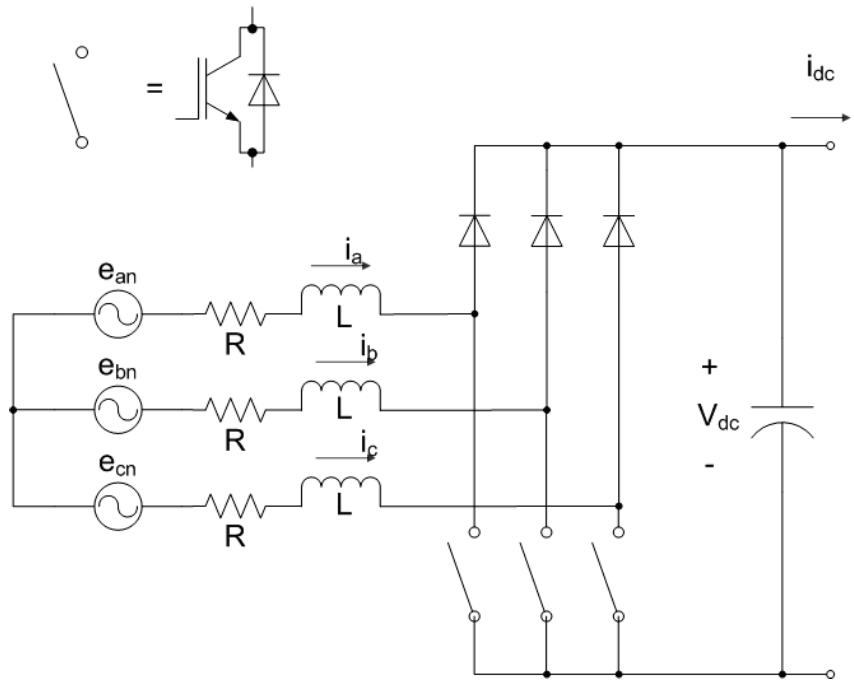



Figure 14: A high level schematic of the switched-mode rectifier.

The SMR allows increased power extraction from the generator relative to that achievable with an uncontrolled rectifier. This, combined with the simple structure and control, makes the SMR attractive relative to a fully-controlled inverter. Through the SMR it is possible to implement maximum power point tracking to maximize the energy extracted from the generator. By adjusting the percentage of time the controllable devices are conducting (also known as the duty ratio), it is possible to change the loading on the generator. As the generator load increases, the speed of the generator is reduced, potentially increasing the output power. It is also possible to decrease the load on the generator, allowing the generator speed to increase and seek a more productive operating point.

Figure 15 shows the expected output power as a function of SMR duty cycle for a dc bus voltage of 150V. Similar characteristics are possible with other dc bus voltages with an appropriate change in duty cycle. The objective of maximum power point tracking is to automatically adjust the duty ratio to maximize the output power regardless of the turbine speed or the dc bus voltage.

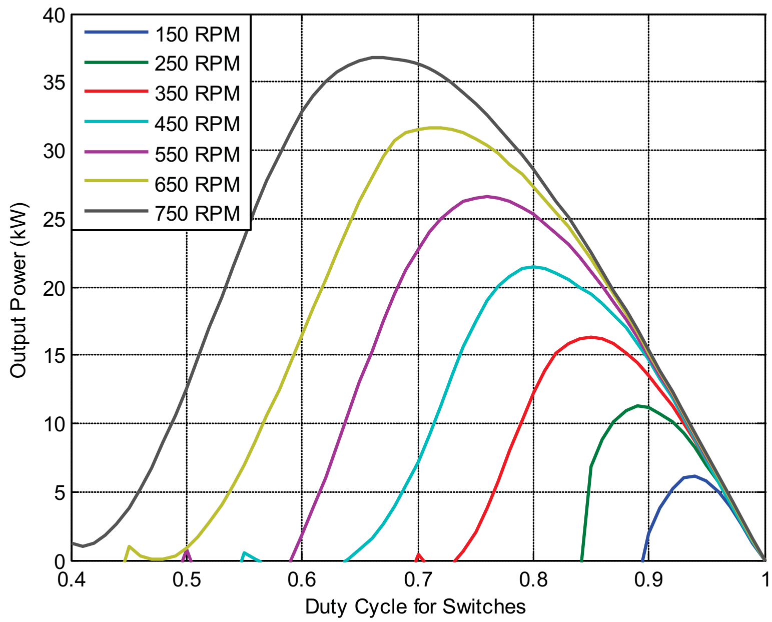



Figure 15: The expected generator output power as a function of SMR duty ratio with a dc bus voltage of 150V.

## Utility Interactive Inverter

Figure 16 shows a high level schematic of the utility interactive inverter used to interface the SMR to the electric utility. The voltage sources shown are the utility voltages. The inductance is used within the inverter to support the instantaneous differences between the inverter output voltages and the utility phase voltages. The resistance is the parasitic resistance of the inductor and the utility connection.

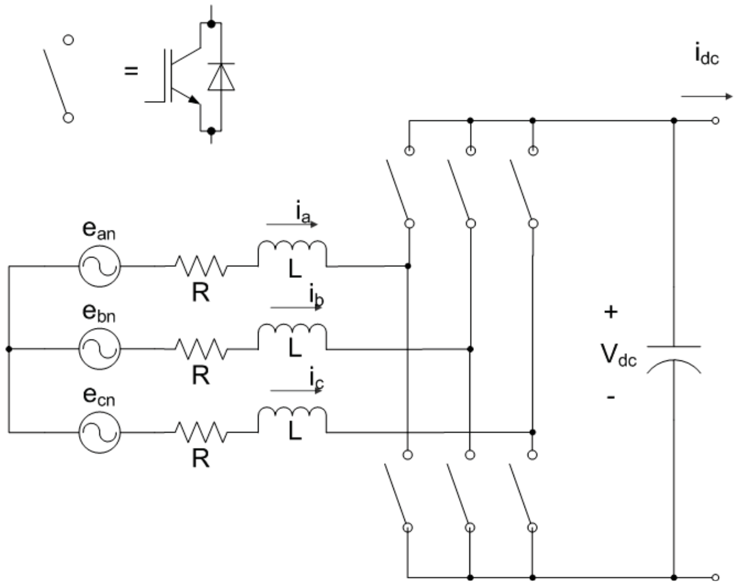



Figure 16: A high level schematic of the utility-interactive inverter.

Through the switching of the controllable devices, it is possible to regulate the inverter output currents to be of high quality, and in phase with the utility voltages. This corresponds to high power factor operation. It will be appreciated that operation at non-unity power factor may be desirable to support reactive power needs within the utility system. Figure 17 shows representative waveforms created by the utility interactive inverter.

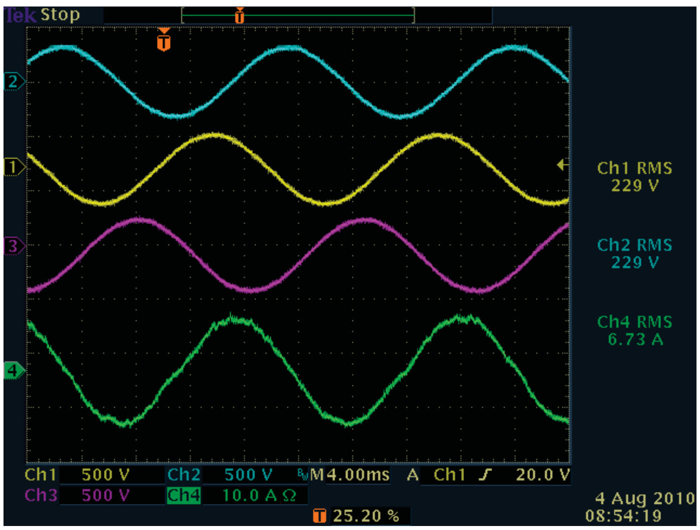



Figure 17: Representative waveforms produced by the utility interactive inverter. The pink, yellow, and blue waveforms correspond to the utility voltages on phases a, b, and c, respectively. The green waveform is the phase a current. It is seen to be out of phase with the phase a voltage, indicating power is flowing from the dc bus to the utility.

Figure 18 shows the electronic conversion system. It is housed in an industrial enclosure. A heat sink for cooling the power semiconductors extends out the back of the enclosure. The disconnect switches on the sides of the enclosure are for the generator (left) and utility (right). The SMR is at the top, and the utility interactive inverter is on the bottom. The components on the right side are filter components, used in smoothing the inverter ac current waveforms.

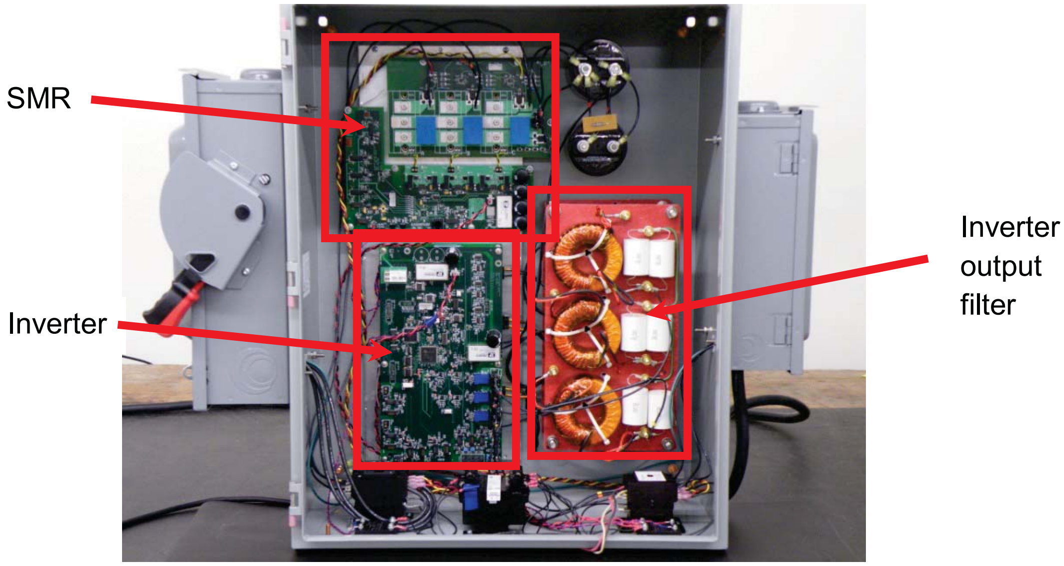



Figure 18: The prototype electronic power conversion system.

## Evaluation of the Prototype Turbine/Generator System

Evaluation of the prototype turbine/generator system consisted of dry testing and wet testing. The dry testing was conducted in-house, and the objective of the testing was to confirm that the generator was fabricated consistent with its design, and that the interface to the electronics worked properly. The dry testing provided an opportunity to evaluate the efficiency of the generator, the SMR, and the utility-interactive inverter.

Wet testing was conducted at Alden Research Laboratory in Holden, MA. Alden has a long history of hydraulic testing. The testing at Alden was based on the fully integrated turbine/generator system, and was intended to allow data collection to focus on the turbine performance as a function of flow and head.

### Dry Testing

Dry testing was comprised of the following elements:

- Basic Set-Up and Operation
    - Winding verification (rotor installed)
        - Phase inductance
        - Phase resistance (tested with power applied)

    - Mechanical clearances
        - Vertical orientation
        - Horizontal orientation
    - Bearing and cogging torque
        - Torque wrench
        - Low-speed transducer measurement
    - Back EMF waveform check
        - Spin by hand, 1rpm ~0.57V line to line
        - Check using scope – 3 differential channels between line to line voltages
        - Check for symmetry
    - Shaft alignment
- Frequency/Structural Testing
    - Frequency response
        - Unloaded test – no SMR or load resistors
        - Run a sweep from 0-800rpm (50rpm increments)
        - Allow speed to settle between measurements
        - Data to obtain:
            - Actual speed
            - Eddy current torque at each point
            - Note any potential resonances
            - Line to line back EMF waveforms at each point for 5 electrical cycles at min sample rate = 7*3*(20*rpm/60) Hz (5600Hz @ 800rpm)
            - Temperatures
                - Ambient
                - Magnets
                - Bearing
                - Stator slot
                - Stator end turn
    - Magnet adhesive and wrap integrity test
        - Slowly bring generator up to anticipated runaway speed (1250rpm @ 25rpm increments from 800rpm)
        - Verify structural integrity of system
        - Data to obtain:
            - Actual speed
            - Eddy current torque at each point
            - Note any potential resonances
            - Line to line back EMF RMS values for each phase
            - Temperatures
                - Ambient
                - Magnets
                - Bearing
                - Stator slot
                - Stator end turn
- Generator Characterization
    - Drive motor in speed control (loaded tests)
        - Loaded tests – load resistor banks
            - Resistor banks produce rated current at 600rpm
            - At constant load, 800rpm testing will overcurrent the phase windings by 33%

        - Run tests from 200-800rpm drive motor speed
        - Data to obtain (for each test):
            - Actual load resistance used
            - Actual speed
            - Torque
            - Measure a single line to line voltage and phase current for 5 electrical cycles at min sample rate = 7*3*(20*rpm/60) Hz
            - Extracted power (power meter)
            - Available power (torque transducer and induction drive)
            - Line to line back EMF RMS values for each phase
            - Temperatures
                - Stator slot
                - Stator end turn
                - Magnets
                - Ambient
    - Drive motor in speed control (loaded tests)
        - Loaded tests – SMR engaged
        - Run tests from 200-800rpm drive motor speed, at several SMR duty ratios
        - Data to obtain (for each test):
            - Actual speed
            - Torque
            - Measure a single line to line voltage and phase current for 5 electrical cycles at min sample rate = 7*3*(20*rpm/60) Hz
            - Inverter current THD
            - Extracted power (controller output verified using power meter)
            - Line to line back EMF RMS values for each phase
            - RMS grid voltage and current
            - Temperatures
                - Stator slot
                - Stator end turn
                - Magnet (PWM heating)
                - Ambient
        - Verify overpower condition current-limiting
            - Set current saturation to arbitrarily small value
            - Assign drive motor speed control and generator speed command setpoint such that the new current limit would be violated (but still be within electrical design limits)
    - SMR Control Algorithm Testing (loaded tests)
        - Loaded test – SMR engaged
        - Wastewater Speed control algorithm
            - Set drive motor to a fixed torque command
            - Set T/G to various speed commands
            - Data to obtain for each test
                - Initial speed
                - Actual speed (instantaneous and waveform)
                - Torque
                - A single RMS Line to Line voltage and phase current
                - Real-Time Data

                - Torque commands (from controller)
                - Current output (from controller)
                - CAN bus can provide up to 200Hz data rate
            - RMS grid voltage and current
            - Temperatures
                - Slot
                - End turns
                - Magnet
                - Ambient
        - Verification made if speed held constant at command
        - Adjust control constants if needed, re-run test
- Drive motor in torque-speed mode (MPPT)
    - MPPT control algorithm test 1
        - For two separate drive motor T-S curves
        - Hold T/G in speed control mode on desired side of peak available power curve
        - With system at speed and stable, engage MPPT algorithm
        - Repeat starting on other side of peak available power curve
        - Data to obtain for each test
            - Steady-state speed (and waveform)
            - Steady-state torque (and waveform)
            - A single RMS line to line voltage and phase current
            - Real-Time Data
                - Speed commands (from controller)
                - Current output (from controller)
                - CAN bus can provide up to 200Hz data rate
            - RMS grid voltage and current
            - Power out using power meter
            - Settling time
            - Temperatures
                - Slot
                - End turn
                - Magnet
                - Ambient
    - MPPT control algorithm test 2
        - For two separate drive motor T-S curves, translated relative to each other
        - Hold T/G in speed control mode on desired side of peak available power curve
        - With system at speed and stable, engage MPPT algorithm
        - When system is stable, change drive motor T-S profile to other curve
        - Measure data for transition period between two curves
        - Repeat test transitioning back to first curve
        - Data to obtain for each test
            - Steady-state speed (and waveform)
            - Steady-state torque (and waveform)
            - A single RMS line to line voltage and phase current
            - Real-Time Data
                - Speed commands (from controller)

            - Current output (from controller)
            - CAN bus can provide up to 200Hz data rate
        - RMS grid voltage and current
        - Power out using power meter
        - Settling time
        - Temperatures
            - Slot
            - End turn
            - Magnet
            - Ambient
- Limit Tests
    - Engage electronics from runaway (unloaded) conditions
        - Begin with lower rpm tests before testing runaway (verify expected response)
        - 400rpm, 800rpm, 1250rpm test points
        - Drive motor begins in torque mode with a maximum speed command set at desired initial condition
        - Engage generator speed control mode at a lower speed setpoint
        - Repeat with MPPT algorithm (drive motor in T-S mode with maximum speed command set at desired initial condition)

## Wet Testing

Wet testing was comprised of the following elements:

- Set-Up / Preparation
    - Attach pressure tap fittings before connection to Alden facility
    - Verify correct electronics grid connection
    - Ensure all test equipment / electronics / personnel are out of splash or leak contact, and are protected against electrical fault
    - Measure bearing torque
- Verify runaway speed – No power extracted (open circuit)
    - Begin test at zero head
    - Slowly increase applied head in 2ft increments
        - Head to be determined by pressure drop across system (P1-P5)
        - Allow rpm to settle before moving to the next point
        - Make note of rpm settling time (for future time estimates)
    - Data to obtain for each test point
        - Pressures
            - P1, P5 from Alden
            - P2, P3, P4 from controller (transducers)
        - Flow rate
        - Actual speed
        - Temperatures
            - Stator slot
            - Stator end turn
            - Water
            - Ambient
    - Test is complete when 12ft of head is reached OR turbine speed exceeds 1250rpm

    - If speed is less than 1250rpm at end of test, decision can be made to increase applied head until the calculated runaway speed is reached
- Generator Characterization – Resistor Bank
- Generator Characterization – SMR Engaged
    - Power Extraction Vs. Head
        - Set generator to speed control mode, beginning at a 900 RPM setpoint
        - At each speed setpoint, adjust applied system head (P1-P5, as measured by Alden) in 2ft increments from runaway head corresponding to starting speed up to a maximum of 14ft
        - Allow pressures and speed to settle - generator speed settles quickly, while applied system head measurements are noisy and require time to settle at desired operating point
        - Data to obtain (for each test):
            - Alden pressures (P1-P5)
            - T/G pressures (P2, P3, P4)
            - Turbine speed
            - Water flow rate
            - Power extracted (meter)
            - Phase voltage (RMS)
            - Phase current (RMS)
            - Temperatures
                - Slot
                - End turn
                - Water
                - Ambient
    - MPPT Testing
        - Hold T/G in speed control mode on desired side of peak available power curve
        - With system at speed and stable, engage MPPT algorithm
        - Measure accuracy of tracking and response time
        - Repeat starting other side of peak available power curve
- Final Required Tests
    - Bearing torque

## Test Results

Figure 19 shows the combined efficiency of the generator, SMR, and inverter as a function of operating point. These data were collected during dry testing. Overall electrical performance is quite good, with efficiencies hovering between 85% and 92% over much of the intended operating region. Efficiency tends to fall off as power output drops. This is typical of this type of system, since the generator and power electronics will have losses that are relatively independent of operating point. These losses become more significant as the output power is reduced, leading to lower component and system efficiencies.

Figure 20 shows the same data as in Figure 19, but as contours of efficiency. The black line delimits the region explored during dry testing.

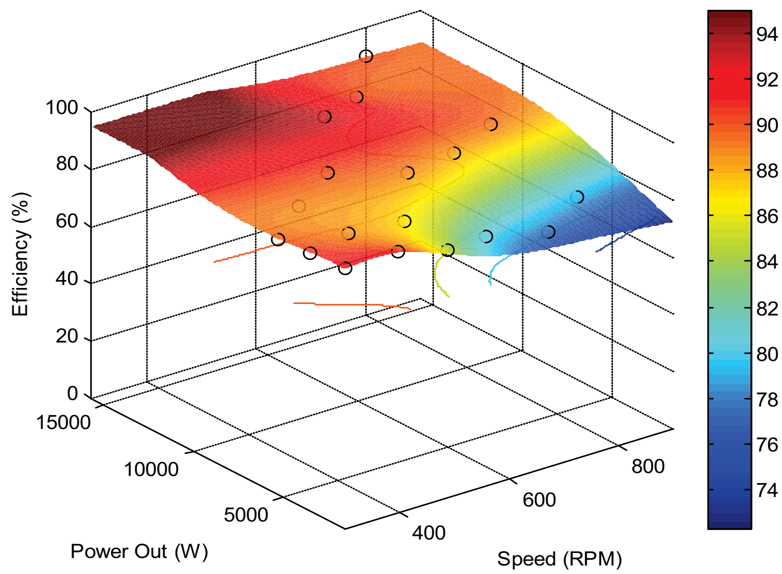



Figure 19: The combined efficiency of the generator, SMR, and inverter as a function of operating speed and output power.

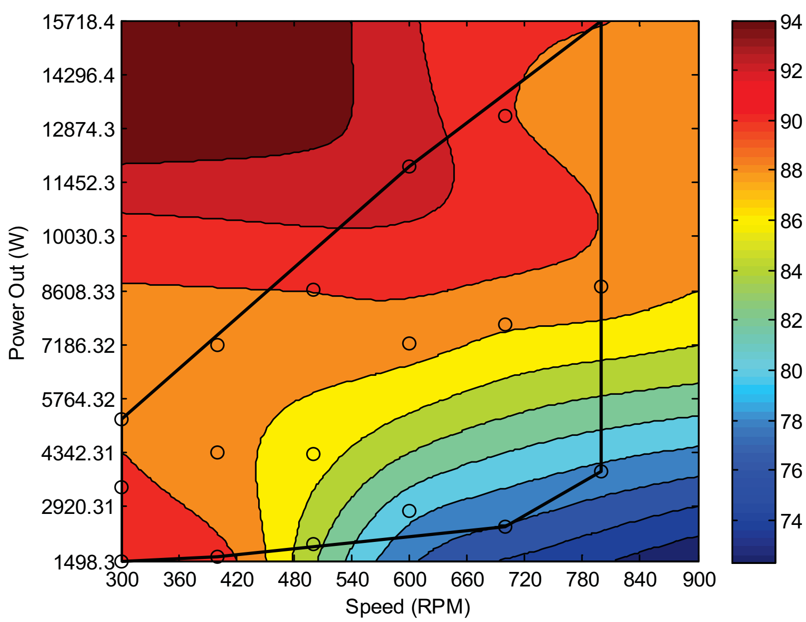



Figure 20: Electrical efficiency contours as a function of speed and output power.

Figure 21 shows a surface plot of the output power as a function of turbine speed and applied head. These data were collected during wet testing. The steepness of the surface is not surprising given the efficiency characteristics of the propeller-type of turbine shown in Figure 5.

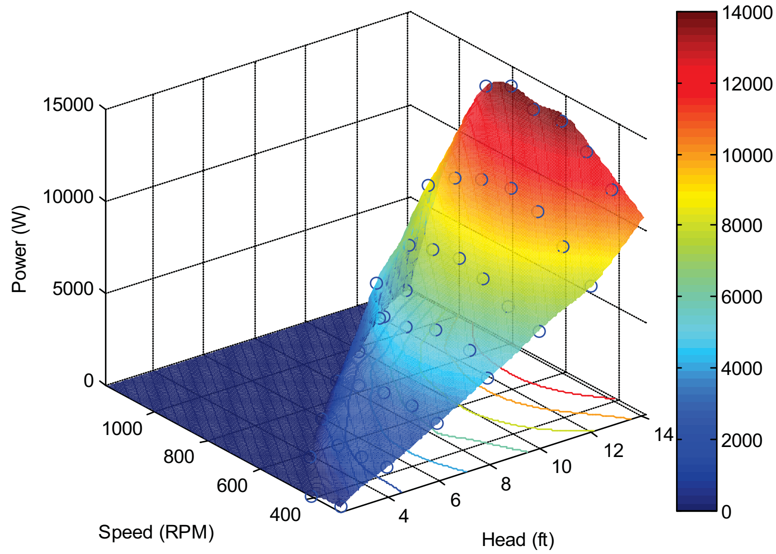



Figure 21: A surface plot of the output power as a function of turbine speed and applied head.

Figure 22 provides a surface plot of the turbine efficiency as a function of turbine speed and applied head. Turbine efficiency was backed out of the total system efficiency using the models of the generator, SMR, and inverter losses developed during the dry testing.

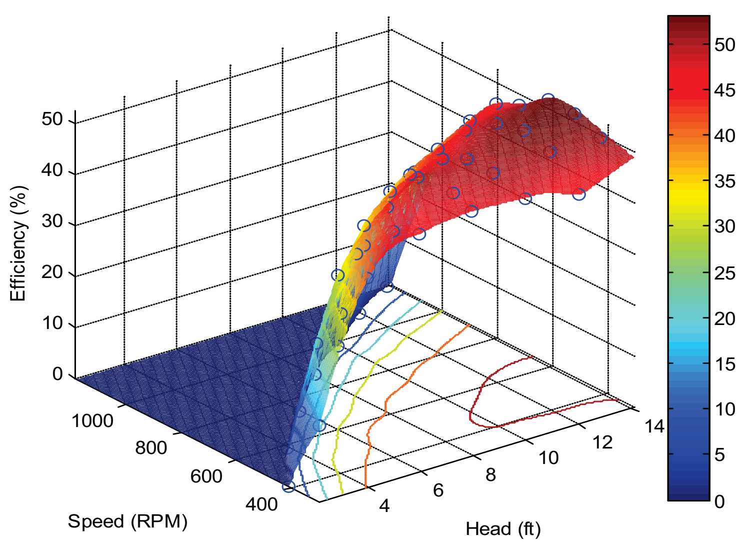



Figure 22: A surface plot of turbine efficiency as a function of turbine speed and applied head.

Figure 23 shows the combined electrical efficiency of the generator, SMR, and inverter as a function of turbine speed and applied head. Efficiency has a tendency to drop off at high speeds and low heads, an operating region where the turbine/generator system is intended to spend little time.

Figure 24 shows contours of output power as a function of head and turbine speed. Peak output power is achieved in the range of 600-800rpm and a head of 14ft, consistent with the system design. The achieved output power of 12.8kW was lower than intended, due to lower turbine efficiency.

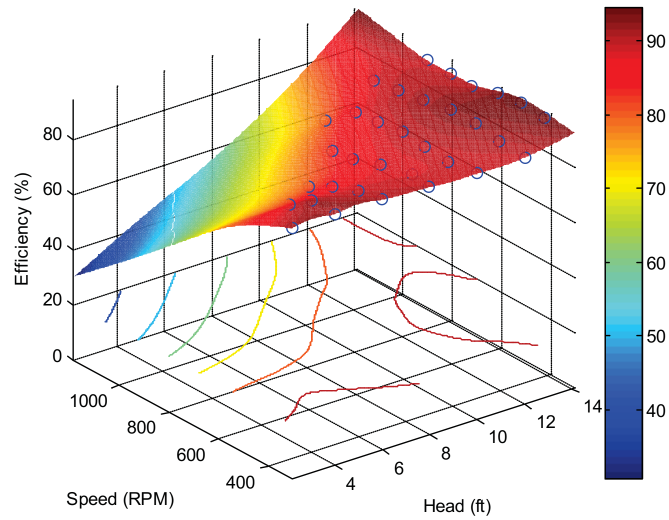



Figure 23: A surface plot of electrical efficiency as a function of turbine speed and applied head.

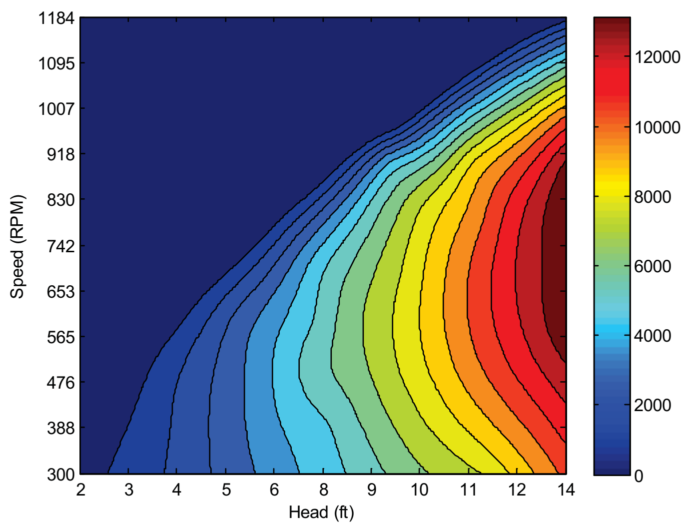



Figure 24: A contour plot showing output power as a function of turbine speed and applied head.

Figure 25 shows contours of system efficiency as a function of turbine speed and head. Figure 26 shows contours of turbine efficiency as a function of turbine speed and applied head. Figure 27 shows contours of electrical efficiency as a function of turbine speed and applied head. A comparison of these three figures shows that the turbine efficiency is driving overall system efficiency much more than the electrical equipment. It follows that a key to wide applicability of this technology requires broadening the efficiency map of the turbine. This may be difficult to do without impacting cost and design simplicity.

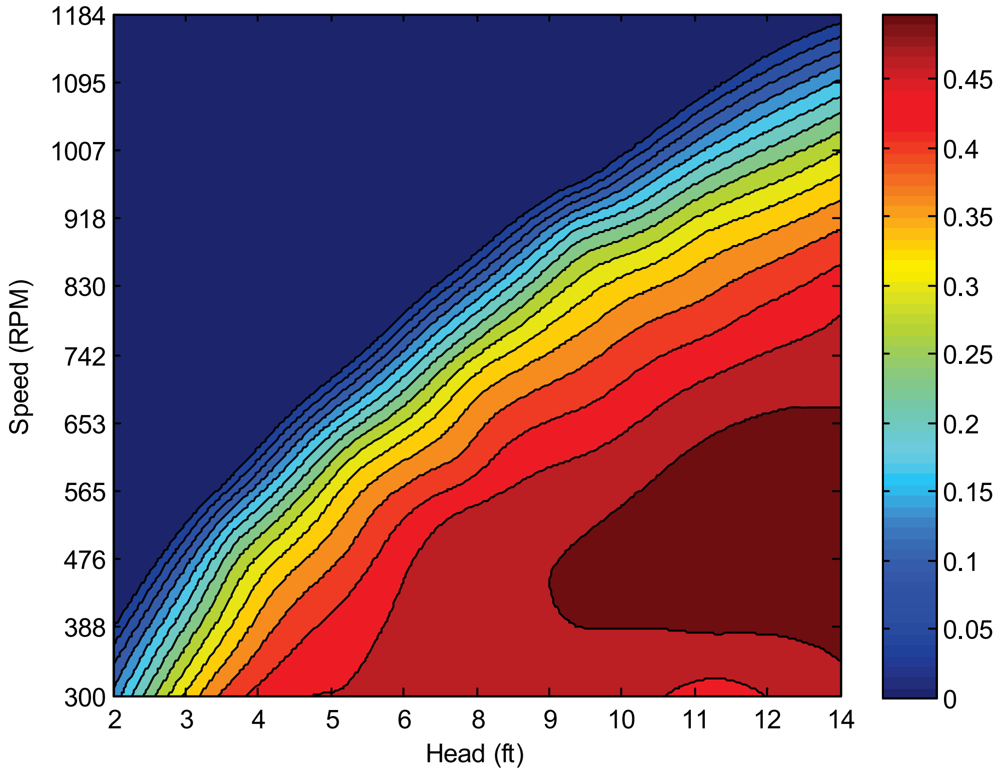



Figure 25: A contour plot showing overall system efficiency as a function of turbine speed and applied head.

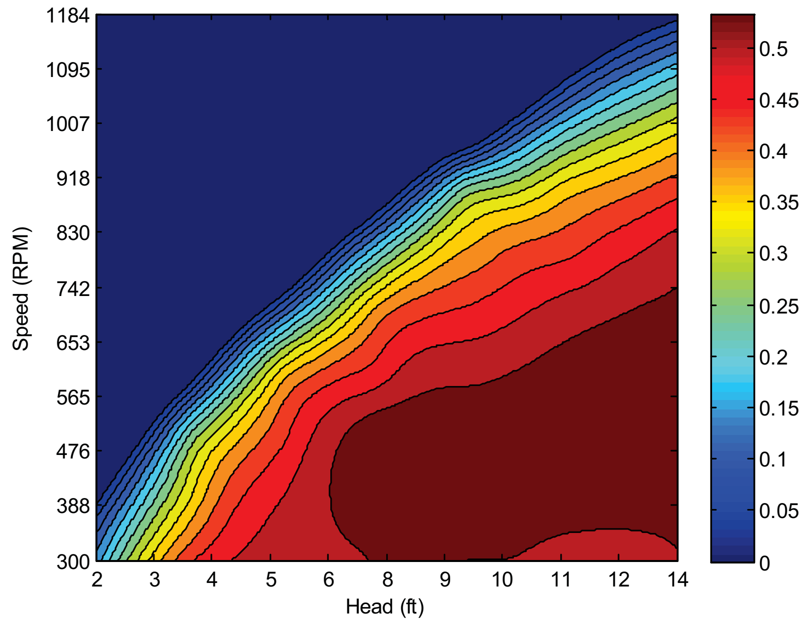



Figure 26: A contour plot showing turbine efficiency as a function of turbine speed and applied head.

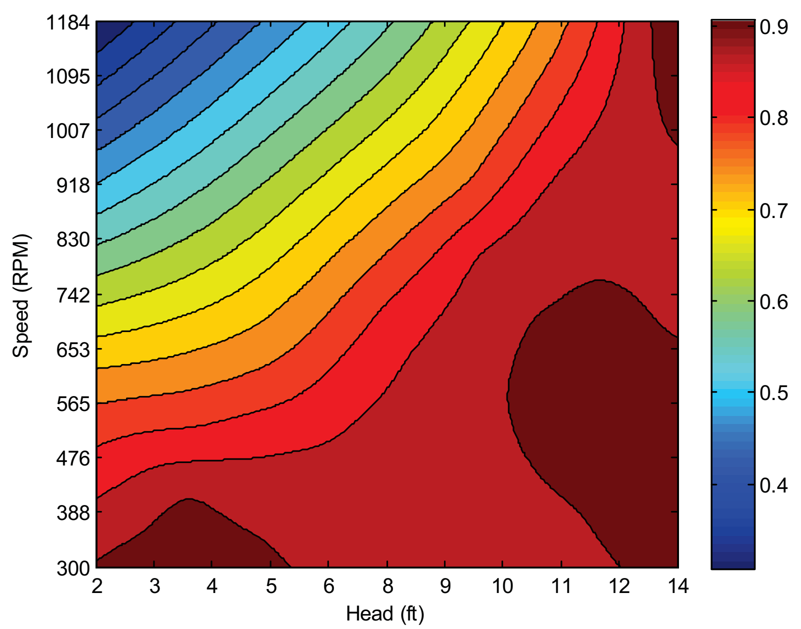



Figure 27: A contour plot showing electrical efficiency as a function of turbine speed and applied head.

As indicated above, during the evolution of the design of this turbine the design conditions changed while some of the operating parameters remained fixed. The design head was increased significantly (from 4 ft to 12 ft of head), while the diameter and rotational speed of the runner were unchanged. The reason for the change was that the design team realized that more head was available at most of the potential installation sites, and the available power is directly proportional to the head, so there was good cause for the change of the design condition. The diameter was left unchanged for packaging reasons and the rotational speed was not increased for generator reliability concerns. This resulted in changes to the turbine design parameters that impact the preferred type of turbine, or result in a performance penalty for the type of turbine that had been selected.

As Figure 8 shows, higher power specific speeds lead the designer to select axial flow turbines, like a Kaplan or propeller type. As the power specific speed drops, the designer would tend to use a turbine with some radial component to the incoming flow. During the design process for this project, the change in head from 4 ft to 12 ft allowed P (power) to increase, but N remained fixed at 400 rpm, and the power specific speed dropped down to about 100. This level of power specific speed would lead the designer to favor a mixed flow (mixed radial and axial flow entering the turbine) more like a Francis type turbine rather than a propeller type turbine. Using a Francis turbine often requires additional components, specifically wicket gates to control the flow entering the turbine. At the point in the design process that the design head increased it was not feasible to change from the propeller type turbine to a mixed-flow turbine. Also, although a propeller turbine at the increased head took a hit in efficiency, it is likely that the manufacturing costs are much less than they would be for a mixed-flow turbine, and the fixed propeller turbine will still generate significantly more power than it would have at the lower head value.

At the design condition, the runner hydraulic efficiency (work supplied by rotor divided by the hydraulic energy available) was predicted to be about 90%. The turbine configuration was analyzed using CFD. The model that was analyzed was different from the actual tested turbine, although the runner itself was the same. The actual turbine was designed to be placed in the outfall of a wastewater treatment plant, and the diffuser downstream of the turbine (draft tube) had to be compromised to due space constraints. The overall hydraulic efficiency of the system was estimated at 52% for the as-design configuration. The as-tested configuration was expected to have a higher efficiency due to improved static pressure recovery downstream of the turbine because the test configuration allowed a higher performance diffuser to be used. Reviewing the test data from Alden, it appears that near the design point of the turbine, the water-to-wire efficiency of the entire turbo-generator was 64%.

Literature suggests that the best hydraulic efficiency to be expected from this type of turbine is about 85% to 90%. Turbo Solutions was not able to find sufficient data to break out the hydraulic efficiency of the runner, but assuming an efficiency beyond the turbine shaft (generator and power conditioning electronics) of 90%, and a 64% water-to-wire efficiency, the hydraulic efficiency of the overall device was about 71%.

Figure 28 shows a plot of the turbine efficiency versus feet of head for the analytical predictions and the test data at various rotational speeds. The analytical points shown are the predicted hydraulic efficiency of the turbine with an estimated 90% efficiency decrement for generator and power electronic losses included, which provides a valid comparison with the water-to-wire efficiency shown in the test data curves. These curves show that the measured efficiency is very similar to the predicted efficiency. The 400 rpm analytical point indicates a slightly lower efficiency than the test data shows. A possible explanation for this is that the model analyzed was in the wastewater outfall configuration, which is expected to have lower performance than the tested configuration.

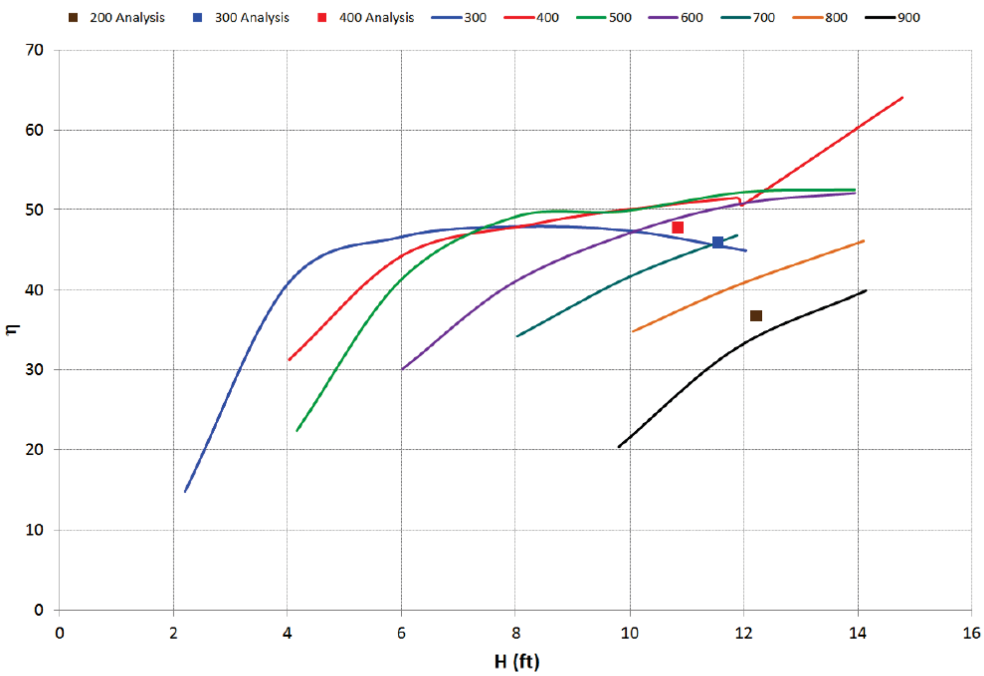



Figure 28: Turbine efficiency as a function of head, comparing calculated to measured quantities.

In order to improve the hydraulic efficiency of the turbine, without changing the fundamental configuration (adding wicket gates, variable pitch blades, runner type, etc.), the following options can be considered for investigation:

1. Redesign runner for improved runner efficiency
2. Redesign struts to reduce losses
3. Improve the diffusion downstream of the runner and struts

At this point it is difficult to say if there is much room for improvement on options 1 and 2, additional test data and/or analyses would be required to determine if changes would be helpful. Regarding option 3, the test configuration did have some diffusion downstream of the turbine before the discharge pressure measurement location. Additional diffusion would reduce the static pressure behind the turbine runner, providing additional head across the runner so that it should produce more power, effectively increasing the efficiency.

In summary, while there may be some room for efficiency improvement by modifying the geometry of various turbine stage components, if the current rotational speed, geometric constraints, and overall head remain fixed, the improvements will likely be modest.

## Tear Down Analysis

A complete tear-down of the turbine-generator was performed following wet testing. Bearing torque measurements taken indicated that the test bearing system had survived complete immersion during the testing period. Still, bearing performance began to degrade approximately two weeks after the system was re-exposed to atmosphere. Oxidation seen in the bearing system grease also became progressively worse during this period, and several spacing rings used in the bearing architecture were heavily corroded. Corrosion-resistant materials will be required in the construction of future bearing systems. Figure 29 shows an example of the corrosion found on the spacing rings.

Figure 29: Corrosion of bearing spacing rings was evident during tear-down analysis.

Generator voltage tests performed after wet testing indicated that the magnets and laminations had not degraded to a measurable extent, suggesting that the carbon fiber wrap was sufficient to protect the surface-mounted magnets from corrosion. The wrap itself did seem to suffer some damage to its exterior in the form of pits and scratches, likely due to debris encountered in the fluid stream. Figure 30 shows the exterior of the rotor wrap. In addition to this, some oxide was visible on the surface of the runner. This oxide was primarily concentrated around several unsealed holes used for data collection during dry testing, leading into the rotor back iron. Figure 31 shows some of the oxide that built up on the turbine runner. Additional faint traces of iron oxide residue were also noted around several sealed holes also used during prototype construction, indicating that additional sealing measures will need to be taken in the future. The epoxy encapsulation also appeared to survive testing, however some cracking and flaking was evident.

Figure 30: The surface of the carbon fiber rotor wrap after testing.

Figure 31: The exterior of the turbine runner after testing.

## Pilot Demonstration

A pilot demonstration of the turbine/generator system was planned for the Albany (NY) North wastewater treatment plant. Reasons for choosing this plant include:

- The plant meets the head and flow target of the prototype design
- The plant operator is an enthusiastic participant; and
- The plant is in close proximity to project participants.

The approach that would be taken would include:

- Using contractors known to the Albany North WWTP
- The project team would design and fabricate mounting hardware
- Contractors would install the system
- The project team would monitor, and subsequently reduce system data; and
- We will use a prototype turbine design, modified as appropriate from the Alden test results.

The purpose of the field test is to:

- Conduct a real world test that will indicate how the system will perform in the field
- Conduct a test that will be at the mercy of the plant flow conditions
- Prove the installation process: it is unsafe for people to be in the pit where the system will be installed; and
- Demonstrate that plant operations will not be significantly interrupted for installation and removal of the system.

Because of the nature of the pilot installation, modifications to the system during testing will be minimized and must be carefully planned. Further, instrumentation and data acquisition will be limited, probably to only flow input and electrical parameters. It will be difficult to have proper instrumentation for breaking out component performance, particularly that of the turbine.

Figure 32 shows an elevation drawing and a picture of the outfall at the Albany North WWTP. Our concept for a pilot installation is shown in Figure 33. It uses a rectangular trough that catches the effluent stream as it passes out of the flow measurement weir. The trough is designed so that if the trough gets completely filled because the turbine is unable to swallow all of the flow, the excess flow will spill over the long edge of the trough thereby preventing any impact on the stream leaving the plant. This is very important since plant flow is measured at the discharge.

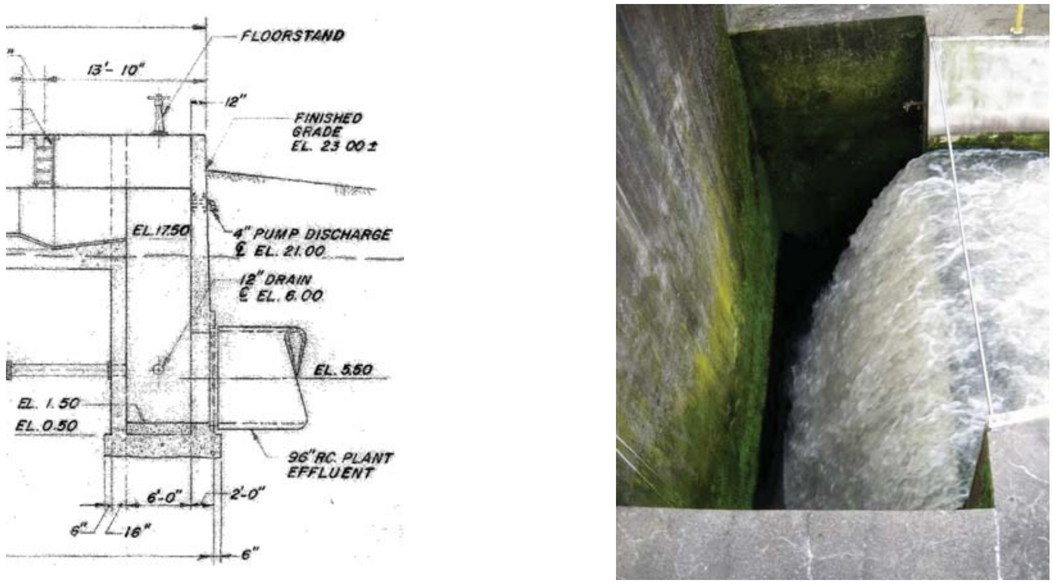



Figure 32: The elevation view and a picture of the outfall at the Albany (NY) North wastewater treatment plant.

Not shown in Figure 33 is a hoist that is mounted over the pipe in which the turbine/generator is installed. This hoist will allow the turbine to be raised for service without having to interrupt operation of the plant. It will, however, be necessary to interrupt the plant output while the trough and its associated structure is installed. With proper planning it should not be necessary to interrupt plant flow for more than three hours to complete installation.

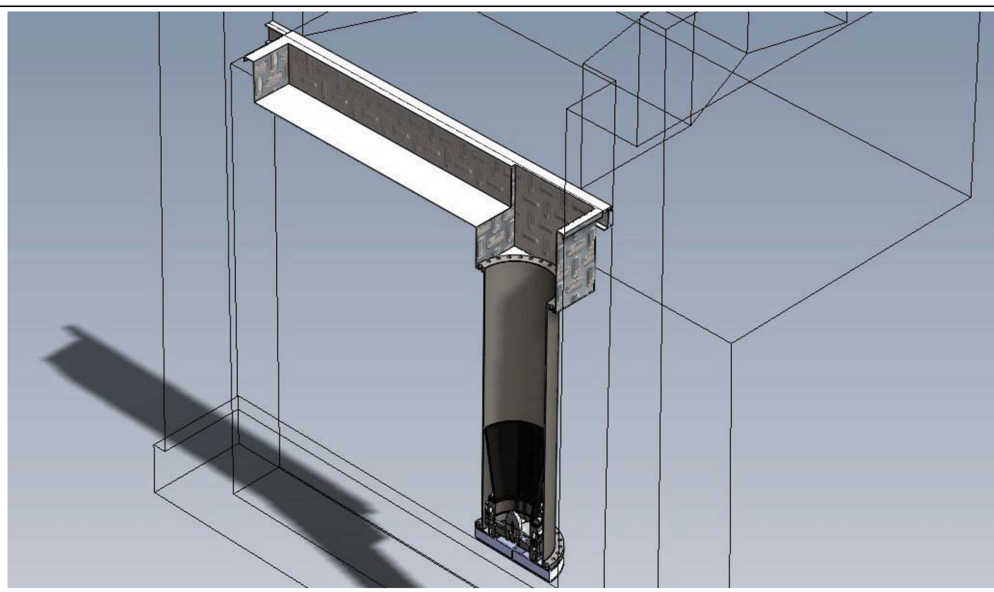


Figure 33: A concept for mounting the turbine/generator in the outfall at the Albany North wastewater treatment plant.

Table 3 summarizes the projected costs of fabricating a prototype system for installation in the Albany North WWTP. These costs leverage the original prototype, while making the modifications suggested by analysis of the prototype turbine/generator performance and the subsequent tear-down analysis. The budget is based on detailed monitoring of prototype performance for six months.

Table 3: A summary of costs associated with installing a prototype turbine/generator unit into the Albany North wastewater treatment plant.

| **Item** | **Description** | **Cost** |
|---|---|---|
| Design | Housing and process design | $50,000 |
| Fabrication Materials | Two prototype systems | $75,000 |
| Process and Performance Demonstration | Installation and removal, performance and wear analysis | $75,000 |
| Management | Coordination, documentation, and reporting | $50,000 |
| **Total** | | **$250,000** |

# Business Development of the Turbine/Generator System

## Market Opportunity

### Reasons for Wastewater Treatment Facilities as Target Market

The decision to enter the WWTP market prior to other markets (e.g. potable water) was influenced by several factors:

- Major energy consumers. Wastewater treatment facilities are large energy consumers (25%-40% of their budget is spent on energy) and are therefore willing to find ways of reducing those costs.
- Few legal issues. The restrictions and legal issues involved in installing a turbine in wastewater treatment plants are small compared to other fields of application. There are practically no environmental issues involved (no fish, etc.). Legal issues that arise are limited to municipal bidding / procurement.
- Grants. The government is currently subsidizing research on reducing the energy costs for wastewater treatment plants and implementing the technology. Even though, in a long-term view, subsidies shall not be seen as an important part of the business model; they are an incentive in the stage of product development.

### The Opportunity I - Cost Benefits

The main value of AEC's turbine/generator is its cheap and efficient way to generate energy out of water flows. The levelized cost of energy of the turbine (LCOE), a metric indicating at which costs energy can be generated, is estimated to be under 0.0375$/kWh. This is significantly lower than the average price per kWh of industry applications in New York (0.1529$/kWh[1]). Consequently, the energy savings for WWTPs are large. With these assumptions, a 15kW turbine that could be installed in a medium size WWTP could generate annual cost savings of around $15,000[2].

## The Opportunity II - Environmental Benefits

The environmental benefits are due to the avoided greenhouse gases associated with conventional electricity production. The avoided $CO_2$ gases of a 15kW turbine are around 50 tons per year. Thus, AEC's turbine/generator offers the opportunity to gain almost emission free "green" energy at very attractive cost-levels and contributes to a reduction in greenhouse gases. As a result, the turbine helps municipalities as owners of WWTPs to become greener and to follow the green trend that is furthered by the current federal administration.

## AEC's Customers

AEC's customers are companies that have an interest in licensing AEC's turbine. The following categories of businesses seem to be the most promising customers:

- Private operators of wastewater treatment plants (can use the turbine to lower operating expenses – competitive advantage, e.g. American Water, Veolia)
- Construction companies that build WWTPs (reduction of operating costs, especially green WWTP with very low greenhouse gas emissions as another selling point thanks to turbine)
- Service oriented engineering companies that repair WWTPs (could use turbine to expand their business to selling and maintaining the turbine as their product, share in cost savings as compensation)
- Companies that produce equipment for WWTPs, like pressure reduction valves (valves be designed in such a way that the turbine is included, energy otherwise lost)
- Companies that deliver other technologies for energy savings to WWTPs and could use the turbine as an additional way to save energy.

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[1] http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html, 05/30/2009.

[2] Assume:

- Turbine power: 15,000 Watt (15 kW)
- Levelized cost of energy of the turbine (LCOE): 0.0375$/kWh (costs energy can be generated)
- Energy Price: 0.1529$/kWh (example price, Jan 09, NY)

The energy savings of a 15kW turbine per year are calculated as:

Energy Savings per year: E = (Energy Price – Energy costs turbine)*(hours per year)*Power turbine
= (0.1529$/kWh - 0.0375$/kWh) * 365 * 24h * 15kW
= $15,163

The annual savings in greenhouse gas emissions can be derived from 2005 New York State Energy Fast Facts, published by NYSERDA. According to this report, the annual savings of $CO_2$ are 3.36 tons per year for a 1 kW turbine, making the total annual savings 15kW * 3.36 tons/kW = 50.4 tons.

### End Customers – Decision Makers

The owners of WWTPs are municipalities. This is important, because they will be the final decision maker, deciding if the turbine should be implemented in the plant or not. As a consequence, their specific requirements for the technology will be incorporated in the turbine design. Two issues are very important:

- Municipalities as operators of WWTPs are very risk averse
- Municipalities usually try to avoid large capital investments

AEC takes this into account by using a construction for the installation that minimizes the risk for WWTPs and by suggesting a cost sharing revenue model that requires no initial investment for the municipalities.

### Market Size

There are currently more than 15,000 wastewater facilities in the United States that process 34,000 million gallons of water a day. As much as 24% to 40% of their operating budget is spent on electric energy. New York State alone could decrease costs by about $2 million.
Still not all of the 15,000 WWTPs can be served. Some might have insufficient head, which leads to the case that they have to pump water in the river if there is a flooding. Examples such as this make an implementation difficult, although the turbine is mostly independent from the head and is only affected by the total flow. Additionally, in some states energy prices are not high enough to generate sufficient high energy savings through the turbine. Consequently, a target market with especially promising states was defined.

### Target Markets and Segmentation

AEC will focus its effort to promote (but not limit) its turbine to licensees located in seven different states. These states are New York, New Jersey, Massachusetts, Pennsylvania, Florida, Texas, and California. These states are especially attractive because energy prices and the amount of wastewater in these states are both very high. In Texas (and also Illinois) energy costs are more reasonable, but the large number of WWTPs and the associated flow warrants consideration.

Figure 34 shows the estimated energy prices in the US in 2011. These estimates are based on a rather conservative projection for future energy prices (increase of only 30%). The analysis shows that especially attractive states are California, Florida and many states in the northeast.

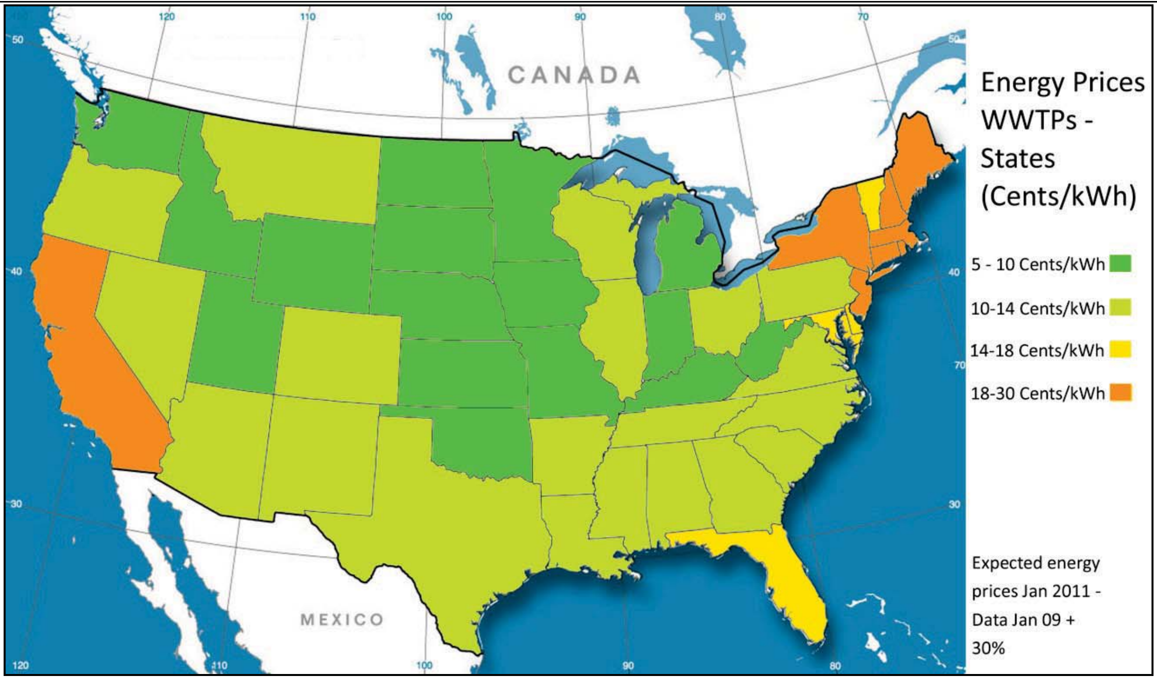


Figure 34: Estimated energy prices in January 2011.

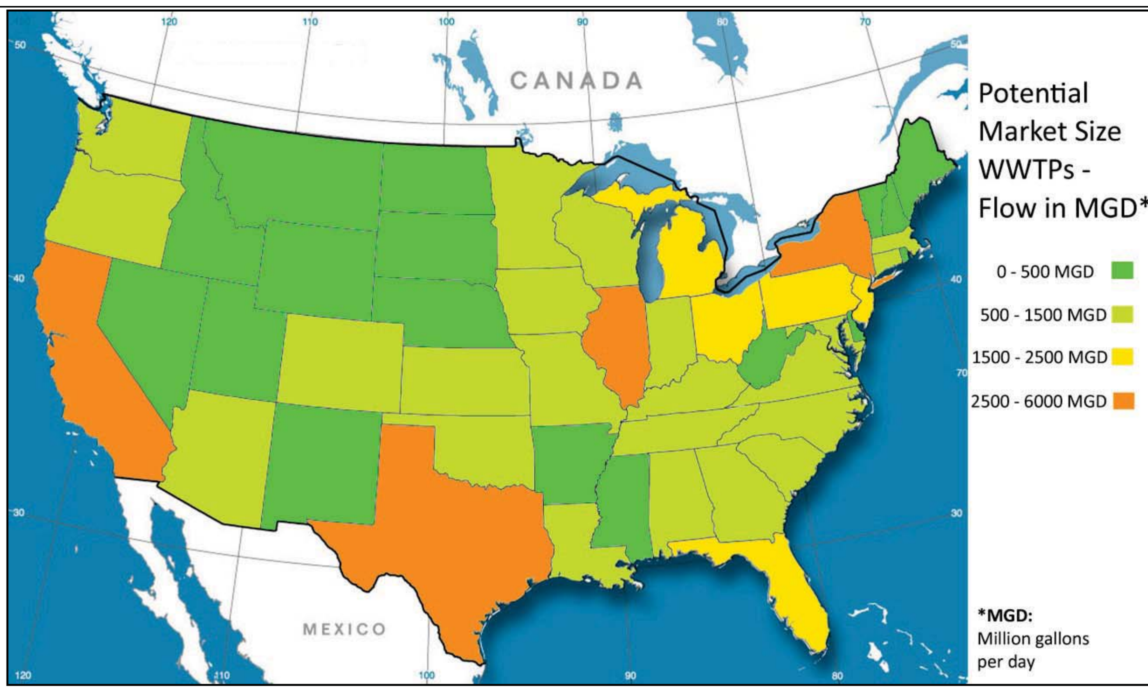


Figure 35: The amount of wastewater by state.

Figure 35 shows how much wastewater is produced in the different states in the US. The scale is million gallons per day (MGD). Again, Florida, California and several states in the northeast seem to be promising. Additionally, Texas is an interesting target.


Figure 36: The identified target market.

Figure 36 shows the result of the analysis, the target market. Seven states were identified that have both high energy prices and plenty of wastewater and are consequently very attractive for AEC and especially its licensees. These states are California, Texas, Florida, Pennsylvania, New Jersey, New York, and Massachusetts.

The segmentation for the licensees will be regional. Probably, there will be one license per state and in large states, like California, maybe two, divided by region, e.g. north and south. The total amount of wastewater treatment plants in the target market that can also be served by the technology is around 2600. With potential energy savings between $5,000 and $30,000, the total amount of potential energy savings in the whole target market per year is somewhere between $13 million and $78 million. An exact calculation cannot be given, because the potential energy savings per WWTP depend on many different factors that are only in parts publicly available.

### Market Trends – Increasing Energy Prices

One of the major trends that would help AEC to become significantly more profitable is a rising energy price. The futures for many resources that are highly correlated to the energy prices indicate that the market expects doubling energy prices within the next year (for details see research paper one). This would increase the potential energy savings of a WWTP through the turbine significantly and would improve the attractiveness of the turbine even further.

Additionally, a higher market share through the improved attractiveness of the turbine is likely and will boost the profits even more.

## Market Trends – Increasing Governmental Support

Through the American Recovery and Reinvestment Act (ARRA), the economic stimulus especially in the fields of green energy means a great chance for all companies active in that sector. President Obama already announced that 25% of the US's energy should be gained through renewable sources by 2025. The FERC estimates, that up to 20% of the hydropower generation in the Unites States can be produced by hydrokinetic turbines (currently: less than 10%).Thus, this is a growing market for AEC's turbine/generators and further governmental support for the technology likely.

## Market Trends - WWTPs Invest in Improving Energy Efficiency

As a result of the two prior defined trends, many WWTPs are currently seeking improvements in the form of new motors, better pumps and aeration systems to reduce the needed amount of energy. They are considered to be worthwhile investments by many WWTPs. Consequently, a hydrokinetic turbine that helps to reduce the energy costs significantly without interfering in the daily operation of the WWTP should find many supporters among operators of WWTPs. AEC should use this trend and leverage its potential benefits. Additionally, currently many WWTPs need renovations or have to be rebuilt in what is another opportunity for AEC to offer its turbine as a way to further increase the efficiency and environmental attractiveness of the new or renovated WWTPs.

## Competition

The turbine/generator has to face competition not only against similar technologies but also against technologies that extract renewable and clean energy from other sources. WWTPs can only invest in a limited number of technologies due to their limited budget.

### Direct Competitors

Several competitors are currently offering micro hydro-turbines. Except for Community Hydro and Rentricity, they are not (yet) targeting the wastewater treatment facility market.
Many manufacturers or project companies furthermore focus on applications in streams (rivers, canals, etc.). This might be kept in mind before considering an expansion of the target market. It is also possible that those companies may decide to enter the WWTP market.

### Competing Technologies

The most critical competing technologies are probably the gas turbine and Stirling engine. The prices are very competitive in comparison to alternative sources of renewable energy and a high number of WWTPs in the "target" states are using anaerobic digestion (necessary for gas turbines and Stirling engines). They are using the unique sources of energy (unlike wind power or photovoltaic) that can be found at WWTPs and that might otherwise be lost.

Wind power may seem like a relatively good source of renewable energy; it is, however, a rather unreliable source of energy and is often overestimated (and siting of WWTP are typically low elevations due to gravity feed while wind is typically sited at high elevations due to less ground friction and higher wind speeds). The popularity of solar energy is growing quickly. Still, solar energy has significantly higher LCOE than AEC's hydrokinetic turbine. Nevertheless, there are strong incentives from the government to invest in wind energy or solar panels. Fuel cells are currently still too expensive, too new and unreliable, but they might become a future threat through massive incentives that are provided for this energy from NYSERDA.

**Expected Actions of Competitors**

So far, no direct competition is expected in the niche market of wastewater treatment facilities. The market size is rather limited, which makes this market not very attractive for large companies, like GE. This reduces the threat of a market entry of a large energy company significantly. Consequently, the niche market WWTPs becomes even more attractive for AEC. Nevertheless, it is likely that other direct companies that produce hydrokinetic turbines would try to enter the WWTP market as well, if AEC achieves a big success in this market. Consequently AEC will try to erect market entry barriers through a strong branding and potentially through long-term contracts with licensees.

**Expansion to Other Markets**

The decision to enter a different market than the WWTP market is a great opportunity for AEC. The number of wastewater treatment facilities is limited and consequently the total profit opportunities in this niche market are limited as well. Exploiting new markets would provide AEC with great potential profit opportunities.

The target group that could be served by AEC through modifying its turbine is quite large. Any businesses that operate in the United States and process wastewater effluent streams, e.g. industrial processes that are heavy users of water, and also the state and provincial government, municipalities, that are the owners of the Water Energy Resources, can be included in the target group.

The largest category of water withdrawals for year 2000 was thermoelectric power (48% of total withdrawals). Irrigation accounted for 34%, public supply 11%, and self-supplied industrial 5% of the total withdrawals. The major categories of water withdrawals that produce large outflow are: industrial, mining and thermoelectric-power withdrawals. Water for thermoelectric power is used in generating electricity with steam-driven turbine generators. The total quantity of water withdrawn for thermoelectric power for year 2000 was an estimated 195,000 MGD (total amount wastewater US: 34,000 MGD). The largest total water withdrawals were in Texas, California, Florida, Illinois, states where there is also significant wastewater effluent.[3] Consequently, this could be potential target markets for a future expansion.

Some industries that use large amounts of water produce food, paper, chemicals, refined petroleum, or primary metals. Industrial withdrawals for year 2000 were an estimated 19,700 MGD. The largest total water withdrawals were in Louisiana, Indiana, and Texas (almost 38% of

[3] Thermoelectric Power, Estimated Use of Water in the United States in 2000, http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-pt.html.

total industrial withdrawals)[4]. Mining withdrawals for year 2000 were an estimated 3,490 MGD. The largest total water withdrawals were in Texas, Minnesota and Oklahoma[5].

Currently, a large number of environmental, legal, and institutional constraints restrict the market entry in the US. This is one main reason why AEC focused development work on the WWTP market. Besides this, AEC's decision to enter the WWTP market prior to other Water Energy Resources markets was influenced by the strong governmental incentives (grants) and few legal issues involved.

The U.S. Department of Energy (DOE) has estimated that approximately 5,400 sites (rivers, canals, etc.) could potentially be developed as small hydro plants and that those sites have a total hydropower potential of a little over 18,000 MWs. The feasible potential hydropower of the United States can be estimated approximately $18,800 million[6].

All of the states are underutilizing their natural stream water energy resources and could realize significant gains in generation from new hydroelectric plant development. [7] This is a vast market and there are a large number of opportunities for AEC to sell their product and increase U.S. hydroelectric generation. This makes AEC's hydrokinetic turbine project even more attractive and shows its huge profit potential, which could be achieved through relatively small product modifications.

## Cost of Market Entry

Research shows that the market requires a cost for the turbine/generator system to be $1500/kW for prototype quantities, moving toward $900/kW for production quantities. Table 4 summarizes projections of system cost for annual quantities of 1000 units. Assumptions associated with this cost projection include:

- Tooling is amortized over the first 1000 units
- Rated power of the turbine/generator system is 15kW
- Cast components include: the turbine runner, the stator backbone, the stator end cap, the turbine baseplate assembly, and the upstream encapsulator; and
- Minimal machining is required for cast components.

[4] Industrial, Estimated Use of Water in the United States in 2000, http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-in.html.
[5] Mining, Estimated Use of Water in the United States in 2000, http://pubs.usgs.gov/circ/2004/circ1268/htdocs/text-mi.html.
[6] U.S. Department of Energy, Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants (report), 2006
[7] The U.S. Department of Energy, Wind and Hydropower Energy Program, http://www1.eere.energy.gov/windandhydro/.

| Table 4: A summary of projected costs for a 15kW turbine/generator system in annual volume of 1000 units. | | |
|---|---|---|
| **Element** | **Cost Basis** | **Cost** |
| Cast components | Quotation | $3,440 |
| Casting tooling amortization | Quotation | $1,506 |
| Finish machining of castings | Estimate based on prototype costs | $925 |
| Generator stator/rotor stacks | Estimate based on scaling other designs | $3,332 |
| Magnets | Estimate based on scaling other designs | $979 |
| SMR/Inverter | Industry norms | $2,250 |
| Bearings, mechanical components | Estimate | $325 |
| **Materials Subtotal** | | **$12,757** |
| Labor for assembly | 4 hours @ $30/hour, fully loaded | $120 |
| Warranty Cost | 5% of COGS | $644 |
| Shipping Cost | | $125 |
| **Total COGS** | | **$13,646** |
| Profit | 40% gross margin | $9,097 |
| **Selling Price** | | **$22,743** |
| **Cost/kW** | | **$1,516/kW** |

The data in Table 4 indicate cost reductions are necessary before the turbine/generator system can be economically attractive without reliance on government-based incentive programs.

It will be appreciated that the majority of the cost for the system is in the turbine/generator hardware, rather than the electronics. To drive down the cost, it is necessary to process more power with the same hardware. This may be possible by applying the turbine/generator to applications that support higher head, thereby giving more output power with the same flow.

## Summary

This report has documented the design, development, and testing of an integrated turbine/generator system for extraction of energy from wastewater effluent. The majority of the technical objectives were accomplished. In parallel with the technology development activities, considerable effort was put into analyzing the potential market for the technology.

In summary:

- A technical specification for the prototype turbine/generator system was developed using analysis of the wastewater market in New York, with the assumption that the market in other states would be similar.
- Concurrent design of the turbine/generator system was undertaken. To simplify the overall structure of the system, a propeller-type turbine was selected. This choice was also consistent with the relatively low heads available at wastewater treatment plants. The rotor of the generator was integrated into the outer rim of the turbine rotor.
- Design of the turbine rotor was supported by one- and three-dimensional flow analysis that was subsequently verified using computational fluid dynamics (CFD) analysis.

- The generator design was based on a fractional slot stator winding that minimized end turn length and simplified the construction of the stator.
- The stator of the generator was integrated into the mechanical design of the turbine/generator support structure. This support structure included a tapered inlet section that allowed the entire turbine/generator to be housed within a section of pipe that was of standard size. Mounting the turbine generator within a section of pipe allows for turbine/generator maintenance without putting personnel at risk or requiring the flow at the WWTP outfall to be shut down, even temporarily.
- Fabrication and test showed that the integrated system operated largely as designed. The significance of the turbine efficiency curve on system performance was underestimated during the design process. In hindsight, it might have been appropriate to select a different type of turbine with a broader efficiency curve. Selecting another style of turbine, however, would have substantially complicated the system design because of the challenges associated with routing the fluid through the turbine and generator.
- An analysis of the potential turbine/generator market within wastewater treatment plants suggests a potential United States market size of $50 -- $100 million by serving the 2,600 wastewater treatment plants that are viable candidates for the technology. Accessing this market will require modest cost reductions in the turbine/generator system that should be achievable.
- Extending the turbine/generator to other markets is possible. Still, these markets are likely characterized by requiring higher head. Operating at higher head allows the possibility of increased energy capture without substantially increasing the size of the turbine/generator. Operation at higher head would require the selection of a different type of turbine, which might improve overall system operation over varying speeds. It would be vital to maintain as much simplicity in system design as possible.

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# Hydropower from Wastewater

Final Report
December 2011

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